**TRL Limited**

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# THE FEASIBILITY OF TRIALS OF RENEWABLE ENERGY GENERATION IN HIGHWAYS

Final

**by D R Carder (TRL Limited)**

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## TRL PR/CSS/14/03 THE FEASIBILITY OF TRIALS OF RENEWABLE ENERGY GENERATION IN HIGHWAYS

by D R Carder

**Project Reference:** 3/302-042 Trials of renewable energy generation in highways.
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**SCOPE OF THE PROJECT**

Renewable energy technologies are likely to become more important as other energy sources become depleted and the cost of power generation using fossil fuels rises. Renewable sources of energy have considerable potential for increasing security of supply although, in most cases, they require significant initial investment. Recognising the importance of developing renewable energy resources, the Highways Agency commissioned a preliminary scoping study in 2001 to explore available methods and assess the possibility of renewable energy generation being exploited within the highway network. This study recommended a positive response by Highways Agency in implementing full-scale trials of renewable energy generation.

One of the more promising techniques was considered to be that of the generation of electricity from solar power using photovoltaic panels mounted on the exposed faces of noise barriers, structures and buildings. Large-scale demonstration projects with panels mounted on noise barriers have been undertaken in the Netherlands, Switzerland, Austria, France, Germany and other countries.

The use of heat exchangers and ground source heat pumps in recovering energy from solar thermal heating of pavements was also identified, although this technique is more suited to direct heating applications rather than electrical power generation. However, in addition to the possibility of direct heating of neighbouring buildings, this particular technique may be of advantage to the Highways Agency for the winter maintenance of pavements, i.e. de-icing and snow melting.

This current study is therefore aimed at further evaluating the feasibility of full-scale monitored trials both of photovoltaic (solar) panels and of interseasonal heat transfer systems. The project included a detailed investigation of the current state of the technologies, the requirements for installation and operation, whole-life cycle costing and environmental life cycle assessment. Potential trial sites on the highway network were also identified.

**SUMMARY**

Although whole-life cost analyses showed that the costs associated with installation and maintenance of solar panel systems are currently far greater than the cost of the power generated, the energy payback period is likely to decrease. This is primarily because of increased mass production of solar cells although a long-term increase in the cost of electricity generated from other sources is also anticipated. A demonstration trial using solar panels mounted on highway noise barriers is expected to provide HA with experience in using these systems and in particular with an assessment of environmental impacts and experience with grid-connection options.

On the basis of whole-life costing which assumes large increases in the price of gas and electricity in the future, it is concluded that an investment in an interseasonal heat storage system is only likely to give any significant financial benefits in certain situations. These are if (a) the costs of the system and its maintenance were considerably lower than those assumed in these analyses, (b) there were significant environmental cost benefits that have not been taken into account, or (c) the high costs of traffic delay and traffic management assumed during system installation were inapplicable. The latter may be the case on a large motorway or trunk road construction scheme or in the construction of local roads for a new housing estate. The use of interseasonal heat transfer systems is currently innovative and at the forefront of technology. There is therefore merit in carrying out a demonstration trial as system costs are likely to reduce when more data are available.

**IMPLEMENTATION**

This feasibility study recommends various options for full scale trials and the results from these should enable an informed decision to be made about wider implementation of the techniques.

# Abstract

Renewable energy technologies are likely to become more important as other energy sources become depleted and the cost of power generation using fossil fuels rises. Renewable sources of energy have considerable potential for increasing security of supply although, in most cases, they require significant initial investment. This report reviews the use of two technologies with potential for producing renewable energy on the highway network. They are the production of electricity using solar panels mounted on highway noise barriers, and the storage and redistribution of direct heat retrieved from the solar thermal heating of pavements.


# 1 Introduction

## 1.1 General

In response to the Sustainable Development agenda there has been an increasing emphasis on the generation of energy from renewable sources. The UK Government's initial target is to exceed 5% from renewable sources by 2003 and 10% by 2010. This target was modified by the Energy White Paper issued on 24th February 2003 which aspired "to double renewables' share of electricity from our 2010 target by 2020". Recognising the importance of developing renewable energy resources, the Highways Agency commissioned a scoping study (Carder, 2001) to explore available methods and assess the possibility of renewable energy generation being exploited within the highway network.

This study recommended a positive response by Highways Agency in implementing full-scale trials of renewable energy generation. One of the more promising techniques was considered to be that of the generation of electricity from solar power using photovoltaic panels mounted on the exposed faces of noise barriers, structures and buildings. Large-scale demonstration projects with panels mounted on noise barriers have been undertaken in the Netherlands, Switzerland, Austria, France, Germany and other countries.

The use of heat exchangers and ground source heat pumps in recovering energy from solar thermal heating of pavements was also identified, although this technique is more suited to direct heating applications rather than electrical power generation. However, in addition to the possibility of direct heating of neighbouring buildings, this particular technique may be of advantage to the Highways Agency for the winter maintenance of pavements, i.e. de-icing and snow melting.

This current study is therefore aimed at further evaluating the feasibility of full-scale monitored trials of both photovoltaic (solar) panels and of interseasonal heat transfer systems. The project will be undertaken in the following main stages.

- Detailed investigation of the current state of the technologies which includes requirements for installation and operation.
- Whole-life cycle costing.
- Environmental life cycle assessment.
- Identification of potential trial sites on the highway network.

For convenience, the findings from this study are reported in two parts. Part I deals with the use of photovoltaic systems whilst Part II discusses interseasonal heat transfer systems.

## 1.2 Whole-life costing

Whole life costing is a technique whereby the overall cost of an asset can be computed over its entire operational life. It is used as a method for comparing various options at the investment stage at the start of a project, or at any time during the life of the project, to enable a balanced decision to be made on the preferred option or to optimise maintenance strategies for existing assets. Generally, the option with the lowest whole life cost would be preferred, although it may not have the lowest capital cost. The technique has been used increasingly on construction projects since the 1960's and is now a mandatory part of HA's project assessment procedures to achieve best value for money from its investment programme.

The principle is to calculate all the costs associated with a project throughout its life to a common base so that comparisons can be made between options. This is done by discounting all the anticipated costs, calculated at present day prices, by a factor which takes account of the time from the start of the project to when the expenditure would be incurred. The discounted costs are then summed to give the *net present cost (NPC)* of the asset. This may be defined as 'the sum of money which would need to be set aside today to meet all the eventual costs, both present and future, after allowing for the accumulation of interest on that part of it intended for future commitments'.

The evaluation of whole life costing for these renewable energy techniques is a complicated exercise, as their cost effectiveness will tend to hinge on trends in the price of electricity purchased from utility companies. This is particularly the case here as, with most renewable energy forms, there is a high initial investment cost, which needs recovering over many years and the discount rate can be a critical factor. Whole life costing should help to provide a valid assessment of the economic viability of the proposed systems.

### 1.3 Environmental life cycle assessment

The structure and composition of many electricity markets around the world is moving away from the centralised power generation and distribution that characterised the industry for much of the 20th century. Many cleaner technologies with more positive environmental effects are increasingly being used in novel applications. Due to this, it is no longer appropriate to use electricity cost as the only measure of effectiveness when comparing different energy production technologies. It is the lack of inclusion of the costs of environmental damage in electricity prices that has meant non-renewable sources have dominated, with the community bearing the environmental costs.

Although many benefits (and costs) are cited in the scientific and trade literature of new and emerging technologies, in the past these have rarely been attributed a value which could be applied to cost/benefit assessment (International Energy Association, 2001). Quantifying energy and non-energy values is critical to illustrating the cost effectiveness of alternative technologies, hence facilitating their wider use to the benefit of the environment.

