PHOTOVOLTAIC NOISE BARRIERS: SCOPE FOR SMALL AND MEDIUM-SCALE DEMONSTRATION SCHEMES AT SURFACE LOCATIONS ON THE LONDON RAIL NETWORK

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Appendix A. Factsheets on applying PV noise barrier concepts
Executive summary

The Mayor's Ambient Noise Strategy seeks a higher profile for reducing noise in the management of transport systems, including railways. Policy 21 of the Strategy states that Transport for London will be expected to "Investigate the potential for noise barrier-integrated photovoltaic power generation along suitable railway lines."

As part of work towards achieving these objectives, Greater London Authority have commissioned TRL Limited to undertake a study identifying potential small-scale and medium-scale sites for the demonstration of photovoltaic noise barriers on the surface sections of the London Underground system. Discussions with London Underground (LU)/TfL have indicated limited potential for photovoltaic noise barriers in the context of current constraints and cost-effectiveness. The majority of asset-related noise complaints on the LU network are as a result of ground-borne noise and vibrations, which cannot be addressed using noise barriers. The scope of the project has therefore been extended to include both Network Rail (NR) and Docklands Light Railway (DLR)

This report provides an overview of the concepts behind PV systems and describes the criteria that need to be taken into account both from an acoustic-related and energy-related perspective when reviewing the use of noise barriers and PV noise barriers alongside railways. These criteria have been balanced against the specific requirements of LU/TfL, NR and DLR for the placement of noise mitigation measures, taking into account that noise barriers might be required in the future in response to the noise maps and action plans produced in accordance with the EU Directive on Environmental Noise (END). A series of factsheets giving advice on how possible PV noise barrier concepts might be applied have been prepared.

The opportunities for potential demonstration sites on the network are also discussed as part of this report.
1 Introduction

The Mayor’s Ambient Noise Strategy (Greater London Authority, 2004a) seeks a higher profile for reducing noise in the management of transport systems, including railways. Policy 21 of the Strategy states that Transport for London (TfL) will be expected “… taking particular account of vandalism, visual amenity, historic building and conservation issues, to:

- Examine the scope for promoting the safe and cost-effective use of railway noise barriers, where source-related measures would not be effective;
- Consider securing noise benefits from routine renewal or improvement of boundary walls/security fencing, including at ventilation ducts, and in the refurbishment of structures, notably bridges;
- Investigate the potential for noise barrier-integrated photovoltaic power generation along suitable railway lines."

The Mayor’s Energy Strategy (Greater London Authority, 2004b) indicated a desire to see renewables make a major contribution to London’s future economy and energy supply mix. Policy 9 of the Strategy states that “The Mayor considers that London should seek to maximise its own generation of renewable energy through developing urban renewables, and use its considerable purchasing power to support renewable energy across the rest of the UK.”

As part of work towards achieving these objectives, Greater London Authority (GLA) have commissioned TRL Limited to undertake a study identifying potential small-scale and medium-scale sites for the demonstration of photovoltaic noise barriers on the surface sections of the London Underground system.

This report describes the criteria that need to be taken into account both from an acoustic-related and energy-related perspective when considering the use of noise barriers and PV noise barriers alongside railways. These criteria have been balanced against the specific requirements of LU/TfL for the positioning of noise mitigation measures.

Following initial discussions with LU, the scope of the investigation has been extended to also include an assessment of the criteria that are applicable to those parts of the London rail network owned/operated by Network Rail (NR) and Docklands Light Railway (DLR).

To assist in the future, wider use of noise barriers on the London rail network (Underground, mainline rail and DLR) system in the longer term, a series of factsheets have been prepared which set out clearly the design considerations for photovoltaic noise barriers and the most promising locations. These factsheets are included in the Appendix to this Report.
2 Overview of the principles behind photovoltaic (PV) systems

The following text provides a short overview of photovoltaic (PV) systems. More detail, including an environmental lifetime assessment, can be found in the TRL report by Carder (2003).

2.1 What are PV cells?

PV cells, which convert sunlight into electricity, are solid-state devices composed of thin layers of semi-conductor materials that produce an electric current in a suitable circuit when exposed to light. Most commercially available cells are manufactured from silicon although other materials are sometimes used. Crystalline types (monocrystalline or polycrystalline\(^1\)) are preferred because they have an electrical efficiency approximately 50% greater than amorphous cells\(^2\). However in the long term, amorphous materials may offer good potential as the cost is likely to reduce by mass production and they respond to a broader range of frequencies than crystalline types. Furthermore, amorphous PV cells are more resistant to vandalism and damage than crystalline cells.

Cells are typically combined into modules that hold about 40 cells. These modules are generally mounted in frames to create a rigid structure. Depending on the size of the desired PV array, modules can then be connected together to form large flat plates/panels.

Whilst the use of flat panels is the most common approach, other configurations have been developed and are available, e.g. parabolic or dish shapes, but these often require tracking systems to maximise output and solar energy collection.

It should be noted that the sizes of commercially available PV modules are usually pre-defined by the manufacturer, and although modules can be grouped to form different size arrays/panels, custom-sized modules to fit a specific application are generally not available.

2.2 What power is produced by PV cells and how is it applied?

PV cells produce direct current (DC) electricity, although adding an inverter to the system allows the production of alternating current (AC). When an inverter is added to the photovoltaic system, a loss of power output of 5-15% occurs. Most electrical appliances and plant are designed to use AC electricity and so an inverter is necessary (more information on inverters can be found in the TRL report by Carder (2003)). Systems may be either connected to an electric utility grid (grid-connected) or “stand-alone” with back-up from either a battery or alternative power source.

Grid-connected systems are designed to operate in parallel with and are interconnected with the electric utility grid. Figure 2.1 shows the basic principal behind such a system. In this example, the AC load is the application/utility to which the array is providing power. “Excess” power is fed into the utility grid; however, when the array provides insufficient power to the application/ utility, the shortfall in power is drawn from the utility grid.

In many of the scenarios related to PV noise barriers, it is most likely that the inverter will be connected into the domestic grid which supports residential properties behind the barrier.

It is necessary to incorporate a conventional electricity meter into the system if the system to which the array is providing power is supported by the utility grid when there is insufficient

\(^1\) Monocrystalline silicon is that which exists in the form of single crystals; polycrystalline silicon consists of small interconnected crystals, which have a size ranging from a few millimetres to centimetres, and is the easier to manufacture than monocrystalline silicon.

\(^2\) Amorphous silicon is where the atoms are arranged irregularly, resulting in a layer thickness of only 0.5 μm. Amorphous PV cells can be manufactured using thin film technology.
power from the array, or if computer logging is being used to monitor the performance of the array. This will log the amount of electricity being used.

![Diagram of a grid-connected PV system](attachment:grid_CONNECTED_PV_system_diagram.png)

**Figure 2.1: Example of a grid-connected PV system**

*Stand-alone systems* operate independently of the electric utility grid. On the following page, Figure 2.2 shows the simplest type of stand-alone arrangement and Figure 2.3 illustrates the basic principal of a stand-alone system with battery storage.

The power output from a PV array is generally expressed in terms of “peak watts (Wp)”, which is a measure of the power produced under optimal conditions when solar irradiation of 1000 W/m² in the reference spectrum AM 1.5⁴ falls on the photovoltaic cell at 25°C.

The power output from a PV array can also be expressed in terms of Performance Ratio (PR), which is the ratio between the actual power output from the array per day and the theoretically available energy output per day based on in-plane irradiation. An assessment of the performance of 260 PV plants listed in an International Energy Agency database (Jahn et al., 2000) has indicated that the following typical performance ratios can be expected:

- Grid connected system: \( 0.6 < \text{PR} < 0.8 \);  
- Stand-alone system without backup: \( 0.1 < \text{PR} < 0.6 \);  
- Stand-alone system with backup generator: \( 0.3 < \text{PR} < 0.6 \).

---

³ The Air Mass 1.5 (AM1.5) standard reference spectrum defines the solar spectral irradiance distribution (diffuse and direct) incident at sea level on a sun-facing 37-degree tilted surface under the following atmospheric conditions: precipitable water vapor, 14.2 mm; total ozone, 3.4 mm; turbidity (base e, lambda=0.5 mm), 0.27. [ASTM Standard G-173-03 (ASTM, 2003)]
2.3 What are the general factors affecting the performance of PV arrays?

For optimum efficiency, the PV array should be oriented along an east-west axis, with the energy collecting surfaces of the array facing south. Calculating the loss in efficiency due to an array not being aligned along this axis cannot easily be calculated.

The angle of inclination of a PV array will affect its performance. The angle of the array needs to be optimised to obtain the greatest benefit, ideally being at 90 degrees to the incident energy. Based on an average of data at various locations across the UK, the angle of the sun (to the horizontal) is generally between 10-15° in January and 55-65° in July. Figure 2.4 illustrates the angle of PV arrays optimised for different conditions. This variation in angle means that on a clear day in July, the solar energy received in the UK may be approximately 6 kWh/m², however in January the energy received can be as low as 0.5 kWh/m².

The usable power output from a south-facing installation in the UK would be expected to be approximately 750 kWh per annum per kWp output from the array, assuming typical weather conditions, etc.
The angle of the array will also be influenced by whether the array installation is connected to the electric utility grid (or providing input into a local network/localised supply) or is providing power directly to a standalone installation.

- Grid connected systems are generally optimised for maximum energy during the summer;
- Systems that are not grid-connected and which provide direct power to stand-alone installations are generally optimised for maximum energy collection during the winter months.