In making a choice between products, or between more than one means of delivering a service, there are a number of criteria that can be used to judge the relative performance of options considered. The decision to choose one option over another may be guided by cost, appearance and/or functionality. However, it is increasingly common to need to compare the environmental impacts of choices, alongside more traditional purchasing criteria. "Life cycle thinking" considers all upstream and downstream processes involved in delivering a product or service, so that the overall impacts on the environment can be determined. In practice, this means examining all the processes that contribute to manufacturing a product or providing a service, from extraction of raw materials, through use of the product or service, until eventually waste management requirements are considered.

Life cycle assessment has developed from this general "life cycle thinking" approach as a formal systems analysis methodology. The objective is to document energy and materials use across the whole life cycle of a product or service, from cradle to grave. It involves procedures to evaluate the environmental burdens associated with products, processes, or activities by identifying and quantifying energy and raw materials used and wastes released to the environment. The process takes account of the entire life cycle of the product, process, or activity, encompassing extraction and processing raw materials, manufacturing, transportation and distribution, use, re-use, maintenance, recycling and final disposal (SETAC, 1993).

In this report, simplified environmental life cycle assessments have been included to attempt to quantify the environmental benefits and disbenefits of both photovoltaic power generation and interseasonal heat transfer throughout their life cycle. For this purpose only published research has been discussed: no new research or testing has been carried out for this element of the project.

# PART I. PHOTOVOLTAIC SYSTEMS

## 2 Current state of the technology

### 2.1 Introduction

Electricity generated from photovoltaic cells already 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 and the basic principles of photovoltaic power generation have been reviewed by Carder (2001). The purpose of this report is to investigate more significant power generation at a larger scale that can be implemented within the highway network and to assess the feasibility of a full scale trial.

Assets owned by the Highways Agency include buildings (eg. maintenance depots, pumping stations, control rooms, etc) and structures (eg. bridges, sign gantries, lighting columns, noise barriers, etc). All of these provide opportune locations at which solar panels can be installed. In addition to these locations, the land adjoining the highway network and owned by the Agency could also be used for mounting photovoltaic panels. Potentially this land will include embankment and cutting slopes together with verge areas wherever they are significant. It must be noted that there may be policy issues involved in some of these installations, in terms of distraction and possible reflections affecting highway users, which would need careful consideration.

One of the most promising sites for mounting photovoltaic systems is onto highway noise barriers (Figure 2.1) and various demonstration projects have been undertaken in Europe. In the following descriptions of these projects, the terminology "peak watt ($W_p$)" is frequently used. This is a measure of the power produced under optimal conditions when solar irradiation of $1000W/m^2$ in the reference spectrum AM 1.5 falls on the photovoltaic cell at $25^oC$.

### 2.2 Previous case history studies in Europe

A large-scale demonstration project, where solar panels were installed on a highway noise barrier, was undertaken near Ouderkerk aan de Amstel on the A9 motorway in the Netherlands. The project was financially supported by the European Commission and by the Netherlands Agency for Energy and Environment and the findings have been reported in detail (Borg and Jansen, 2001; Rijkswaterstaat, 1999). The photovoltaic system consisted of 2,160 AC-modules solar panels (polycrystalline) which were mounted on the upper part of the acoustic baffle construction of a 1.65km long noise barrier to investigate their suitability. The orientation of the baffle was south to southwest and its angle of inclination was $50^o$ to the horizontal. The mains-coupled system has a capacity of $220kW_p$ and has generated about 176,000kWh of electricity per annum since its installation in 1998. The yields, for a standard climatic year in the Netherlands, range between 600 and $800kWh/kW_p$. The study also investigated two different types of inverter, one of which was found to have a better efficiency and serviceability than the other (Borg and Jansen, 2001). A rough estimate of the effect of accumulated traffic dust was a loss of efficiency of about 8% per annum and annual cleaning after the winter season is recommended. The total costs of the demonstration project amount to almost Eur 2.4m; the photovoltaic system itself cost Eur 1.9m.

This was not the first trial of photovoltaic noise barriers in the Netherlands, in 1995 an acoustic baffle with 1,116 solar panels was installed along a 550m length of the A27 near De Bilt with the dual purpose of generating electricity and reducing noise levels. The panels are oriented towards the Southwest and are at an approximate angle of $50^o$ to the horizontal. The mains-coupled system, incorporating a DC/AC inverter, has an output of 55kW$_p$ that has yielded about 30,000kWh per annum. The cost of purchase and construction amounted to Eur 1.1m of which the production of the PV panels comprised Eur 544,000.

A noise barrier on the A21 in northeast France was constructed in 2000 incorporating solar panels, which were grid connected. The barrier was 650m long and about 4m high with a power rating of 63kW$_p$.

A 100kW$_p$ grid connected system using 2208 polycrystalline modules inclined at an angle of 45$^o$ was constructed alongside an 800m length of the N13 motorway in Switzerland in 1989. Since then it has fed an average of 110,000kWh into the grid per annum and operated at an average performance of 75%. During a 10 year period, 12 modules were stolen and 21 were damaged and had to be replaced.

A further major installation was undertaken in 1995 at Giebenach along the N2 near Basle in Switzerland. This installation comprised 752m$^2$ of photovoltaic panel with a 104kW$_p$ rating. In this case the panels were mounted on the non-traffic side of the noise barriers. The average output to the grid from 1996 to 1998 was about 97,000kWh.

A demonstration 40kWp system was installed along a 264m length of the A1 near Gmunden in Austria. This system has produced about 31,500 kWh per annum since it became operational in 1992. The cost of the photovoltaic panels represented about 43% of the total cost of installation.

In 1995 a German utility has installed two grid-connected systems near the intersection of the A6 and A620 motorways close to the border of Germany and France. One is a 40kW$_p$ system, which is installed on a 232m length of transparent sound reflecting acrylic plastic. The other is a 20kW$_p$ system extending 217m along a non-transparent section of sound absorbing barrier.

The locations of the European trials are shown in Figure 2.2 and the performances of the various systems are summarised in Table 2.1. The data serve as an approximate guide as to likely performance although because of recent advances in technology the performance of future systems is likely to be better.

**Table 2.1. Summary of European trials**

| Location | Installation date | Capacity ($kW_p$) | Output (kWh per annum) | Output/capacity ($kWh/kW_p$) |
|---|---|---|---|---|
| A9, Netherlands | 1998 | 220 | 176,000 | 800 |
| A27, Netherlands | 1995 | 55 | 30,000 | 545 |
| A21, France | 2000 | 63 | N/a | n/a |
| N13, Switzerland | 1989 | 100 | 110,000 | 1100 |
| N2, Switzerland | 1995 | 104 | 97,000 | 933 |
| A1, Austria | 1992 | 40 | 31,500 | 788 |
| A6, Germany | 1995 | 40/20 | N/a | n/a |

Studies have also been carried out on the feasibility of zigzag structures to combine noise absorption (by the elements facing down) with production of solar energy (with the areas showing upwards). An international ideas competition was organised and the six winning concepts are described by Fröhlich (2000): the prototypes of these are being erected as test facilities. Other options of multiple edge barriers and other barrier shapes are a solution to enhancing the acoustic performance of barriers without raising their height (Watts, 2001), but their integration with solar systems needs further investigation.

## 2.3 Operational performance of photovoltaic systems

A database has been assembled by the International Energy Agency (IEA) containing the technical and operational data of different types of photovoltaic system (Jahn et al, 2000). This database covers different types of system which may be grid connected, stand alone with backup generator, or hybrid. Some account is taken of the different climatic conditions by using normalised performance indicators where possible.