As a compromise, large-scale PV arrays in the UK are normally aligned at 25-35 degrees from the horizontal. This angle is considered to have been derived from the application of PV arrays on roofs, etc; individual small-scale arrays, such as those used to provide power to illuminated warning signs, are normally inclined at far greater angles and used in conjunction with other energy generation systems to provide power when the arrays are not exposed to adequate sunlight.

In the Highways Agency (HA) trial of PV barriers on the M27 (see Section 3.1 for further details), the panels are inclined at 60° and 68° to try to minimise the footprint of the barrier whilst retaining sufficient angle for the panels to be useful.

A minimum inclination of 15° degrees to the horizontal is generally sufficient for the panels to be cleaned by rainfall.

It is estimated that the power output of the array with respect to the sun’s angle of incidence can be approximated by a cosine function for angles from 0-50°. Beyond an incident angle of 50°, the available solar energy drops off rapidly, becoming negligible at 85°.

### 2.3.1 Expected lifetime of solar panel systems

Manufacturers of PV modules generally give warranties on performance in terms of the power output which they will continue to deliver whilst in service. In most cases, these warranties guarantee good performance for a period of twenty to twenty-five years. This period may be fairly conservative as some of the earliest solar panels, which were made about 35 years ago, are still producing energy today.
2.3.2 Examples of commercially available PV components

Table 2.1- Table 2.3 provide a very limited sample of the different PV arrays that are available on the market, illustrating the different sizes and power outputs. The costs shown in the Table are based on prices obtained from various wholesale outlets identified from the internet and are intended for illustrative purposes only. These costs do not include the costs of inverters, installation, fittings, etc.

The manner and configurations in which PV components might be installed on a noise barrier, as well as the proposed use for the collected energy, will influence the choice of panels for each individual case.

Table 2.1: Examples of commercially available amorphous PV modules and laminates

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>PV type*</th>
<th>Model No.</th>
<th>Size [length x width x depth] (mm)</th>
<th>Weight (kg)</th>
<th>Peak Power per module (Wp)</th>
<th>Total Cost (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uni-Solar (uni-solar.com)</td>
<td>FM</td>
<td>US-64</td>
<td>1345 x 730 x ?</td>
<td>9.1</td>
<td>64</td>
<td>399</td>
</tr>
<tr>
<td></td>
<td>FM</td>
<td>ES-62T</td>
<td>1258 x 793 x 32</td>
<td>10.9</td>
<td>62</td>
<td>350</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>PVL-136</td>
<td>5486 x 394 x 2.5</td>
<td>7.7</td>
<td>136</td>
<td>400</td>
</tr>
</tbody>
</table>

* FM: Framed module; L: Laminate  ** Cost rounded to nearest £25
† Based on nearest whole number of panels to generate 1 kWp
†† Based on nearest whole number of panels to cover 100m²

Table 2.2: Examples of commercially available monocrystalline PV modules

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>PV type*</th>
<th>Model No.</th>
<th>Size [length x width x depth] (mm)</th>
<th>Weight (kg)</th>
<th>Peak Power per module (Wp)</th>
<th>Total Cost (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE Energy (formerly Astropower) gepower.com/solar</td>
<td>FM</td>
<td>GEPV-050</td>
<td>858 x 661 x 54</td>
<td>7.5</td>
<td>50</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>FM</td>
<td>GEPV-110</td>
<td>1485 x 666 x 55</td>
<td>11.9</td>
<td>130</td>
<td>350</td>
</tr>
</tbody>
</table>

** Cost rounded to nearest £25
† Based on nearest whole number of panels to generate 1 kWp
†† Based on nearest whole number of panels to cover 100m²
Table 2.3: Examples of commercially available polycrystalline PV modules

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>PV type*</th>
<th>Model No.</th>
<th>Size [length, width, depth] (mm)</th>
<th>Weight (kg)</th>
<th>Peak Power per module (Wp)</th>
<th>Total Cost (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evergreen Solar</td>
<td>FM</td>
<td>EC-100 series</td>
<td>1588 x 653 x 35</td>
<td>12.7</td>
<td>110, 115 or 120</td>
<td>325 *** 2925*** 31,200</td>
</tr>
<tr>
<td>evergreensolar.com</td>
<td></td>
<td></td>
<td>325 ***</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kyocera</td>
<td>FM</td>
<td>KC130GT</td>
<td>1425 x 652 x 36</td>
<td>12.2</td>
<td>130</td>
<td>£325 2275 34,775</td>
</tr>
<tr>
<td>kyocerasolar.com</td>
<td></td>
<td></td>
<td>1425 x 652 x 36</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BP Solar</td>
<td>FM</td>
<td>BP 350</td>
<td>839 x 537 x 50</td>
<td>6.0</td>
<td>50</td>
<td>£200 4000 44,200</td>
</tr>
<tr>
<td>bp.com</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>
| We have already stated that the usable power output from a south-facing installation in the UK would be expected to be approximately 750 kWh per annum per kWp output from the array, assuming typical weather conditions, etc. Considering two of the options from the above Tables (UniSolar ES-62T modules and PVL-136 laminates), which are similar to those used on the HA M27 survey, then we can make the following calculation:

<table>
<thead>
<tr>
<th>Module / Laminate</th>
<th>No. required to cover 100 m²</th>
<th>Total cost of panels*</th>
<th>Peak power of array (Wp)</th>
<th>Annual energy generated (kWh)</th>
<th>Cost of energy generated (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ES-62T</td>
<td>100</td>
<td>35,000</td>
<td>6.2</td>
<td>4650</td>
<td>418.50</td>
</tr>
<tr>
<td>PVL-136</td>
<td>46</td>
<td>18,000</td>
<td>6.2</td>
<td>4650</td>
<td>418.50</td>
</tr>
</tbody>
</table>

* It is expected that costs would be lower due to discounts for bulk purchase

assuming that 1 unit of electricity (1 kWh) costs £0.09 inc VAT. The annual household energy consumption for a typical 3 bedroom house is estimated to be approximately 4200 kWh. Based on these costs (noting that the cost of the PV system is based on the modules alone, i.e. there are no costs included in this calculation for the additional components required by such a system, nor for installation or maintenance etc), it is seen that the time required to recoup the costs of the PV installation are considerable. Clearly, at the current time, the approach does not appear to be cost-effective. However, if multiple large arrays could be installed as part of a single system, the costs of the PV system would be reduced and the payback period also reduced.
3  Review of PV noise barrier trials elsewhere in Europe

Various demonstration projects of PV noise barriers have been undertaken in Europe in recent years, although these have been predominantly confined to barriers alongside highways. The following section provides a brief overview of the different schemes and, in relation to railway noise barriers, addresses the use of standard barriers as well as those fitted with PV arrays.

3.1  Experiences with PV noise barriers alongside highways

Electricity generated from PV cells has many current applications at small scale on the highway network. Highway safety equipment (such as roadside call boxes, lighted highway signs) is increasingly being powered by solar systems, particularly in remote locations. These uses have been reviewed by Carder (2001). However, the larger scale application of PV cells on the highway network is less common. Buildings (e.g. maintenance depots, pumping stations, control rooms, etc.) and structures (e.g. bridges, sign gantries, lighting gantries, etc.) provide potential locations for the installation of solar panels. However the following overview is restricted to the use of PV cells on noise barriers.

The first trial combining noise barriers and PV arrays took place in 1989 in Switzerland and demonstration projects have subsequently been carried out in several countries across Europe. Table 3.1 on the following page provides a summary of some of these different projects; all of these systems are grid-connected, i.e. they feed power directly into the main electricity network.

Bi-facial barriers (i.e. PV cells on both sides of the barrier) are less common and in fact only one example of such a barrier has been constructed. Further details on some of the individual projects can be found in the TRL Report by Carder (2003). The authors are also aware of a small number of other projects, but these are not included due to the limited amount of information available. These projects are included in a list which can be found at pvresources.com (www.pvresources.com/en/noise.php).

In the UK, a trial of PV noise barriers is presently being carried out on the M27 near Southampton, as shown in Figure 3.1 (Carder and Barker, 2006). Both the upper and lower barrier in the Figure are approximately 55 m long, with a DC peak power output of 5.12 kWp. The panels are inclined at 60º and 68º to try to minimise the footprint of the barrier whilst retaining sufficient angle for the panels to be useful. Groups of the panels are connected to junction boxes and double pole isolators within each barrier and then to the DC input of an inverter. Two inverters were used for each barrier with their outputs being fed as three phase AC electricity at a nominal voltage of 230 to 240v to a nearby transformer pole owned by the Scottish & Southern Energy PLC.

![Figure 3.1: Photovoltaic noise barriers in the M27 at Southampton](image-url)
To put the annual outputs into perspective, it is estimated that the annual household energy consumption for a typical three-bedroom house is approximately 4200 kWh.

Figure 3.2 shows one example of a photovoltaic road-traffic noise barrier on the A27 at Utrecht in the Netherlands (see above Table for details of the barrier). Figure 3.3 shows an example of PV arrays being used as both a parapet and noise barrier on an elevated section of highway on the A31 near Emden in Germany.

Studies have also been carried out on the feasibility of zig-zag structures to combine noise absorption (on the elements of the barrier facing downwards) with the production of solar energy (from the elements of the barrier facing upwards). An international ideas competition was organised and the six winning concepts taken forward for testing are described by Frolich (2000).