The evaluation procedures are based on the European guidelines (Commission of the European Communities, 1997) and the IEC Standard 61724 (1998). Energy yields are normalised to the nominal power of the array, efficiencies to the photovoltaic array energy, and performance ratio to in-plane irradiation. On this basis the final yield ($Y_f$) is the energy delivered to the load per day and $kW_p$: the reference yield ($Y_r$) is based on the in-plane irradiation and represents the theoretically available energy per day and $kW_p$. The performance ratio (PR) is then calculated from $Y_f / Y_r$ and represents the ratio of photovoltaic energy actually used to the energy theoretically available.

From the performance of 260 photovoltaic plants in the IEA database, the following annual performance ratios can be expected for the different types of system:

- Grid-connected systems – PR of between 0.6 to 0.8
- Stand-alone systems without backup – PR of between 0.1 to 0.6
- Stand-alone systems with backup generator – PR of between 0.3 to 0.6.

## 2.4 Expected life time of a solar panel system

Manufacturers of photovoltaic cells generally give warranties on performance in terms of the power output, which they will continue to deliver when 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 electric panels, made about 35 years ago, are still producing energy today.

A few examples of current performance warranties are as follows.

(a) Siemens solar modules are designed to withstand the toughest environmental conditions and are characterized by their long service life. Siemens solar modules are covered by a *25 year limited warranty on power output* – “your guarantee of trouble-free solar power generation”.

(b) Kyocera offer a *25 year warranty* and their quality assurance system ensures that their multicrystal modules exceed the US government specifications for tests involving thermal cycling, thermal shock, thermal/freezing and high humidity cycling, electrical insulation, hail impact, various mechanical and wind loads, salt mist, light and water exposure, and field exposure.

(c) All products manufactured by BP Solar are individually tested and labelled. A *20 year performance warranty* guarantees that the solar module will continue to deliver a minimum of 80% of its rated power with all modules rated at 40w and above. Many modules with higher power output have a *25 year performance warranty*.

(d) All AstroPower modules carry a *20-year limited warranty*, and are designed and manufactured to meet all relevant international safety and performance certifications.

(e) Evergreen solar and Uni-solar also offer a 20 year limited power warranty on most photovoltaic modules. Uni-solar rigid panels are framed in anodised aluminium which is highly resistant to corrosion.

It should be noted that the performance warranties given above are only a few selected examples and there are many other manufacturers, some of which may offer a longer warranty. For the purpose of whole life costing, the assumption of serviceability over 25 years is not unreasonable. After 25 years, the modules may well continue to function although some reduced efficiency should be assumed.

Warranties on materials and workmanship generally vary from between 1 to 5 years depending on the supplier.

# 3 Cost of photovoltaic installation on a noise barrier

## 3.1 Introduction

For the purpose of cost evaluation, it has been assumed that a 100m length of a noise barrier on the Highways Agency network will provide a suitable demonstration project. It is envisaged that solar panels will cover the uppermost 2m of the barrier and can be fixed at an angle suitable for maximising the irradiation, or alternatively be fixed at an angle on the top of the barrier. A south facing orientation will also generally optimise output from the photovoltaic system. Although there are other options on orientation, such as fixing solar panels vertically to both sides of the barrier when the barrier runs north-south, these are not considered in this study because of the increased capital cost. Costs of other layouts can however be derived from the data if so wished.

On this basis, the active surface area of the photovoltaic panels will be 200m$^2$. For the current exercise only silicon panels were investigated, other types such as gallium arsenide, copper indium diselenide, and cadmium telluride have not been considered at this stage. Three types of panel have been considered, they are:

- **Monocrystalline,** these have the highest output per unit area but are the most expensive
- **Polycrystalline,** these are cheaper than monocrystalline but have lower output
- **Amorphous**, these are cheapest of the three types considered but have theoretically the lowest output per unit area. However, they respond to a broader range of frequencies than the crystalline types and may therefore be more suitable for the more cloudy conditions encountered in the UK. They are also more suited to mass production and costs may reduce.

Initial costings have been established assuming the output from the system will be synchronised with either the HA private grid or the national grid using an inverter. In this way the power generated will be used immediately with no requirement for battery or generator back-up. The solar array would therefore be better placed near to where there is a daytime power demand (eg. tunnel, maintenance depot, highway junction) to avoid transmission losses in the cables.

In remote localities where there is no existing grid, a stand alone system will be needed. In this latter case, the cost of routing the grid to the location will be an important factor in deciding on its financial merits.

## 3.2 Cost data

The main costs are those involved with (a) provision of the solar panels, (b) grid synchronised inverters, and (c) design, provision and installation of array support structures and cabling. Other costs are more site specific and will include those of site investigation and preparation, planning approval, risk and environmental assessments, and maintenance. The various costs are now considered in turn.

### *3.2.1 Provision of the solar panels*

Typical costs and theoretical maximum outputs from different types of photovoltaic panels are given in Table 3.1. Costs are based on those advertised in late 2002 by various suppliers for single solar panels, although discounted prices would be expected for bulk purchase. For example, some suppliers have indicated that a realistic discount on purchases of about 200m$^2$ of solar panel, such as would be required for the demonstration project, would be of the order of 25% off the advertised single panel retail prices.

**Table 3.1. Undiscounted retail price of solar panels (only)**

| **Panel type** | **Panel maximum output ($W/m^2$)** | **Array maximum output per $200m^2$ (kW)** | **Cost of single panel (£)** | **Array cost per $200m^2$ (£000)** | **Cost per kW (£000)** |
|---|---|---|---|---|---|
| Monocrystalline | 123.2 | 24.6 | 700 | 143.7 | 5.83 |
| Polycrystalline | 83.5 | 16.7 | 480 | 89.1 | 5.33 |
| Amorphous | 64.6 | 12.9 | 350 | 70.7 | 5.47 |

**Notes:**

(i) The above costs are based on those of single panels and are therefore ceiling values as discounts would be anticipated for bulk purchase.

(ii) Array costs have been worked out using panel surface area.

(iii) The above costs of panels were sourced in late 2002 and are expected to fall as mass production techniques become more viable in response to an increased demand.

In Table 3.1 it is interesting to note that, although monocrystalline cells are theoretically the most efficient in power production, they are also the most expensive. In terms of the cost per kW there is little difference in the purchase price of the different types of cell. However, a larger surface area of solar panel will be theoretically required to achieve the same power output with the amorphous type of photovoltaic cell. This will have an effect on the number of support frames/structures required and hence have a cost implication.

When considering the costs involved in a photovoltaic array in the UK, the direct comparison of the three types of silicon based panels given in Table 3.1 can be misleading when the manufacturers quoted maximum outputs are used in isolation. Under UK conditions, the output measured over a complete annual cycle from amorphous (the cheapest) and monocrystalline (the most expensive) panels are very similar. This is to some extent born out by a trial carried out at a location in the UK in which the whole year output of an amorphous 64 watt panel was found to be approximately equal to that of a 75 watt monocrystalline panel (Energy Development Co-operative, 2002). As previously discussed this is because the amorphous cell is able to utilise a far wider portion of the solar spectrum than the moncrystalline.

### *3.2.2 Grid synchronised inverters*

There appear to be two approaches in the use of inverters, these are:

- *Series connection*, where panels are linked in series to give a high voltage and handled by a powerful inverter capable of handling over 3kW
- *Parallel connection*, where each panel or small group of panels are linked to a much lower capacity inverter capable of about 150W.

One range of products that features frequently in case studies is the "Sunny Boy" inverter. The maximum output of an inverter of this type, which costs about £1400, is up to 3kW and the output is grid synchronised. Another suitable product is from the range of Fronius inverters and costs about £1000, this handles up to 2.6kW and is also appropriate for grid connection. Both of these inverters conform to the Engineering Recommendations G77 (Electricity Association, 2000) and are currently approved for connection to the national grid, because they shut down automatically on grid failure so preventing damage elsewhere. The range of tested inverters is being continually expanded to include those from manufacturers such as NKF Electronics (Dutch) who have experience with photovoltaic installations in Europe. For embedded generating plant in the grid, if size is greater than 5kWp and not covered by G77, engineering recommendations G59 (Electricity Association, 1991) apply.