** Table 3.1: Summary of European PV noise barrier trials alongside highways **

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>DC Peak Power (kWp)</th>
<th>Annual power output (kWh)</th>
<th>Barrier length (m)</th>
<th>PV panel description</th>
<th>Inclination and orientation</th>
<th>No. of modules</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>A9 Ouderkerk-aan-de-Amstel, The Netherlands</td>
<td>220</td>
<td>176,000</td>
<td>1650</td>
<td>Top mounted</td>
<td>50 S – SW</td>
<td>2160</td>
</tr>
<tr>
<td>1995</td>
<td>A27, Utrecht, The Netherlands</td>
<td>55</td>
<td>30,000</td>
<td>550</td>
<td>Top mounted</td>
<td>50 SW</td>
<td>1116</td>
</tr>
<tr>
<td>1999</td>
<td>A21, Foquaire, France</td>
<td>63</td>
<td>Not known</td>
<td>650</td>
<td>Top mounted (Upper half of 4 m high barrier is made up of PV cells)</td>
<td>Not known</td>
<td>2000</td>
</tr>
<tr>
<td>1989</td>
<td>N13, Domat/Ems, Switzerland</td>
<td>100</td>
<td>110,000</td>
<td>800</td>
<td>Top mounted</td>
<td>45 SSE</td>
<td>2208</td>
</tr>
<tr>
<td>1995</td>
<td>N2, Giebenaach, Switzerland (1995)</td>
<td>104</td>
<td>97,000</td>
<td>752 m² (Length unknown)</td>
<td>Panels mounted on non-traffic side of barrier</td>
<td>Not known</td>
<td>Not known</td>
</tr>
<tr>
<td>1992</td>
<td>A1, Gleisdorf, Austria</td>
<td>40</td>
<td>31,500</td>
<td>264</td>
<td>Unknown</td>
<td>Not known</td>
<td>Not known</td>
</tr>
<tr>
<td>1995</td>
<td>A6/A620, Saarbrücken, Germany</td>
<td>40 &amp; 20</td>
<td>50,000 &amp; 217</td>
<td>232 &amp; 217</td>
<td>40 kWp array incorporated into transparent sound reflecting acrylic panels</td>
<td>Not known</td>
<td>Not known</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20 kWp array extends along sound absorptive, non-transparent barrier</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td>A1, Zurich-Aubrugg, Switzerland</td>
<td>10</td>
<td>Not known</td>
<td>120</td>
<td>Bifacial (full height PV panels on both sides)</td>
<td>Vertical &amp; W E</td>
<td>Not known</td>
</tr>
</tbody>
</table>

** Size of individual modules used on these barriers is not known **

To put the annual outputs into perspective, it is estimated that the annual household energy consumption for a typical three-bedroom house is approximately 4200 kWh.

Figure 3.2 shows one example of a photovoltaic road-traffic noise barrier on the A27 at Utrecht in the Netherlands (see above Table for details of the barrier). Figure 3.3 shows an example of PV arrays being used as both a parapet and noise barrier on an elevated section of highway on the A31 near Emden in Germany.

Studies have also been carried out on the feasibility of zig-zag structures to combine noise absorption (on the elements of the barrier facing downwards) with the production of solar energy (from the elements of the barrier facing upwards). An international ideas competition was organised and the six winning concepts taken forward for testing are described by Frolich (2000).
3.2 Noise barriers and PV noise barriers for railways

The use of railway noise barriers in general does not appear to be widespread across Europe. However, Switzerland makes extensive use of noise barriers on the national network; according to current plans, approximately 271 km (9%) of the Swiss rail network will be equipped with noise barriers by 2015 (Swiss Federal Railways, 2004). Railway noise barriers are also known to be used in Finland. In the Helsinki metropolitan area, approximately €13 Million has been spent on the construction of noise barriers in the period 2000-2005 (Finnish Rail Administration, 2006). The barriers along the Kerava–Lahti railway line (see Figure 3.4) are the largest single noise barrier project in Finland. This project involves approximately 7 km being installed by autumn 2006; an additional 1 km of plot-specific barriers (i.e. barriers to screen individual buildings or small groups of buildings) will additionally be installed close to towns and cities.

Railway noise barrier installation has generally been difficult to achieve in the UK, due in part to safety concerns. However, they have been introduced in some London Boroughs, Kent and Surrey to reduce noise from intensified freight traffic as a result of the opening of the Channel Tunnel, and are also used on the Channel Tunnel Rail Link (CTLR), i.e. their use is generally restricted to new-build lines rather than as mitigation on existing lines.
On the first section of the CTLR running from the Channel Tunnel to Fawkham near Swanley in Kent, which was opened for commercial service in September 2003, over 20 km of noise have been installed (Glover, 2003). Two types of barrier have used. The first type are timber barriers up to 5 m high, comprised of machined tongue-and-groove softwood timber planks 35 mm thick on vertical supports. Absorptive linings secured by perforated steel panels have been used in some cases. The second type are low-level barriers installed closer to the wheel rail interface. These are 1.4 m high galvanised steel panels with absorptive linings protected by profiled, perforated steel panels, and mounted on the track ballast retention kerb. (Johnson, 2003). Of the remaining 39 km, which is due to open in 2007, 19 km will run in tunnels; the status and type of barriers to be used on the surface sections is not known.

Various types of noise barrier have also been used on the Docklands Light Railway (DLR) in London. In 1993/4, high level, absorptive timber noise barriers were installed alongside track running through a residential area on the north route of the railway between All Saints and Devons Road stations. In 1994, high-level metal clad absorptive noise barriers were erected between Limehouse and Westferry stations, mounted on a Victorian brick viaduct situated within a medium rise residential area.

DLR's research and development programme has resulted in the use of absorptive timber noise barriers spanning between steel posts cantilevered off the sleeper ends, so as to keep the barrier as close as possible to the kinematic envelope of the rolling stock. An example of these low-level barriers is shown in Figure 3.5.

A review of the literature has identified relatively few examples where photovoltaic systems have been used in conjunction with noise barriers on railways. The main two sites are listed in Table 3.2. Generally, the PV arrays are installed on the side of the barriers facing away from the track.

---

4 The kinematic envelope defines the envelope within which the rolling stock is contained when operating.
Figure 3.5: Low-level noise barriers in use on the Docklands Light Railway  
(Reproduced by kind permission of Gramm Barrier Systems, www.grammbarriers.com)

Table 3.2: Summary of European PV noise barrier trials alongside railways

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>DC Peak Power</th>
<th>System type</th>
<th>Barrier length</th>
<th>Array mounting</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>Vaterstetten, Germany</td>
<td>180 kW</td>
<td>Grid connected</td>
<td>400 m</td>
<td>Cap fitting</td>
</tr>
<tr>
<td>1998</td>
<td>Zürich – Wallisellen, Switzerland</td>
<td>9.6 kW</td>
<td>Grid Connected</td>
<td>Unknown</td>
<td>Integrated part of barrier structure</td>
</tr>
</tbody>
</table>

Photographs of the two designs are shown in Figure 3.6. They clearly show how the designs can be incorporated as an additional element on the top of an existing barrier or directly as part of the main barrier structure itself. No information is available on how these barriers are supported.

(a) Noise barrier fitted with PV array, Vaterstetten, Germany  
Reproduced by kind permission of Phönix SonnenStrom AG

(b) Aluminium cassette noise barrier fitted with PV laminates, Wallisellen, Switzerland  
Reproduced by kind permission of TNC Consulting AG  
(Copyright TNC Consulting AG)

Figure 3.6: Examples of photovoltaic noise barriers trialled on railways in Germany and Switzerland
No performance information other than the DC peak power is available for the German trial. The zig-zag barrier construction used in the Swiss scheme (Figure 2.1b), most likely based around panels which are sound absorptive on the track-facing side, was situated in a densely inhabited area with some local shadowing. Its performance and specific yield was comparatively low due to in part to the inclination of the panels and the local shadowing (Clavadetscher and Nordmann, 2002).

Trials on PV railway noise barriers have also been conducted in the Netherlands, although no details are available as to the location of the site(s) or the types of array used; the arrays appear to be installed as a single panel on the receiver side of the barriers and appear to be oriented at approximately 60 degrees to the horizontal.

A further problem which has only been tackled to a limited degree is the reduction of noise levels at tunnel portals or openings where sub-surface underground lines emerge. Reports of “shields” or covers to tackle low-frequency noise from tunnels on high-speed railway lines have been reported in Japan (Maeda, 1999). Such tunnel extensions with sound absorptive linings could provide for the incorporation of PV noise barriers (for road tunnels as well as rail tunnels). The use of noise barriers at tunnel portals and sound-absorptive materials on the inner wall of tunnels has been considered by Nakagura (2005).
4 Criteria for the use of noise mitigation and PV arrays on railways

For the routine installation of noise barriers and other noise mitigation measures alongside railways, a range of acoustic considerations must be taken into account, that are generally more stringent than for installation of road traffic noise barriers and which vary depending upon the type of railway (e.g. mainline rail, surface sections of underground railway and light rail).

The installation of PV noise barriers, requires both acoustic and energy considerations to be taken into account, but since the orientation and inclination of PV arrays is so important, the number of sites where PV barriers might be used is far fewer than for standard noise barriers. There are also other practical issues which must be considered, e.g. the exposure of PV cells on public rights of way, etc.

4.1 General criteria related to acoustic performance

4.1.1 Barrier positioning and height

To optimise the screening performance of a noise barrier it is important that it is placed as close as possible to the source that is to be screened.

In the case of rolling stock operating on the London Underground and on Docklands Light Railway, the dominant noise sources are wheel/rail noise and noise from the electric motors powering the trains. The motors are located beneath the main body of the carriages close to the track. The localisation of these noise sources close to ground level makes screening far easier to achieve using lower barriers.