### *3.2.3 Design, provision and installation of array support structures and cabling*

There are many methods of mounting solar arrays and generally companies will design to order but are not able to issue standard costs for frame mountings and support structures. In this particular application, where photovoltaic panels are to be installed on highway noise barriers, there are a number of site specific decisions to be made. The fundamental considerations are whether the panels are to be:

- attached to the top of an existing noise barrier,
- attached to the face of an existing barrier,
- form part of a new barrier.

Other options such as stand alone units behind an existing barrier, or attaching the panels to poles exist, but are not considered as being particularly likely because extra landtake may be required.

Particular design considerations, some of which would require input from a structural engineer, include:

- calculating the structural stability particularly with respect to wind loadings,
- assessing any risk of vehicular impact,
- producing a vandal proof system,
- maintaining an aesthetic appearance,
- ensuring that the traffic noise reducing capability is maintained.

In addition to the above considerations, optimisation of the angle of the solar array needs to take place. Table 3.2 gives an idea of the variation of the sun angle to the horizontal at some arbitrary locations in the UK.

**Table 3.2. Sun angle at various UK locations**

| Location | Angle of sun (degrees to horizontal) | |
|---|---|---|
| | **January** | **July** |
| Winchester | 15.9 | 62.0 |
| Cardiff | 15.5 | 61.6 |
| Birmingham | 14.5 | 60.6 |
| Durham | 12.2 | 58.3 |
| Stirling | 10.6 | 56.9 |
| Aberdeen | 9.8 | 55.9 |

Generally the variation in sun angle across the UK is small compared with the seasonal variation. A minimum tilt of $15^o$ off horizontal is recommended to allow the rain to wash dust off the array.

The optimal angle selected for photovoltaic panels will depend on whether the installation is grid connected or stand alone. If the system is grid connected, the optimum is the summer settings, which will produce more power annually with significant generation in the summer. If the system is stand alone then maximum conversion may be advisable in the winter to keep batteries charged. As a compromise panels in the UK are normally inclined at between $25^o$ to $35^o$ from the horizontal.

Because of the various site specific requirements, the cost of the frame for mounting solar arrays on noise barriers is difficult to estimate. However for the purpose of this study it is proposed on the advice of suppliers to estimate frame costs as follows:

- 15% of photovoltaic panel costs when the frames are to be attached to the top of an existing noise barrier at the optimum angle to the horizontal,
- 5% of photovoltaic panel costs when the mounting frames are to be fixed directly onto the face of an existing barrier.

Preliminary estimates indicate that the costs of procuring cabling, isolators and meters are about £4000 for $200m^2$ of solar panel. Labour costs in installing the mounting frames and panels on the noise barriers together with cabling and metered connection to the grid are expected to cost about £40k for the 2m high by 100m long array.

### *3.2.4 Maintenance costs*

A rough estimate of the effect of accumulated traffic dust in a European demonstration project was a loss of efficiency of about 8% per annum and annual cleaning after the winter season is recommended. The cost of cleaning a $200m^2$ area of solar panels mounted on noise barriers is therefore not high and a provision of £300 per annum should suffice provided traffic management is not required.

### *3.2.5 Summary of trial costs*

On the basis of the previous information, a summary of the breakdown in costs for a trial on the highway network involving $200m^2$ of photovoltaic panel is given in Table 3.3. The costing assumes that panels are fixed to the tops of the south face of existing barriers at an angle of $25^o$ to $35^o$ from the horizontal. No allowance has been made for any traffic management during panel installation as it has been assumed that sufficient verge is available to provide safe working with equipment access from behind the barrier. In some instances it may be appropriate to consider mounting panels on the non-trafficked side of the barrier.

The usable power output from a south facing trial installation in the UK would be expected to be about 750kWh per annum per $kW_p$ (British Photovoltaic Association, 2002). This is within the range of outputs of 545 to 1100kWh per annum per $kW_p$ given in Table 2.1 for recent European trials. For a trial using amorphous panels, the panel ratings would give $12.9kW_p$ for a $200m^2$ array. On this basis an annual power output of 9.7MWh would be anticipated.

If, as an alternative, panels were fixed directly to the vertical face of existing barriers with a suitable spacer so that the final panel angle was at $70^o$ to the horizontal, about 80% of optimal power would be anticipated as yield. However the cost of the support frames in Table 3.3 would then be expected to reduce by £7070 to 5% of the panel costs and their structural design would be less complicated with a reduction in cost of about £3000. The total cost would then be £126,560 with a power output of about 7.8MWh per year.

**Table 3.3. Estimate of installing solar panels at the optimum angle on top of an existing noise barrier**

| ELEMENT | COST (£) | COMMENTS |
|---|---|---|
| **Design and supervision** | | |
| Design of support frames and photovoltaic system | 10000 | Allowance for design work by electrical and structural engineers. |
| Supervision of construction | 10000 | Allowance for on site supervision of all construction aspects of the work. |
| **Components** | | |
| Photovoltaic panels | 53025* | Provision of 200m$^2$ of amorphous solar panel. Includes allowance for 25% discount because of bulk purchase. |
| Inverters | 7000 | Provision of grid synchronised inverters. |
| Cabling, isolators, meters and trunking | 4000 | Assumes nearby grid network |
| Support frames | 10605 | Calculated from 15% of undiscounted panel costs |
| **Mechanical installation** | | |
| Site installation of PV system | 40000 | Mounting on noise barrier and supply and installation of cabling and meters. Assumes nearby grid network. |
| Testing and commissioning | 2000 | |
| **TOTAL** | **136,630** | ***Excludes contingency of £70,000 for instrumentation during construction, monitoring and interpretation of performance of trial for first year.*** |

**Notes:**

* The costs of panels are expected to fall, as mass production techniques become more viable.

# 4 Whole-life cost of photovoltaic installation on noise barriers

A model has been developed to determine the effect of a number of factors on the whole-life cost of a solar panel installation of the type described in the previous section. Generally, three sets of data are required for whole-life cost analyses, namely:

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

## 4.1 Cost data

The cost data covers all costs associated with the installation from conception to decommissioning. The following cost components have been considered for the solar panel system:

- design,
- installation,

- power generated by panels (a benefit),
- operation and maintenance,
- traffic management,
- traffic delay,
- decommissioning and salvage.

Rather than determine the whole-life cost of a trial involving 200m$^2$ of panels, the whole-life cost of a larger installation involving, say, over 2000m$^2$ panels has been calculated. This is because some cost data for the trial installation would be an unrepresentatively high proportion of the whole-life cost compared to that for a larger installation. However, for comparison purposes, the whole-life costs for the larger installation have been normalised so they correspond to the same area of panels as the trial installation, i.e. 200m$^2$.

## 4.2 Performance data

The performance data concerns all aspects of the performance of the solar panel system, as follows:

- the efficiency of the panels, including the effects of damage and theft,
- the service life of the panels,
- the efficiency of the inverters,
- the service life of the inverters,
- the service life of the cabling and ancilliary electrical equipment.

## 4.3 Discount rate data

The principle of whole-life costing is to calculate all costs throughout the life of a project to a common base so that comparisons can be made between different options. All costs, calculated at present day prices, are discounted by dividing them by the factor $(1+ r)^t$, where r is the discount rate and t is the time from the start of the project to when the cost would be incurred. The discounted costs are summed to calculate the net present value (whole-life cost), which represents the sum of money that must be set aside today to meet all costs throughout the life of the project, after allowing for the accumulation of interest on the part intended for future costs.