In the case of rolling stock operating on the national rail network, particularly mainline rail, it is also necessary to consider the noise sources on any locomotives that operate at the sites being considered for mitigation. Power unit noise from locomotives varies with the type of locomotive and is less dependent on movement of the train than other sources and is generally emitted from the exhaust vents. On high-speed rail lines, aerodynamic noise is also a consideration.

The position of the barrier in relation to the track will be dependant upon the designated maximum speed of the railway line and be specified in the relevant operating standards (Section 5 provides more specific details for the individual networks).

A noise barrier should typically be high enough to provide adequate screening for all of the dominant noise sources. However the height may be restricted by the operating environment, e.g. the preference for unobstructed views for passengers on a train. The specific requirements of the different operators in relation to both barrier position and height are discussed later in this report.

4.1.2 Barrier orientation and acoustic treatment

In general noise barriers should be vertical or tilted towards the track to achieve optimum screening behind the barrier. However, to minimise the chance of increased noise levels on the far-side of the barrier due to reflected sound, tilting the noise barriers away from the track is preferred. Work by Watts (1996) on highway noise barriers has indicated a tilt of 10-15 is sufficient to prevent additional noise on the far-side of the road. The screening of noise from railway and tube stock is a specific case which requires further consideration due to the occurrence of multiple reflections between the noise barrier and the sides of the rolling stock. The use of sound absorptive materials on the track-facing side of the barrier will help reduce these multiple reflections.
Barriers can incorporate acoustic treatment in a variety of ways; the barrier can be constructed directly from sound absorptive material such as wood-cement concrete (e.g. beton-bois) or more usually from “cartridge-type” panels formed from a perforated metal box with the acoustically absorptive material contained inside the box section. A report by Watts and Morgan (2005) provides more detailed information on absorptive barriers. The selection of absorptive materials on noise barriers on the London Underground network may be dependant upon fire safety regulations etc. imposed by London Underground.

Morgan et al (1998) demonstrated that the effectiveness of sound absorptive treatment on railway noise barriers is influenced by the profile of the rolling stock. For carriages with predominantly vertical sides (slab-sided stock), the use of absorptive treatments significantly improved the performance of a plane vertical screen. On carriages with a more curved profile where the lower surfaces of the carriage curve in towards the bogies, the benefit of the absorptive treatment was reduced. It is believed that when the barrier is reflective, the lower surfaces reflect sound towards the ballast which is sound absorptive. When the barrier was absorptive, the level of screening appeared to be largely independent of the profile of the rolling stock. However, the use of absorptive barriers is still recommended since they will allow lower barriers to be used than if they were completely reflective.

The influence of the carriage profile on noise levels on the far side of the track was not been investigated.

It is worth noting that future development/replacement of rolling stock used in the UK could result in a change from curved profile stock (which is the most predominant type – see text below) to slab-sided stock. Any specification of noise barrier profiles should take this possibility into account, so that there is no significant degradation of the acoustic screening performance if the rolling stock is changed.

The rolling stock used on the London Underground network falls into two categories:

- “Sub-surface” stock, is by far the larger, operating on the Metropolitan, East London, Circle, District and Hammersmith & City Lines. Three different types are currently in operation with the typical height being approximately 3.6 m above the railhead and the width approximately 2.8-2.9 m.

- “Tube stock” or “deep-line stock”, operating, for example, on the Central, Jubilee, Northern and Piccadilly lines. There are currently seven different types in operation with the typical height being approximately 2.9 m and the width approximately 2.6 m;

Examples of the two different types of rolling stock are shown in Figure 4.1a). The difference in profile and height can be clearly seen. Figure 4.1b) shows the curved profile of tube-stock in more detail.

Clearly the profile of the carriages approaching a height of approximately 2 m above the railhead changes significantly between the two stock types, so that a barrier design that is effective for one rolling stock type may perform differently in the presence of the other type. Since some of the deep tube lines have sections which run above ground, e.g. on the Central line, it would therefore be necessary to consider barrier options for each type of rolling stock.

The rolling stock used on mainline railways generally has a profile similar to that of the sub-surface Underground stock, as shown in Figure 4.2.
3.6m

2.9m

D Class
Sub-surface stock

1996 Tube stock

(a) Comparison of Sub-surface and Tube stock profiles

(b) Example of curving profile of tube stock

Figure 4.1: Rolling stock on the London Underground

(a) Examples of mainline rail rolling stock

(b) Cross-section of mainline rail rolling stock

Figure 4.2: Rolling stock on national rail

In contrast, the profile of rolling stock used on the Docklands Light Railway is far more trapezoidal as shown in Figure 4.3.

Figure 4.3: Rolling stock on Docklands Light Railway
4.1.3 Barrier profile and design

In instances where the barrier height has to be restricted, the performance can be enhanced by the use of novel-shaped caps which have a minimal effect on the height of an existing barrier but which provide an improvement in screening which is in excess of that which would be achieved by increasing the height of a plane barrier by a greater amount than the height of the cap. Examples of such designs are multiple-edge profiles such as those tested by Watts et al (1994) and other more elaborate devices such as the Calmzone interference profile tested, for example, by Hampl et al (1991) and Holzman and Venhaus (1989) specifically for the screening of railway noise (see Figure 4.4).


![Figure 4.4: Examples of novel noise barrier caps](image)

Clearly, not all novel barrier profiles are suitable for use in combination with PV cells, since the cross-section is relatively small and the inclination of the cells may be inappropriate. Some of these designs studied by Morgan and Watts (2004) may offer the potential for incorporating PV cells, examples of which are shown in Figure 4.5.

![Figure 4.5: Examples of barrier profiles investigated by Morgan and Watts (2004)](image)

An example of a barrier profile specifically incorporating a PV array into the design has been modelled by Watts and Morgan (2005), as shown in Figure 4.6. The performance of this configuration was examined in an urban environment for screening road traffic noise. Relative to the reference condition of a plane reflective screen, this novel profile provided an additional 3.1 dB(A) average noise reduction behind the barrier. For comparison, the same
design without the PV array provided an additional 3.3 dB(A) reduction, and a plane screen inclined at 60 degrees away from the road provided a 0.2 dB(A) increase.

4.2 General criteria required for the use of other noise mitigation measures

In addition to using noise barriers, other possibilities exist for reducing the impact of noise from railways. Most of these will be aimed at reducing the effects of reflected noise. At tunnel portals, not only is there the direct noise from trains as they exit the tunnel to consider but also the noise reflected off the tunnel lining (reverberant noise). Whilst noise barriers may be installed at tunnel portals to reduce the impact of noise from exiting trains, they can also reduce the impact of reverberant noise. This problem may be further addressed by the use of sound-absorptive treatments on the walls of the tunnel close to the portal (see for example, Nakagura, 2005).

Similar types of treatment can be applied to bridge parapets, building facades, walls, etc. The use of such types of mitigation measure must not intrude within the limiting envelopes of the associated railways.

4.3 General criteria required for the use of PV arrays

The following section sets out the requirements that should be satisfied for PV arrays to be used with optimal efficiency.

4.3.1 Orientation and inclination

For optimum efficiency, the PV array should be oriented along an east-west axis, with the energy collecting surfaces of the array facing south. As already outline in Section 3, the angle of the array should be optimised for to obtain the greatest benefit. However, since the arrays are to be mounted on noise barriers, the size of the array may well have a direct impact on the inclination.

**Large-panel PV arrays:** If the arrays are to be mounted as large panels on the main surface of the barrier, e.g. so that the full surface area of the barrier is fitted with PV modules, it is important that while the angle from the horizontal be sufficient for the panels to generate a usable amount of solar energy, at the same time the angle should be sufficiently large so the
overall footprint of the barrier is not excessive. An angle of 60° from the horizontal would result in a footprint of approximately 1 m for a single continuous array mounted on a 2 m high barrier; it is considered that it would be unfeasible in most cases to use an angle any less than this unless the array was comprised of multiple elements such as that shown in Figure 3.6b).

The opportunity for fitting large panel PV arrays to the track-facing side of existing structures and noise barriers on the rail network would therefore appear to be limited since most of these structures will already be in close proximity to or at the limit of the structure gauge. Existing barriers and fences might offer some potential if the arrays are fitted onto the side facing away from the track, however this would still depend on the space between the structure and the boundary of the railway property, and would require regular maintenance of the vegetation to keep the panels from being obscured. It is noted that it is unlikely that the PV cells could form the outer face of a barrier at the boundary to public areas due to the risk of vandalism.

More scope is available in the construction of brand-new PV noise barriers, but again space limitations will dictate the size of the structure.

Since it is considered that the greatest acoustic benefits would be achieved with acoustically absorptive barriers, this would require the use of smaller panels or strips as described below. Although serving no acoustic benefit, large arrays of PV modules could be mounted onto the roofs of stations, service depots etc if the size of the array was particularly important.

**Strip arrays:** It is considered that a better option for use alongside railways on existing noise barriers would be to use strip arrays, either in the form of barrier caps or additional tilted panels added onto the top of the existing barrier as shown, for example in Figure 3.6a). This offers the scope for a wider variation in tilting. This would allow the majority of the noise barrier to be acoustically absorptive and also offer a smaller footprint than barriers fitted with large panels. It is noted that adding height to the barrier will usually result in enhanced acoustic screening performance.

To provide an illustration of how array size and orientation on a noise barrier might translate into power output, Table 4.1 provides an indication of the expected power output for an array mounted onto a noise barrier. The length of the array is assumed to be 5.0 m and the width varies depending on whether the array is fitted as a cap or as an additional panel 5 m in width and with varying depth depending upon its angle and inclination.

Based on the dimensions and outputs of PV modules similar to those being used as part of a trial on the M27 for the Highways Agency, Table 4.2 gives examples of the power outputs that might be achievable for the above configurations assuming the previously stated expectation that a south-facing array in the UK would yield approximately 750 kWh per annum per kWp output from the array. To put the annual outputs into perspective, it is estimated that the annual household energy consumption for a typical three-bedroom house is approximately 4200 kWh.
Table 4.1: Expected maximum power output (arbitrary units) for different PV barriers

<table>
<thead>
<tr>
<th>PV array installed as a panel on the barrier</th>
<th>South-facing 30º elevation (100m × 2m)</th>
<th>South facing, 60º elevation (100m × 2m)</th>
<th>South facing, 70º elevation (100m × 2m)</th>
<th>South facing 80º elevation (100m × 2m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>200.0</td>
<td>173.2</td>
<td>153.2</td>
<td>128.6</td>
</tr>
<tr>
<td>Winter</td>
<td>133.8</td>
<td>190.2</td>
<td>198.0</td>
<td>200.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PV array installed as a cap on the barrier</th>
<th>Horizontal (orientation irrelevant) (100m × 2m)</th>
<th>Horizontal (orientation irrelevant) (100m × 1m)</th>
<th>South facing 15º elevation (100m × 1m)</th>
<th>South facing 30º elevation (100m × 1m)</th>
<th>South facing 60º elevation (100m × 1m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>173.20</td>
<td>86.6</td>
<td>96.6</td>
<td>100.0</td>
<td>86.6</td>
</tr>
<tr>
<td>Winter</td>
<td>41.6</td>
<td>20.8</td>
<td>45.4</td>
<td>67.0</td>
<td>95.2</td>
</tr>
</tbody>
</table>

Notes: Maximum power output per m²= area x cos (90º – angle of sun – angle of cells)
Midday angle of sun in summer = 60º
Midday angle of sun in winter = 12º

Table 4.2: Expected maximum power outputs (kWp) for different PV barriers
(annual energy outputs, in thousands of kWh, are stated in brackets)

<table>
<thead>
<tr>
<th>PV array installed as a panel on the barrier (9.8 kWp)</th>
<th>South-facing 30º elevation (99m × 1.59m)</th>
<th>South facing, 60º elevation (99m × 1.59m)</th>
<th>South facing, 70º elevation (99m × 1.59m)</th>
<th>South facing 80º elevation (99m × 1.59m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>9.80 (7.35)</td>
<td>8.49 (6.37)</td>
<td>7.51 (5.63)</td>
<td>6.30 (4.73)</td>
</tr>
<tr>
<td>Winter</td>
<td>6.56 (4.92)</td>
<td>9.32 (6.99)</td>
<td>9.70 (7.28)</td>
<td>9.80 (7.35)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PV array installed as a cap on the barrier (4.9 kWp; 12.2 kWp for option*)</th>
<th>Horizontal * (orientation irrelevant) (98.8m × 1.97m)</th>
<th>Horizontal (orientation irrelevant) (98.8m × 0.8m)</th>
<th>South facing 15º elevation (5m long × 1m)</th>
<th>South facing 30º elevation (5m long × 1m)</th>
<th>South facing 60º elevation (5m long × 1m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>10.57 (7.93)</td>
<td>4.24 (3.18)</td>
<td>4.73 (3.55)</td>
<td>4.90 (3.68)</td>
<td>4.24 (3.18)</td>
</tr>
<tr>
<td>Winter</td>
<td>2.54 (1.91)</td>
<td>1.02 (0.77)</td>
<td>2.22 (1.67)</td>
<td>3.28 (2.46)</td>
<td>4.66 (3.50)</td>
</tr>
</tbody>
</table>

Notes: Maximum power output per m²= Wp x cos (90º – angle of sun – angle of cells)
Midday angle of sun in summer = 60º
Midday angle of sun in winter = 12º

4.3.2 General considerations

As already observed, it is important that the PV array is exposed to as much sunlight as possible and therefore not obscured either by tall buildings or overhanging vegetation. The
use of large panels on the face of barriers would require that strict maintenance in the vicinity of the barrier be regularly carried out. Biodiversity, visual and amenity issues would need to be considered.

The angle and installation and treatment of the panels during the manufacturing process should generally ensure that the panels do not need to be specially cleaned. However, the barriers may be subject to vandalism and graffiti which may be required to be specifically addressed. The opportunities for this may be addressed by in part by installing the panels on the track-facing side of the barriers, however this prevents the use of fully sound absorptive barriers. Fitting the PV panels as barrier caps or extensions would make access to vandals more difficult.

Theft of the panels is also an issue that must be addressed. It is recommended that any panels are installed with vandal-proof nuts and bolts, in a similar manner to those used in the M27 study. It is noted, that over the duration of that study to date, there have been no issues related to either theft or vandalism of the PV barrier elements.

The main focus of this report is the potential installation of PV arrays on purpose-built noise barriers. However, the use of PV arrays on other structures which provide some form of noise mitigation, e.g. boundary walls, fences, bridge parapets, should also not be ignored. In general, these may be lower and shorter than purpose-built noise barriers at the trackside, but the same considerations described in this section apply.
5 Application of noise barriers on the rail network

This section of the report outlines general considerations related to the actual use of noise barriers on the rail network in London, including any criteria that are specific to an individual operator, and comments on either the selection or unavailability of potential demonstration sites for PV barriers.

5.1 London Underground

5.1.1 General considerations

Discussions with London Underground/TfL indicated limited potential for photovoltaic noise barriers in the context of current constraints and cost-effectiveness. The majority of asset-related noise complaints on the LU network are as a result of ground-borne noise and vibrations, which cannot be addressed using noise barriers. There are few locations where above-ground asset-related noise has at some time in the past been an issue for residents, and in the majority of cases these problems have been rectified using more cost-effective solutions than noise barriers. For example, the main source of complaint in these cases is where the line is located on an embankment; the high civil engineering costs of reinforcing the embankment to overcome stability issues for installing noise barriers means that it is far cheaper to implement alternative solutions such as grinding the track.

The complaints issue aside, the opportunities for using noise barriers on the network are still very restricted for the following reasons:

- It appears that there is generally very little space between the boundary fences and the cable runs alongside the track that mark the closest point for installation;
- Furthermore, for safety reasons, the use of structures in close proximity to the track which might prevent escape in the event of emergency or hinder the safety of daytime patrols performing routine visual inspections is not permitted. Similarly, the same applies to the use of structures in-between the tracks unless these were very low level;

Some noise barriers have been constructed as part of the Jubilee line extension, however these have been designed as a part of the overall scheme rather than being added retrospectively to address unforeseen noise issues.

The replacement of boundary fences with noise barriers is also unlikely. Paragraph 3.3.1 of Standard 2-01302-460 (London Underground, 2006) states that “At sites where increased security measures are not considered necessary, standard chain link fencing or similar approved type shall be provided” (1.4 or 1.8 m high depending upon the location). In cases where security fencing is required, Paragraph 3.4.3 states that “Category A, B and C security fencing shall be designed in conformity with BS1722: Parts 1 and 10” as well as satisfying additional LU requirements.

As a consequence, the only locations on the LU network where noise barriers could be practicable for providing noise mitigation on the existing network are at junctions/discontinuities i.e. set of crossings. The cost-effectiveness of using barriers at these locations in comparison to other noise reduction measures would have to be investigated.

It is however recognised, that in the light of the noise mapping and action plans that are required to be prepared under the EU Directive on Environmental Noise (Commission of the European Communities, 2002), that consideration might have to be given in the future to the possibilities of using noise barriers on the network, even in the absence of noise-related complaints. Consequently, the remainder of this Chapter addresses the possibilities for
potential demonstration sites on the LU network and the criteria specific to LU that must be satisfied if noise barriers and PV noise barriers are to be used. From the perspective of installing PV arrays on other structures, it is understood from LU engineers that bridges and built structures provide little opportunity for the application of the technology as the kinetic envelope (the operational envelope defined by the rolling stock) will be too restrictive.

5.1.2 The potential for selection of demonstration sites

The limited and location-specific issues related to sets of crossings mean such locations are not inherently suited to demonstration projects. At the one site where a very small number of complaints have been received, any barrier would run along a North-South axis. Although this still raises the possibility of some energy generation from a PV barrier, LU would require to be convinced that noise barriers were a cost-effective solution to the problem before a noise barrier could even be considered, and even then there are still all of the necessary safety issues etc (and precedence - see below) to consider.

The possibility of using shared high-speed sections with Network Rail, e.g. on the Metropolitan line has been considered. However these are generally 4-6 tracks wide, so the potential benefits of using noise barriers may be limited. However, the same issues regarding cost-effectiveness and safety would also require to be addressed.

It is not considered cost-effective to trial barriers where there is no immediate need for noise reduction. Modelling is considered to be adequate for demonstrating the benefits of a barrier in these circumstances rather than actually constructing the barrier.

LU would be concerned at any precedent being set in advance of any target-setting or decisions on funding for noise reduction which are understood to be functions of the proposed National Noise Strategy and action planning under the Environmental Noise Directive.

The potential for using the existing barriers on the Jubilee line extension has also been ruled out since the preference of LU for the placement of PV cells is that they be on the track-facing side of the barrier (see following section), and therefore the inclination required by any PV arrays would most likely hinder safe access to/emergency escape from the track.