In accordance with current Treasury rules, an annual discount rate of 3.5% has been assumed in the model. As the discount rate has fallen from 8% to the current rate over recent years, the factor by which future costs are discounted has decreased significantly. For example, the discounted costs of an operation costing £10000 after 20 years are £2145 and £5026 for discount rates of 8% and 3.5%, respectively. Therefore, costs incurred and benefits received in the future have a greater effect on the whole-life cost when the discount rate is lower.

## 4.4 Cost and performance data assumed for the solar panel system

### *4.4.1 Design and installation costs*

It has been estimated that the design and supervision costs for a large installation (calculated per 100m length) would be £1000 and £5000, i.e. 10% and 50% of the costs given in Table 3.3 for the trial installation.

The costs of the components for the installation have been assumed to be those listed in Table 3.3. However, some whole-life costs have been calculated assuming lower costs for the components taking into account reductions for bulk purchases and government grants.

The cost of the installation on site has been assumed to be £30,000, 75% of the cost given in Table 3.3 for the trial installation. The cost assumed for testing and commissioning is £1000, 50% of the cost given in Table 3.3.

#### *4.4.2 Power generated by panels*

The power generated by the panels, 9.7MWh, would reduce the power that the Highways Agency purchased from an electricity company. The cost saving would be dependent on the unit cost of electricity. Electricity prices from power stations vary according to the time of day and the season. Because of excess generating capacity and changes in the regulation of the power industry, the price of electricity is currently lower than it has been for several years. Nevertheless, recent instability in the wholesale electricity market has caused prices to range from under £20/MWh (2p/kWh) to over £100/MWh. The Highways Agency has several types of electricity supply contract, dependent on the usage. Certain contracts for street lighting are for the supply of unmetered electricity. However, most electricity is metered and is supplied at a fixed rate per MWh, the rate varying with the type of contract. A price of £50/MWh has been assumed to be the current rate for contracts supplying power throughout the day when solar panels generate power. This is the price currently paid for power generated by wind that includes benefits to suppliers of green energy that have Renewable Obligation Certificates. A higher price of £80/MWh has been assumed for some analyses in order to investigate the effect of the price on the whole-life cost. For comparison, prices to domestic users are currently about £60/MWh for the standard day/night rate and £25/MWh for the night rate.

It is likely that the price of electricity will increase in real terms over the next few years when excess generating capacity has been removed. However, it is unlikely that increases above the rate of inflation can be sustained in the long term because of the dependence of the national and world economies on the price of electricity. For the purposes of this study, the following changes in the price of electricity have been assumed:

- no increase above the rate of inflation,
- increasing by a factor of 2 over the first 10 years (equivalent to 7.2% annual increase), then no further increase,
- increasing by a factor of 4 over the first 10 years (equivalent to 14.9% annual increase), then no further increase.

The six electricity price cases described above are summarised in Table 4.1.

Based on the data given in Section 2.2 for an installation of 2208 panels on the N13 in Switzerland, it has been assumed that 3 panels of the solar panel system under consideration would be damaged or stolen every 10 years. It is possible that as many panels may be stolen from a small installation of 200 panels as would be stolen from a larger installation, so more than 3 such replacements may be appropriate for the trial. Nevertheless, the periodic replacement of small numbers of panels is unlikely to be economical, so a reduction in the power generated equivalent to the loss of 3 panels every 10 years, starting after 5 years, rather than panel replacement, has been assumed.

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

It has been assumed that the inverters would perform with no loss of efficiency until they require replacement.

It has been estimated that the times taken to replace an inverter (1 week) would result in a loss of power of 0.2MWh.

**Table 4.1. Assumed variation in price of electricity above rate of inflation**

| CASE | PRICE OF MWh (£) | |
|---|---|---|
| | YEAR 1 (percentage increase/year 1 to year 11) | YEAR 11 TO YEAR 30 |
| 1 | 50 (0) | 50 |
| 2 | 50 (7.177) | 100 |
| 3 | 50 (14.87) | 200 |
| 4 | 80 (0) | 80 |
| 5 | 80 (7.177) | 160 |
| 6 | 80 (14.87) | 320 |

### *4.4.3 Operation and maintenance costs*

Operation and maintenance costs could be incurred for:

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

*Washing panels*

It has been assumed that the panels would be washed annually at a cost of £200 per annum, £100 less than for the trial. No decrease in power generated has been assumed because of the accumulation of contamination on the panels between each wash.

*Electrical testing*

The cost of electrical testing has been estimated to be £50 every 3 years for short inspections, and an extra £50 every 6 years for more detailed inspections.

*Replacing panels*

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

It has been assumed that the panels would be refurbished after 30 years.

*Replacing inverters*

It has been assumed that the inverters would have a 20-year performance warranty and function with no loss of efficiency over that period. Any replacements within that period would be free of charge. It has been estimated that the five inverters would be replaced as shown in Table 4.2. The cost of installing and commissioning a replacement inverter has been estimated to be £300. As indicated above, it has been assumed that the time for replacement would result in a loss of power generated equivalent to 0.2MWh (1 week).

**Table 4.2. Replacement of inverters**

| INVERTER NUMBER | YEAR REPLACED | |
|---|---|---|
| 1 | 20 | 40 |
| 2 | 20 | 45 |
| 3 | 25 | 45 |
| 4 | 25 | 45 |
| 5 | 25 | 50 |

*Replacing/maintaining meter and cables*

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

*Maintaining support structure*

A galvanised steel support structure should be maintenance free for over 40 years, provided the galvanising layer is not broken down by de-icing salts transmitted by spray. To minimise or prevent such damage, a high quality protective treatment could be applied to the galvanised layer, and it has been assumed that the support structure would require one reapplication of the protective treatment costing £1000 when the panels were replaced/refurbished 30 years after installation. An aluminium support structure should not require maintenance before 60 years, but the initial cost could be higher than for a galvanised steel structure with a high quality protective treatment.

### *4.4.4 Traffic management and traffic delay costs*

Traffic management and traffic delay costs are dependent on the installation location. It has been assumed that the installation would be located on an embankment away from traffic, so traffic management and traffic delay costs would not be incurred.

### *4.4.5 Decommissioning and salvage*

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

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

The cost of removing the panels and the support structure to clear the site would be significant. However, the panels would have a salvage value as they could be refurbished after the useful life of the photovoltaic material, assumed to be 30 years. The support structure could also have some salvage value and, presumably, could be refurbished and used at another site. On this basis, it has been assumed that the salvage value of both the panels and the structure would equal the cost of removing them from the site.

#### *4.4.6 Summary*

The power, operation and maintenance, and end-of-use costs and the performance data described above are summarised in Table 4.3.

**Table 4.3. Summary of assumed power, operation and maintenance, and salvage costs**

| ELEMENT | COST (£) | FREQUENCY |
|---|---|---|
| **Power output** | | |
| Power output | 9.7MWh | Annually, but decreasing due to loss of performance, and damage and/or theft<br>Loss due to performance: 0.8% each year for first 25 years, 1.6% each subsequent year<br>Loss due to damage and/or theft: 1.5% every 10 years after 5 years<br>Loss due to inverter replacement: 0.2MWh |
| **Routine maintenance** | | |
| Washing panels | 200 | Annually |
| Basic electrical inspection | 50 | 3 years |
| Detailed electrical inspection | 100 | 6 years |
| Installation and commissioning of replacement inverter | 300 | See below for frequency |
| **Replacement components** | | |
| Replacement inverter | 1400 | 2 at 20 years<br>3 at 25 years<br>(1 at 40 years)<br>(3 at 45 years)<br>(1 at 50 years) |

### 4.5 Effect of price of electricity on whole-life cost

Column 2 of Table 4.4 shows whole-life costs calculated for an accounting period of 30 years for the six electricity price cases shown in Table 4.1, assuming the cost and performance data shown in Tables 3.3 and 4.3. The initial cost of the components and their installation is £111,630. Column 4 of the table shows the power generated and its whole-life cost benefit.

### 4.6 Effect of cost of panels on whole-life cost

Column 3 of Table 4.4 shows the whole-life costs for the six electricity price cases shown in Table 4.4, assuming that the costs of the new and replacement components are 50% less than those shown in the Tables 3.3 and 4.3, or the installation is subsidised to the same value. No reductions in the costs of the installation of the components have been assumed. The initial cost of the components and their installation costs for this case is £74,315, i.e. £37,315 less than for Column 2 of Table 4.4.

**Table 4.4. Variation in whole-life cost with price of electricity and components**

| ELECTRICITY PRICE CASE (cost/MWh in £) | WHOLE-LIFE COST (£) | |
|---|---|---|
| | COST OF COMPONENTS (percentage of costs in Tables 3.3 and 4.3) | |
| | 100% | 50% |
| 1 (50) | 105,100 | 68,300 |
| 2 (50 at yr.1 ? 100 at yr.11) | 99,500 | 62,700 |
| 3 (50 at yr.1 ? 200 at yr.11) | 88,800 | 52,100 |
| 4 (80) | 100,200 | 63,400 |
| 5 (80 at yr.1 ? 160 at yr.11) | 91,200 | 54,400 |
| 6 (80 at yr.1 ? 320 at yr.11) | 74,200 | 37,400 |

The results in Table 4.5 show the net present value of the power generated by the solar panel system. It must be noted that this value has already been taken into account in the whole-life costs presented in Table 4.4.

**Table 4.5. Variation in net present value of the power generated**

| ELECTRICITY PRICE CASE (cost/MWh in £) | NET PRESENT VALUE OF POWER GENERATED (=291MWh) (£) |
|---|---|
| 1 (50) | 8,200 |
| 2 (50 at yr.1 ? 100 at yr.11) | 13,800 |
| 3 (50 at yr.1 ? 200 at yr.11) | 24,400 |
| 4 (80) | 13,100 |
| 5 (80 at yr.1 ? 160 at yr.11) | 22,100 |
| 6 (80 at yr.1 ? 320 at yr.11) | 39,100 |

## 4.7 Discussion

The whole-life cost analyses have shown that, for the assumptions made, the costs associated with the installation and maintenance of the assumed solar panel system are far greater than the cost of the power generated by the panels. This is the case even assuming increases in the price of electricity significantly above the rate of inflation, and either significant reductions in the costs of the components or significant subsidies. Assuming present day electricity prices and component costs, a subsidy greater than £105,100 would be required to yield a 'whole-life cost benefit'. Even with significant increases in the cost of electricity and significant decreases in the cost of components, a subsidy greater than £37,400 would be required to yield a 'whole-life cost benefit'. Therefore, it is concluded that it is unlikely that an investment in a solar panel system would give any financial benefits unless the costs of the system and its maintenance were considerably lower than those assumed and/or there were significant environmental cost benefits that have not been taken into account in these analyses.

# 5 Environmental life cycle assessment of photovoltaic power generation

## 5.1 Introduction

According to the International Energy Association, photovoltaic systems pose few environmental problems when compared to more traditional electricity generation that utilises fossil fuels (http://www.oja-services.nl/iea-pvps/pv/envcons.html). The generating component produces electricity silently, there are no moving parts and it does not emit any harmful emissions during normal operation.

The most significant life cycle stage of photovoltaic cells in terms of their environmental impact comes during their manufacture. Although they are mainly manufactured out of silica, which is relatively non-toxic and abundant, there are some by-products from the process. In addition to this, the silica used in photovoltaic cells has to be very pure and a large amount of energy is needed for this. This has led many commentators in the past to be sceptical about whether photovoltaic cells can actually generate as much energy over their lifetime as they took to manufacture (their embodied energy). Due to this, there has been a lot of research carried out on energy requirements of solar cell manufacture and energy pay back times. This report draws substantially on this research.

The remainder of this section will analyse the different stages in the life cycle of photovoltaic systems and will quantify as far as possible their positive and negative impacts. Due to the high degree of complexity of the analysis framework, lack of data and consensus on environmental impacts, simplified life cycle assessment has been applied to the assessment of photovoltaic power systems in the past using such indicators as energy usage and $CO_2$ mitigation potential (IEA Photovoltaic Power Systems Task Force, 1997). This assessment will follow the same approach referring to previously published research.

## 5.2 Production

The production of photovoltaic cells is the stage of the life cycle with the most significant environmental impact. This section will examine the environmental impacts of materials used within the process, energy used and harmful by-products of the process.

### *5.2.1 Material use*

A wide range of materials is used in the manufacture of photovoltaic cells. The materials used depend on the type of cell and the manufacturing process used.

Monocrystalline and polycrystalline cells

Monocrystalline and polycrystalline cells use essentially the same process of melting and casting silicon (into single crystals, into poly-crystals or the drawing of thin layers of ribbon silicon from the melt). This is a high-energy process at more than 1500°C. Further processing involves doping with trace amounts of phosphorous and boron; photolithography involving photoresist (a light sensitive chemical which hardens to form a protective barrier); and contacting with gold and copper usually by electroplating. The contacting process can involve using cyanide compounds.

Various common solvents and acids are used in processing, including hydro-fluoric acid. Module fabrication is essentially the same as for amorphous silicon, which is described below.

To a large extent the material flows in monocrystalline and polycrystalline cell production will also be the same (Alsema, 1996). The following materials are needed for the production of silica based photovoltaic cells:

- water;
- silica;
- carbon (used in the reduction process of the silicon);
- gold (sometimes silver) and copper used for the contacts;
- boron and phosphorous;
- cyanide compounds for electro-plating;
- EVA (ethyl vinyl acetate) foil;
- backing material (either rigid plastic or aluminium);
- Mineral oil and silicon carbonide which are used in the wafering process;
- HCl to produce high purity carbon and high purity silicon. This is neutralised with $Ca(OH)_2$ and $CaCl_2$ and is discharged as solid waste; and
- low iron content glass for the front panels.

Materials that dominate are the bulk materials like glass, EVA and aluminium. Other materials that are required in large amounts include carbon sources for reduction (wood scrap, coal etc). Next to the reduction and module assembly processes, the wafering process has a large requirement for silicon carbide and mineral oil. The amount of HCl is also large and methods to reduce its use should be investigated (Phylipsen and Alsema, 1995).

The main constituents of crystalline solar cells do not need any scarce resources to be produced. The only constituent that could be considered to be very scarce is the gold (and sometime silver) used for contacts. Data from a study carried out in 1995 (Phylipsen and Alsema, 1995), suggests that if crystalline photovoltaic cell technology contributed 5% of the worlds electricity production, it would require 30% of the world's silver production. Silver (and gold) consumption deserves attention from a resource conservation point of view. The use of copper, a moderately scarce resource will not contribute much to resource depletion, because the amount required is low in comparison to the total production.

Amorphous cells

The primary material for amorphous silicon cells is a silicon/hydrogen alloy, with a secondary material of germanium. These are doped with phosphorous and boron. During processing the silicon and germanium are deposited as silane and germane using plasma assisted chemical vapour deposition. These are compounds of silicon and germanium with hydrogen and are toxic. They are controlled by waste stream burn off.