5.1.3 LU-specific criteria for the application of (PV) noise barriers

This section details criteria which would require to be taken into account should noise barriers (or PV noise barriers) be required to be used in the future on the surface-sections of the London Underground network.

**Barrier position:** The proximity of any mitigation measures to the track are based upon the standard London Underground structure gauge envelope (i.e. the boundary enclosing the clearances required outside the kinematic envelope to enable the railway to be operated in safety.

The structure gauge includes provision for staff safety where staff are permitted on the railway whilst trains are running) and specified in Standard 2-01302-120 (London Underground 2006). Paragraph 3.1.4.2 states that “The minimum distance from the running edge of the nearest rail to the face of a cable post shall be 2440 mm. This dimension shall be increased to allow for cant effect and vehicle throw on curves…” Paragraph 3.1.4.3 states that “The minimum distance from the running edge of the nearest rail to the face of a cable stile shall be 1420mm (tube stock only) or 1550mm (all other lines) These dimensions shall be increased to allow for cant effect and vehicle throw on curves…”

The relevant documentation in cases where these increased dimensions are required.
**Barrier height:** Since noise barriers are not generally used on the LU network, there does not appear to be a predetermined requirement set by London Underground in terms of the maximum height of such a barrier. However, while the barrier should ideally be as high as possible, the authors consider that the top of any barrier design should not normally intrude above the bottom edge of the carriage window; this minimises any visual intrusion for Tube passengers. This has been discussed with London Underground and is considered to be a valid starting guideline. Consequently, this leads to a barrier height of approximately 2.0 m for lines operating sub-surface rolling stock and approximately 1.5 m for lines operating tube stock.

**Orientation of PV cells:** From discussions with London Underground, it is evident that there is a preference for the PV panels to be mounted on the track facing side of the barrier. This will minimise the possibility of the PV cells being subject to either vandalism or theft. This means that it may only be possible to install PV cells on barriers located on the north-side of the track (assuming east-west alignment).

**Usage of power generated by the PV barriers:** All power used by London Underground is taken from the National Grid, rather than being generated by LU. Due to the different operating voltages, it is unlikely that the power could be fed directly back into the track or other electrical systems. It is therefore considered that any power generated by the PV barriers would either have to be fed directly back into the UK National Grid or used to power independent utilities, for example at stations, that do not form an integral part of the LU system.

This information and other relevant details are included on the PV noise barrier factsheets included in the Appendix of this report.

5.2 National rail

5.2.1 General considerations

Discussions with Network Rail have identified that, as with London Underground, the majority of noise-related complaints are not of the type that can be addressed using noise barriers.

The complaints issue aside, it is considered that noise barriers are unlikely to be a preferred solution for noise attenuation, not only from the perspective of cost but also of the potential hazards that they may pose to track workers. In the case of low barriers that might be mounted on the sleeper ends, these would need to be removed before tamping machines and other equipment could be operated.

As well as the risk of vandalism by individuals wishing to spray graffiti on the barriers, thereby leading to increased maintenance costs and potential visual intrusion to rail passengers, there is the added danger to the safety of those trespassing on rail property in order to carry out acts of vandalism.

5.2.2 The potential for selection of demonstration sites

It is anticipated that Network Rail would be reluctant to agree to the erection of any new noise barriers before the completion of the noise mapping and action plans for the Environmental Noise Directive as this could be interpreted as implying that any chosen site was in fact subject to unacceptable noise levels, when any target-setting or decisions on funding for noise reduction have not yet been made.
The possibilities for demonstration of PV arrays on noise barriers being constructed on the new section of the CTRLR is at this stage unknown. This section of line is not scheduled to open until 2007.

5.2.3 NR-specific criteria for the application of (PV) noise barriers

This section details criteria which would require to be taken into account should noise barriers (or PV noise barriers) be required to be used in the future on the national rail network.

**Barrier position:** The proximity of any mitigation measures to the track are based upon the standard Network Rail structure gauge as defined in Part J of Railway Guidance Note GE/GN8573 (Rail and Safety Standards Board, 2004). The proximity depends upon the designated speed of the rail line, resulting in three different categories as shown in Table 5.1.

<table>
<thead>
<tr>
<th>Speed</th>
<th>Distance to track centre-line (mm)</th>
<th>Distance to closest rail (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 160 km/h</td>
<td>2667.5</td>
<td>1950</td>
</tr>
<tr>
<td>&gt; 160 km/h, &lt; 225 km/h</td>
<td>3497.5</td>
<td>2780</td>
</tr>
<tr>
<td>&gt; 225 km/h</td>
<td>4167.5</td>
<td>3450</td>
</tr>
</tbody>
</table>

These dimensions should be increased on straight track to allow for lateral cant or increased on curves to allow both cant effects and vehicle throw to be accounted for. The relevant documentation should be consulted in these cases to determine the dimensions.

**Barrier height:** Although there is no specific height specification for noise barriers, previous studies by TRL for Network Rail have been based on the requirement that the top of any barrier design should not intrude above the bottom edge of the carriage window; this minimises any visual intrusion for rail passengers. Consequently, this leads to a barrier height of approximately 2.0 m above the railhead.

**Orientation of PV cells:** As with London Underground, it is expected that there would be a preference for the PV panels to be mounted on the track facing side of the barrier. This will minimise the possibility of the PV cells being subject to either vandalism or theft. This means that it may only be possible to install PV cells on barriers located on the north-side of the track (assuming east-west alignment).

**Usage of power generated by the PV barriers:** It is considered that any power generated by the PV barriers would either have to be fed directly back into the UK National Grid or used to power independent utilities, for example at stations, that do not form an integral part of the rail network.

This information and other relevant details are included on the PV noise barrier factsheets included in the Appendix of this report.
5.3 Docklands Light Railway

5.3.1 General considerations

The DLR network extends through both commercial and densely populated areas, and as such noise and vibration matters are of major importance to the operators of the network. The noise and vibration policy of DLR Limited gives the following undertakings:

- To use best practicable means to minimise levels of exterior noise in locations where noise levels measured adjacent to existing buildings exceed the target levels set out in the noise policy;
- The adoption of system wide procedures for monitoring and for railway maintenance in the control of noise.

As such, noise barriers form a key noise mitigation tool on the DLR. Examples of the different types of noise barrier that have been employed on the DLR are given in Section 3.2 of this report.

Since large sections of the DLR are elevated above ground level, there is generally limited clearance between the track and any noise barriers or railings. This means that the opportunities for installing PV cells on the track-facing side of any barriers or overhanging the upper edge of the barriers are very limited; in most cases, the cells would require to be installed on the side of the barrier facing away from the track. However the height of the panels above the ground is therefore likely to keep them clear of interference from ground level, reducing the opportunities for theft and vandalism.

In the case of barriers on the north side of the track, any PV cells would therefore require to be mounted on to the top of the barriers, cantilevered away from the track; this may prove prohibitive to cost-effective installation since more complicated mountings would be most likely be required.

The greatest opportunity for the use of photovoltaic noise barriers on DLR is therefore considered to be on new line extensions, where consideration of the requirements necessary for the use PV cells can be taken into account during the design process.

5.3.2 The potential for selection of demonstration sites

As already noted, in Section 3.2, noise barriers are already installed at a number of locations along the DLR. Some of these barriers can immediately be discounted as potential demonstration sites due to their incorrect alignment for the efficient operation of PV cells.

Preliminary investigations have identified that of those barriers with an appropriate orientation, the lower height designs on the DLR are too close to the track and not substantial enough to be used for retrofitting PV cells. It is possible that the high level barriers installed on an elevated section between Westferry and Limehouse stations may be suitable. However insufficient information has been collated at the time of writing to allow any recommendations to be proposed. It is considered that a fully detailed site inspection and further consultation are necessary as a first step.

5.3.3 DLR-specific criteria to be satisfied for the application of (PV) noise barriers

This section details criteria which require to be taken into account when noise barriers (or PV noise barriers) are to be used on the DLR.

**Barrier position:** The proximity of any mitigation measures to the track is based upon the structure gauge used by DLR (set out in Drawing No. RS260, Issue B (Serco Docklands Ltd, 2001c) with additional information provided by Drawing Nos. RS253 Issue B (Serco...
Docklands Ltd, 2001a) and RS 259 Issue B (Serco Docklands Ltd, 2001b)). This sets the minimum distance between a structure and the centreline of the track at 1480 mm. Masts and isolated structures less than 2 m in length are located at 2005 mm from the centreline of the track. Where there is a walkway running alongside the track, the structure gauge shall not encroach upon the walkway; in this instance, the closest the structure can be to the centreline of the track is 2460 mm (assuming the minimum permissible width of 700 mm for the walkway and the minimum permissible separation of 430 mm between the walkway and the vehicle gauge).

These dimensions should be increased on straight track to allow for lateral cant or increased on curves to allow both cant effects and vehicle throw to be accounted for. The relevant documentation should be consulted in these cases to determine the dimensions.

**Barrier height:** The different types of barrier in use on the DLR suggests that there may be no specific guidelines relating to a maximum permissible height for noise barriers and therefore greater flexibility than on the other rail networks considered in the study. However this has not been confirmed.

**Orientation of PV cells:** As already noted, it is considered likely that because of the limited clearances and the need for PV cells to be inclined for efficient solar operation, cells will have to be installed on the sides of the barrier facing away from the track. This may override any possible preference for cells to be installed on the track-facing side to minimise the risk of theft and vandalism.