Amorphous silicon modules can be made from single junction cells; which means that they have only one layer absorbing sunlight. This type contains no germanium. However, these cells are less efficient at converting sunlight to electricity than crystalline silicon cells, because the amorphous nature of the silicon allows many energised electrons to be lost. To some extent this can be compensated by the incorporation of an extra one or two layers (triple junction cell), which absorb slightly different parts of the solar spectrum and so boost efficiency. These extra layers do contain some germanium as well as the silicon and hydrogen. Modules are made by two chief methods:

- The active layers of amorphous materials are deposited onto a sheet of boro-silicate glass that has previously been coated with indium tin oxide. The latter acts as a transparent front contact. The back contact, usually an alloy of gold, nickel and aluminium, is then deposited by direct evaporation of the elements.
- The active layers are deposited onto a stainless steel substrate, pre-treated with a reflective aluminium layer and zinc oxide that doubles as a back contact. Front contact is then made by evaporation of indium tin oxide.

Module fabrication is then completed by the interconnection of several cells with (copper/aluminium) wiring, sealing usually with ethyl vinyl acetate (EVA) and in many cases finishing with an aluminium frame.

The elements present in the completed module are:

- silicon;
- germanium;
- hydrogen;
- indium;
- tin;
- oxygen;
- zinc;
- aluminium (gold, nickel);
- silicon, sodium and boron (from the glass); or
- iron, carbon and chromium (from the steel).

There are also trace amounts of phosphorous and boron present from the doping process. There may also be small amounts of nitrogen and carbon impurity. During processing no other elements are introduced, although there will be some cleaning and etching stages using standard acids and organic solvents. There is also use of sulphur and fluorine compounds used in etching equipment. Completed modules will also contain copper and aluminium and wire coating (usually polyethylene or polypropylene). Hence there are no heavy metals present in finished modules or used in their processing.

With respect to the triple junction amorphous silicon modules, the deposition process on the cells use several toxic gases like silane, phosphine, disilane, germane and boron trifluoride. These gases however are widely used in the semiconductor industries and there are well known procedures for scrubbing them so that no toxic discharge takes place to the atmosphere. A commercial scrubber is used in conjunction with a burnbox so that any toxic gas discharged into the atmosphere is several orders lower than permissible levels.

In terms of depletion of scarce resources there are seen to be few problems with amorphous cells because even if they supplied 5% of the world electricity needs, there would be no significant use of scarce resources (Alsema, 1996). One problem may be the use of indium, which is a scarce resource. This is not currently seen to be too significant as the layer of indium tin oxide is only 60nm thick and only small amounts of indium are required (personal communication, Solar Century). However, this may need further consideration if the production of photovoltaic cells increases to a larger scale. One approach to reducing this is to recycle modules at the end of their life by etching off the active material leaving the indium tin oxide intact. This will be an important issue in the future for photovoltaic manufacturers.

The source of silica for solar cells is an issue that is likely to evolve in the next few years. The photovoltaic industry in the past has used off-specification silicon or waste silicon from semiconductor manufacturing. But because the photovoltaic industry is growing so rapidly, there is not enough reject material. Alternative ways of making PV silicon feedstock will have to be developed.

In terms of material usage for all types of solar cell the expected trend is towards improved material and energy efficiency.

### *5.2.2 Energy used*

A review was carried out by the University of Utrecht (Alsema, 1998) which examined past research on energy requirements of photovoltaic systems and tried to establish on which data there is consensus. This section of this report is based largely on this 1998 review.

Published estimates for the energy requirement of present day crystalline silicon modules vary considerably: between 2400 and 7600MJ/$m^2$ for polycrystalline technology and between 5300 and 16500 MJ/$m^2$ for monocrystalline technology. Partly these differences relate to assumptions made in the analysis about process parameters such as wafer thickness.

The most important source for these differences, however, is the energy requirement estimation for the silicon feedstock used to produce photovoltaic wafers. The production of silica pure enough to be used in a photovoltaic cell uses a lot of energy, which forms a significant proportion of the energy used the completed product. This is especially the case as some processes require two phases of crystallisation. However, it is now agreed by most analysts (Alsema et al, 1998) that past studies have been too pessimistic about the energy needs of both the primary and secondary crystallisation steps. Unfortunately, there remains considerable variation in the energy estimates for both primary and secondary processes. It is reported that this cannot be resolved due to lack of reliable and detailed data.

To reduce the uncertainty of these effects, Alsema has presented two estimates for energy usage. The low estimate is based on lower values for crystal purification and does not include primary crystallisation (this step is only included if the silicon that is used is waste from the micro – electronics industry). The high estimate assumes 2400 MJ/kg for the primary crystallisation step (this is when silica is taken from ingots and requires two steps of crystallisation). Table 5.1 presents a break down of energy requirements for both monocrystalline and polycrystalline cells. Please note that the energy requirements are presented as "equivalent primary energy requirements", that is the amount of primary (or fuel) energy necessary to produce the component. All electrical energy input is converted into primary energy requirements, with an assumed conversion efficiency of 35% (so 1 MJ of primary energy can supply 0.097 kWh of electrical energy).

It is unfortunate to have such a range of estimates but Alsema (1998) is of the opinion that the lower end of the estimate is more likely than the higher end. He has also considered the likely changing energy requirements projecting technology forward to 2007 and has estimated that future improvements in wafer production technology will bring down the energy requirements of crystalline-based photovoltaic cells.

In terms of amorphous thin film modules, Table 5.2 shows a best estimate of for energy requirements for their production.

**Table 5.1. Break down of energy requirements for elements of monocrystalline and polycrystalline modules (Alsema, 1998)**

| Process | Polycrystalline | | Monocrystalline | | |
|---|---|---|---|---|---|
| | **Low** | **High** | **Low** | **High** | **Unit** |
| Mg silicon production | 450 | 500 | 500 | 500 | MJ/m$^2$ module |
| Silicon purification | 1800 | 3800 | 1900 | 4100 | MJ/m$^2$ module |
| Crystallisation and contouring 1 | - | 5350 | - | 5700 | MJ/m$^2$ module |
| Crystallisation and contouring 2 | 750 | 750 | 2400 | 2400 | MJ/m$^2$ module |
| Wafering | 250 | 250 | 250 | 250 | MJ/m$^2$ module |
| Cell processing | 600 | 600 | 600 | 600 | MJ/m$^2$ module |
| Module assembly | 350 | 350 | 350 | 350 | MJ/m$^2$ module |
| Total Module (frameless) | 4200 | 11600 | 6000 | 13900 | MJ/m$^2$ module |
| *Total Module (frameless)* | *35* | *96* | *47* | *109* | *MJ/Wp* |

**Table 5.2. Break down of energy requirements for elements of an amorphous silicon module (Alsema, 1998)**

| | **Energy requirement (MJ/m$^2$ module)** | **Share (%)** |
|---|---|---|
| Cell material | 50 | 4 |
| Substrate and encapsulation material *(assumes glass and glass)* | 350 | 29 |
| Cell / module processing | 400 | 33 |
| Overhead operations | 250 | 21 |
| Equipment manufacturing | 150 | 13 |
| Total module (frameless) | 1200 | 100 |
| *Total Module (frameless)* | *20 MJ/Wp* | |

It is less clear with the amorphous cells, the effect that time will have on improved energy usage. However Alsema predicts that a decrease in the energy requirement for production can be assumed but that this will not be as significant as the reduction that can be expected in crystalline cells.

Support structures and units such as inverters (balance of system components) also require energy for their production. Table 5.3 shows estimates for the energy requirements of balance of system components.