**Usage of power generated by the PV barriers:** It is considered that any power generated by the PV barriers would either have to be fed directly back into the UK National Grid or used to power independent utilities, for example at stations, that do not form an integral part of the DLR network.
6 Recommendations for barrier concepts

Taking into account the various requirements listed in previous sections, it is possible to put forward proposals for possible concepts for photo-voltaic noise barriers. These concepts are based as far as possible on the dimensions of PV panels used on the M27 study (Carder and Barker, 2006; see Section 3.1) and, in the case of absorptive barrier components, on cartridge-type panels previously used in full-scale trials at TRL (Watts, 1994).

It should be noted that these designs have not been fully validated; a limited number of 2-D BEM calculations have been performed in order to provide some indication of how the combination of acoustically reflective and absorptive elements might perform in practice. It should be noted that the track and rolling stock cross-sections used for these preliminary calculations correspond to those in a previous study by Morgan and Watts (2004) for investigations on mainline high-speed railways, with the separation between the nearside rail and the closest barrier element being no greater than 4.167 m. The structure gauges reported in previous sections of this report will allow the barriers to be positioned closer to that track, so it is expected that the screening performance should improve, although it is not possible to quantify these improvements.

In all cases, it should be noted that no consideration has been given to the ease of/method of construction of any of the designs, in terms of fixing of the PV panels, or other elements on more complex barrier profiles. Design calculations such as wind loadings etc have also not been undertaken. In all of the Figures, it is generally assumed that the PV modules will be mounted onto a frame which is connected to the barrier; the mountings shown in the Figures are not based on actual designs.

6.1 Options for screening noise from sub-surface underground and national rail rolling stock

It is considered that the same basic barrier designs can be applied to screening the noise from both types of rolling stock, since there are similarities between the size and profile of the stock. The following design considerations have been taken into account:

- The overall height of the barrier may not exceed 2 m above the railhead;
- The inclination of the PV arrays have been selected to minimise the footprint of the barrier configurations whilst retaining a suitable angle for solar energy collection;
- It is considered that the inclusion of sound absorptive elements will provide better acoustic performance than using fully reflective barriers. As such, the use of full-face PV arrays has been avoided;
- All PV cells have been installed on the track-facing side of the barrier to minimise the risk of theft/vandalism and to avoid, as far as possible, additional trackside maintenance to control vegetation.

The three options that have been identified are shown in Figure 6.1. In all cases, the track is located on the right-hand side of the barrier.

The acoustic performance of the different designs in the following descriptions is expressed in terms of the additional average noise reduction\(^5\) relative to a reference barrier, i.e. a 2.0 m high reflective plane screen (all heights are expressed as the height above the railhead, which itself is approximately 0.38 m above ground). For comparison, a 2 m high sound-absorptive plane barrier provides approximately 4.4 dB(A) additional average noise reduction.

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\(^5\) Determined from noise levels predicted at six receiver positions located at 20, 40 and 80 m behind the barrier at heights of 1.5 and 4.5 m above the outlying (flat) ground.
Option 1: Single tilted panel PV panel.
This design incorporates a single large PV panel fitted to the top of a plane absorptive barrier and inclined at 60 degrees.

Acoustic performance: Approximately 4.9 dB(A) additional average noise reduction compared to the reference barrier.

Expected power output (assuming optimum conditions): 4.9 kWp per 100 m length of barrier

Option 2: Multi-faceted barrier.
This design incorporates 2 PV arrays on the barrier, both inclined at 60 degrees with the largest being located towards the top of the noise barrier.

Acoustic performance: Approximately 3.3 dB(A) additional average noise reduction compared to the reference barrier.

Expected power output (assuming optimum conditions): 7.3 kWp per 100 m length of barrier

Option 3: T-profile OR inverted L-profile barrier.
This design incorporates a single horizontal PV panel fitted to the top of a plane absorptive barrier. The advantage to this design would be that the orientation of the barrier would not have any impact on the solar performance of the array; however, it is noted that maintenance might be required to keep the PV array clean as rainfall would not clean a flat panel as well as one that is tilted.

Acoustic performance: Approximately 4.9 dB(A) additional average noise reduction compared to the reference barrier.

Expected power output (assuming optimum conditions): 4.9 kWp per 100 m length of barrier

Figure 6.1: Potential PV barrier options for screening noise from sub-surface underground and national rail rolling stock (The track is located on the right-hand side of the barriers)
The expected power output is based on optimum conditions (when solar irradiation of 1000 W/m² in a specified reference spectrum [see standard ASTM G-173-03 (ASTM, 2003)] falls on the PV cell at 25°C.

It is considered that Option 1 would most likely be the cheapest design as well as having the smallest footprint of the three options. An example of how Option 1 might look in practice (albeit alongside a road rather than a railway is shown in Figure 6.2)

![Figure 6.2: Example of cranked PV noise barrier in use on highways](http://www.oja-services.nl/iea-pvps/pvpower/06_02.htm)

A fourth option has also been investigated; this is an asymmetric version of the profile shown in Figure 4.6 (i.e. both of the additional diffracting edges are on the side of the barrier facing away from the track). In this instance, it has been assumed that the gap between the horizontal PV array and the main barrier would allow the overall height to be greater than 2 m since vision from the carriage windows would be relatively unobstructed. The overall height of the barrier is therefore approximately 2.3 m (the upper edges of the main barrier and panels being at 2.0 m). Such an arrangement offered approximately 6 dB(A) additional average screening relative to the reference barrier.

### 6.2 Options for screening noise from deep tube rolling stock

Due to the reduced height of the rolling stock operating on deep-tube lines, the maximum height of any noise barrier designs is lower than that used in the previous section, being approximately 1.5 m above the railhead. It is therefore considered that profiles similar to Options 1 and 3 from Figure 6.1 would be the most appropriate designs for use in such circumstances. These are shown with their revised dimensions in Figure 6.3. The multi-faceted design suggested for sub-surface rolling stock is considered inappropriate because it is not possible here to include the sound absorptive panel at the foot of the barrier.

No 2-D BEM calculations have been performed for these designs, so it is not possible to comment on the acoustic performance. The expected power outputs for these designs are the same as for the equivalent barriers in Figure 6.1.
6.3 Options for screening noise from DLR rolling stock

As already noted, it has not been possible to obtain any information on barrier height specifications. Therefore, no specific designs are proposed for use on DLR. However, the following general concepts may provide some guidance on the types of design that could be possibly be considered. No dimensions are given for the heights of the barriers and although only a single PV panel is shown, depending upon the conditions, there may be scope for installing larger panels.
7 Summary and Conclusions

The Mayor’s Ambient Noise Strategy seeks a higher profile for reducing noise in the management of transport systems, including railways, whilst promoting the concept of electricity generation by photovoltaic (PV) arrays. Policy 21 of the Strategy states that Transport for London will be expected to “Investigate the potential for noise barrier-integrated photovoltaic power generation along suitable railway lines.”

As part of work towards achieving these objectives, Greater London Authority have commissioned TRL Limited to undertake a study identifying potential small-scale and medium-scale sites for the demonstration of photovoltaic noise barriers on the surface sections of the London Underground system. The study was subsequently extended to include Network Rail and Docklands Light Railway.

The criteria that need to be taken into account both from an acoustic-related and energy-related perspective in the use of noise barriers and PV noise barriers alongside railways have been assessed and balanced. These criteria have been balanced against the specific requirements of LU/TfL, NR and DLR for the placement of noise mitigation measures.

The current costs of PV modules indicate that the cost-effectiveness is poor at the present time. Large-scale systems are required to improve the cost-effectiveness.

Discussions with London Underground (LU)/TfL have indicated limited potential for photovoltaic noise barriers in the context of current constraints and cost-effectiveness. The majority of asset-related noise complaints on the LU network are as a result of ground-borne noise and vibrations, which cannot be addressed using noise barriers. Discussions with Network Rail (NR) have revealed similar limitations.

Discussions with Docklands Light Railway have revealed that noise barriers are already used for noise mitigation on the DLR, however there are very limited possibilities for introducing PV cells onto existing barriers and these require further investigation to assess their suitability. The potential use of photovoltaic noise barriers on new barriers in the future will be dependant upon site conditions and would require a detailed assessment of all relevant considerations to first be undertaken.

However, with the use of noise barriers as part of the design process on the CTRL and taking into account that noise barriers might be required on the different parts of the London rail network in the future (in response to the noise maps and action plans produced in accordance with the EU Directive on Environmental Noise [END]), a series of PV barrier concepts have been proposed. These concepts have not been validated but are based on the criteria from the first part of the study. A series of factsheets giving advice on how these concepts might be applied have been prepared and are included in Appendix A of this document.
Acknowledgements

The work described in this report was carried out in the Environment Group of TRL Limited. The authors are grateful to Professor Greg Watts who carried out the quality review and auditing of this report. The assistance of Chris Beach and Richard Barton (London Underground Limited), John Amoore (Network Rail) and Gareth Hood (Docklands Light Railway Limited) is gratefully acknowledged.

References


Appendix A. Factsheets on applying PV noise barrier concepts
Factsheet: Applying Photovoltaic Noise Barrier Concepts on surface sections of the London Underground (Sub-surface lines)

This factsheet provides general guidelines on the specifications and conditions that must be met or considered for the use of photovoltaic (PV) noise barriers. The specifications are based on formal London Underground Standards. All other conditions are those required to achieve optimum performance; the performance of the PV noise barriers will be reduced if these conditions are not met.

Barrier specifications:

Position:
- The barrier should be positioned as close as possible to the noise source. However, no element of the barrier may be less than 2.44 m from the nearest rail, in accordance with Paragraph 3.1.4.2 of Standard 2-01302-120 (London Underground, 2006).
  