**Table 5.3. Energy requirements for balance of system components (Alsema, 1998)**

| | Unit | Present energy requirement | Future energy requirement |
|---|---|---|---|
| Module frame (Al) | $MJ/m^2$ | 500 | 0 |
| Array Support – roof integrated | $MJ/m^2$ | 700 | 500 |
| Inverter (3 kw) | MJ/W | 1 | 1 |

The assumptions above are that 3.5kg and 2.5 kg of aluminium are used in for example the rooftop supports and the module frame respectively for each $m^2$ of module. It has been assumed in the study that, in the future, modules will be frameless.

However, frames used for this study are likely to comprise metallic rails, which fix to the noise barrier using vandal proof bolts. It is likely that this kind of support structure will require less energy than a roof mounted structure which is grid connected, although no evidence has been produced to support this.

A useful way of rating the energy requirements of photovoltaic systems is through energy pay back period. Detailed information on efficiency and use of the system is needed in order to calculate the energy pay back period. However, it is widely acknowledged that amorphous cells are currently less efficient than the same surface area of crystalline cells so the energy pay back period is likely to be longer. Amorphous cells currently have a shorter life span than crystalline cells so are likely to produce less electricity over their lifetime.

### *5.2.3 Harmful emissions*

The refining of silica produces $CO_2$ as a by-product. The production of aluminium also produces $CO_2$ from the consumption of carbon electrodes. However, this has been shown to be lower than both coal produced electricity and the average EU electricity mix. A study undertaken by Alsema (1998) calculated life cycle carbon dioxide emissions from PV generators to be only 6-15% of those from coal fired power stations and 11-26% of the average EU generation mix. He expects them to drop to 3-5% of the average mix by 2008.

Other greenhouse gases are more important than $CO_2$ because they have a much stronger global warming potential. The greenhouse gases $SF_6$ and $CF_4$ are used for the cleaning of reactor chambers for silica production. $SF_6$ has 24,000 times the global warming potential of $CO_2$. $CF_4$ has 6,500 times the global warming potential of $CO_2$. A Japanese study has shown that $CO_2$ equivalent emissions for a silicon based rooftop system are less than 25g – C/kWh (but this does not include $CO_2$ emissions from silicon purification.). But these are much lower than an average emission of 126g – C/kWh for the average output of the Japanese utilities (Kato et al, 1997).

Other harmful by products are released from the production of photovoltaic cells. These include $NO_x$ and $SO_x$. However, where photovoltaics replace coal fired electricity generation, life cycle $NO_x$ emissions are halved and $SO_2$ emissions are reduced by 90% (BHP, 2000). Work by Baumann (1997) has compared a façade mounted photovoltaic system with the 1995 UK electricity mix in terms of life cycle emissions. Comparing the emissions of the façade system (130 g-CO /kWh, 0.2 g-SO /kWh, 0.3 g-NOx/kWh) with average 1995 UK electricity generation mix (519 g-CO /kWh, 0.62 g-SO kWh, 1.22 g-NOx/kWh) it can be noted that this PV system leads to 66-75% emission reduction. These numbers will be significantly improved in the future when further developments lead to considerable reductions in material and energy requirements. It should be noted that the LCA results are determined very strongly by the choice of the 'fuel mix' for the electricity production system.

There are other by-products due to the production of photovoltaic cells. For crystalline photovoltaic cells this includes flourine, chlorine, nitrate, isopropanol, respirable silica particles and solvents. Amount of emissions rely heavily on process conditions and emission control measures but most would be expected to have a negligible environmental impact (Alsema, 1996). In terms of amorphous cells, the only chemical hazards in manufacture come from the toxicity of silane and germane, and these can be safely controlled and not be vented to the atmosphere (personal communication, Solar Century).

Since photovoltaic systems generate less emissions over their life cycle than fossil fuel generated electricity, some commentators believe that a small component should be added to the total break even costs. Values up to US$ 0.035 per kWh have been estimated (Buchanan et al, 1991). However, a literature search has not found any more up to date UK estimates.

In terms of health and safety, many advances have been made to reduce the risk of handling hazardous gases in photovoltaic facilities (Fthenakis, 1997). A number of substances are considered to pose risks to the workforce in the photovoltaic industry e.g. etchants, acids, solvents etc. Most of these substances are not unique to the photovoltaic industry. Silane, the primary feed stock gas used in amorphous cell production is a highly flammable gas that may ignite spontaneously in air. Because self-ignition does not always occur, large gas clouds may build up which can cause a severe explosion. Proper control measures are therefore necessary to prevent these situations. The safety hazards of these substances are controllable by the safety measures usually employed in the chemical or semiconductor industries (Phylipsen and Alsema, 1995). A report on occupational health risks of photovoltaic industry by the Brookhaven National Laboratory (Owens et al, 1980) states that dermal contact with chlorosilanes, HCl and $HNO_3$ and inhalation of HF and $HNO_3$ as a moderate acute hazard on workers in crystalline silicon solar cell industries. However, at high exposure levels, inhalation of the corrosive gas HF can cause death. Dermal contact with HF is considered to be a high acute hazard. Exposure to HF and silane is considered to be a moderate chronic risk. Other materials are expected to pose no or low hazards on workers in crystalline silicon PV industry. It is expected the hazards of these substances to be controllable within the safety measures usually employed in chemical industries (Phylipsen and Alsema, 1995). However, it is always better to design out the use of harmful chemicals if possible.

## 5.3 Installation

### *5.3.1 Energy emissions and pollution associated with transportation*

It is impractical to measure what the detailed impacts associated with the transport of the units would be without knowing:

- the location of the trial site,
- the location of the photovoltaic cell manufacturing plant,
- the number and type of vehicles used for transport,
- the routing of the vehicles.

With this information it would be possible to predict:

- noise and air emissions of the vehicles,
- fuel used by the vehicles,
- effects on sensitive environments that may be affected by the vehicle routing.

This information is not available. However, it has been assumed that relative to existing transport movements the transport required to install the system is likely to be negligible. It has also been assumed that no traffic management is needed during installation so impacts on traffic using the highway would also be minimal.

#### *5.3.2 Energy emissions and pollution associated with installation*

It will be possible to make some general predictions concerning typical emissions and risk of pollution but without knowing the sensitivity of the receiving environment, it is difficult to make these predictions very accurate. The assumption has been made that the installation of the cells is likely to have a relatively minor impact compared to other stages of the life cycle.

#### *5.3.3 Health and safety risk to installation staff*

The risk of this would not be significant unless the modules broke. Studies seem to confirm that exposure to the elements within photovoltaic cells would not be harmful unless an individual was exposed over long periods (IEA Photovoltaic Power Systems Task Force, 1997). Risk of electrocution is small as individual panels are low voltage.

### 5.4 Use / maintenance

#### *5.4.1 Maintenance issues – frequency and type of maintenance needed*

The only maintenance needed is annual washing of the cells after the winter period. The only impacts of this would be water use and impacts of detergent. Water use is expected to be relatively insignificant. It is assumed that a standard highway drainage design is present and that this can deal with the detergent used for washing without causing pollution of receiving waters. If receiving waters are environmentally sensitive it is a reasonable assumption to make that the specification of the highway drainage would be of a higher specification.

#### *5.4.2 Visual impact*

The photovoltaic cells will be mounted on noise barriers, which in themselves have a visual impact. One issue that may become an important impact on safety is driver glare but it has been assumed that anti glare surfactants have been applied. Anecdotal evidence suggests that amorphous cells may have a reduced risk of glare than crystalline silicon cells.

Where the concept of PV noise barriers has been raised with personnel associated with road construction and maintenance, they have mentioned concerns over visual aspects and glare. However, these could probably be overcome with suitable demonstration projects and the use of results from similar installations elsewhere in Europe (Thermie, 1999)

#### *5.4.3 Health and safety risks*

During operation a release of harmful substances into the environment and to humans can only occur as a result of an accident or vandalism. Damaged modules