  Note! For curved track, these dimensions will be increased; the relevant documents should be consulted in these cases.

Height:
- No element of the barrier may normally be greater than 2.0 m above the railhead to prevent additional visual intrusion for train passengers.

Acoustic treatment:
- For the most efficient performance, the track-facing surfaces of the barrier should be sound-absorptive.

Concept profiles:
- Three barrier profile concepts incorporating PV arrays are shown on this factsheet. In each case, the track is located on the right-hand side of the barrier.
  - No specific design or construction calculations or assessments have been performed for these designs;
  - Panel dimensions are approximate and based on PV panels/laminates tested on the M27 (Garder, 2006) and noise barrier elements tested by TRL (Watts et al., 1994). All fixings/mountings are for illustrative purposes only.

Concept performance:
- The performance of the three barrier concepts is expressed in terms of the following parameters (these figures are only indicative and have not been validated):
  - Relative Insertion Loss: The additional average noise reduction compared to a 2 m high reflective plane barrier. Note that the figure is calculated based on a barrier sited at 4.3 m away from the nearside rail.
  - Power Output: The output based on optimum conditions (when solar irradiation of 1000 W/m² in a specified reference spectrum [see standard ASTM G-173-03 (ASTM, 2003)] falls on the PV cell at 25ºC)

PV array specifications:

Orientation:
- The barrier should be aligned on an East-West axis with the track on the south side of the barrier;
- The panels in the PV array should normally be mounted facing the track to minimise the risk of theft or vandalism. This may restrict the opportunities for use to those barriers located on the north side of the track.

Inclination:
- The panels should be mounted at 60º to the horizontal to maximise efficiency but minimise the overall footprint of the noise barrier.
PV array specifications (continued):

**Screening or shading:**
- The PV panels should not be obscured by trees, bushes, etc. This may require regular maintenance of the surrounding vegetation; biodiversity, visual and amenity issues should be considered.
- The PV panels should not be in the shadow of surrounding buildings during the daytime.

**Power usage & connections**
- It is considered that the most appropriate use for power generated by the PV array will normally be for it to be fed back into the National Grid. In this case the inverter connected to the PV array should be connected into the NG as close as possible to the barrier (most likely the domestic grid serving residential properties adjacent to the railway).
- If the power is not to be fed into the National Grid but used instead for local systems/utilities, it is recommended that backup power be provided either from the Grid or via battery.

**Other considerations**
- The use of amorphous PV modules is preferred since these are more resilient than crystalline PV arrays.
- PV arrays should be fastened to the noise barrier using appropriate vandal-proof fixings.
- An angle of 60º will allow the panels to be cleaned by incident rainfall.

For further information see:

References:
Factsheet: Applying Photovoltaic Noise Barrier Concepts on surface sections of the London Underground (Deep bored tube lines)

This factsheet provides general guidelines on the specifications and conditions that must be met or considered for the use of photovoltaic (PV) noise barriers. The specifications are based on formal London Underground Standards. All other conditions are those required to achieve optimum performance; the performance of the PV noise barriers will be reduced if these conditions are not met.

Barrier specifications:

Position: The barrier should be positioned as close as possible to the noise source. However, no element of the barrier may be less than 2.44 m from the nearest rail, in accordance with Paragraph 3.1.4.2 of Standard 2-01302-120 (London Underground, 2006).

Note! For curved track, these dimensions will be increased; the relevant documents should be consulted in these cases.

Height: No element of the barrier may normally be greater than 1.5 m above the railhead to prevent additional visual intrusion for train passengers.

Acoustic treatment: For the most efficient performance, the track-facing surfaces of the barrier should be sound-absorptive.

Concept profiles: Two barrier profile concepts incorporating PV arrays are shown on this factsheet. In each case, the track is located on the right-hand side of the barrier.

The following statements must be noted:
- No specific design or construction calculations or assessments have been performed for these designs;
- Panel dimensions are approximate and based on PV panels/laminates tested on the M27 (Garder, 2006) and noise barrier elements tested by TRL (Watts et al., 1994). All fixings/mountings are for illustrative purposes only.

Concept performance: The performance of the two barrier concepts is expressed in terms of the following parameters (these figures are only indicative and have not been validated):
- Power Output: The output based on optimum conditions (when solar irradiation of 1000 W/m² in a specified reference spectrum [see standard ASTM G-173-03 (ASTM, 2003)] falls on the PV cell at 25°C)

PV array specifications:

Orientation: The barrier should be aligned on an East-West axis with the track on the south side of the barrier;

The panels in the PV array should normally be mounted facing the track to minimise the risk of theft or vandalism. This may restrict the opportunities for use to those barriers located on the north side of the track.

Inclination: The panels should be mounted at 60° to the horizontal to maximise efficiency but minimise the overall footprint of the noise barrier.
PV array specifications (continued):

**Screening or shading:**
- The PV panels should not be obscured by trees, bushes, etc. This may require regular maintenance of the surrounding vegetation; biodiversity, visual and amenity issues should be considered.
- The PV panels should not be in the shadow of surrounding buildings during the daytime.

**Power usage & connections**
- It is considered that the most appropriate use for power generated by the PV array will normally be for it to be fed back into the National Grid. In this case the inverter connected to the PV array should be connected into the NG as close as possible to the barrier (most likely the domestic grid serving residential properties adjacent to the railway).
- If the power is not to be fed into the National Grid but used instead for local systems/utilities, it is recommended that backup power be provided either from the Grid or via battery.

**Other considerations**
- The use of amorphous PV modules is preferred since these are more resilient than crystalline PV arrays.
- PV arrays should be fastened to the noise barrier using appropriate vandal-proof fixings.
- An angle of 60º will allow the panels to be cleaned by incident rainfall.

For further information see:

References:
Factsheet: Applying Photovoltaic Noise Barrier Concepts on national rail, including the mainline network

This factsheet provides general guidelines on the specifications and conditions that must be met or considered for the use of photovoltaic (PV) noise barriers. The specifications are based on formal Network Rail standards. All other conditions are those required to achieve optimum performance; the performance of the PV noise barriers will be reduced if these conditions are not met.

Barrier specifications:

Position:
- The barrier should be positioned as close as possible to the noise source. However, no element of the barrier may encroach within the limits as defined in Part J of Railway Guidance Note GE/GN8573 (Rail and Safety Standards Board, 2004). These limits are speed dependant as follows:

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>Distance to closest rail (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 160</td>
<td>1950</td>
</tr>
<tr>
<td>&gt; 160, &lt; 225</td>
<td>2780</td>
</tr>
<tr>
<td>&gt; 225</td>
<td>3450</td>
</tr>
</tbody>
</table>

Note! For curved track, these dimensions will be increased; the relevant documents should be consulted in these cases.

Height:
- No element of the barrier may normally be greater than 2.0 m above the railhead to prevent additional visual intrusion for train passengers.

Acoustic treatment:
- For the most efficient performance, the track-facing surfaces of the barrier should be sound-absorptive.

Profile:
- Three barrier profile concepts incorporating PV arrays are shown on this factsheet. In each case, the track is located on the right-hand side of the barrier.

- The following statements must be noted:
  - No specific design or construction calculations or assessments have been performed for these designs;
  - Panel dimensions are approximate and based on PV panels/laminates tested on the M27 (Carder, 2006) and noise barrier elements tested by TRL (Watts et al., 1994). All fixings are for illustrative purposes only.

Concept performance:
- The performance of the three barrier concepts is expressed in terms of the following parameters (these figures are only indicative and have not been validated):
  - **Relative Insertion Loss**: The additional average noise reduction compared to a 2 m high reflective plane barrier. Note that the figure is calculated based on a barrier sited at 4.3 m away from the nearside rail,
  - **Power Output**: The output based on optimum conditions (when solar irradiation of 1000 W/m² in a specified reference spectrum [see standard ASTM G-173-03 (ASTM, 2003)] falls on the PV cell at 25°C)

Example of barrier positioning relative to track for Concept 1: Cranked barrier
Rolling stock profile based on Siemens Desiro UK rolling stock

* Dimension in figure applies to line speeds < 160 km/h. For higher line speeds see Table above.
PV array specifications:

**Orientation:**
- The barrier should be aligned on an East-West axis with the track on the south side of the barrier;
- The panels in the PV array should be mounted facing the track to minimise the risk of theft or vandalism. This may restrict the opportunities for use to those barriers located on the north side of the track.

**Inclination**
- The panels should be mounted at 60° to the horizontal to maximise efficiency but minimise the overall footprint of the noise barrier.

**Screening or shading:**
- The PV panels should not be obscured by trees, bushes, etc. This may require regular maintenance of the surrounding vegetation; biodiversity, visual and amenity issues should be considered.
- The PV panels should not be in the shadow of surrounding buildings during the daytime.

**Power usage & connections**
- It is considered that the most appropriate use for power generated by the PV array will normally be for it to be fed back into the National Grid. In this case the inverter connected to the PV array should be connected into the NG as close as possible to the barrier (most likely the domestic grid serving residential properties adjacent to the railway).
- If the power is not to be fed into the National Grid but used instead for local systems/utilities, it is recommended that backup power be provided either from the Grid or via battery.

**Other considerations**
- The use of amorphous PV modules is preferred since these are more resilient than crystalline PV arrays.
- PV arrays should be fastened to the noise barrier using appropriate vandal-proof fixings.
- An angle of 60° will allow the panels to be cleaned by incident rainfall.

For further information see:


References: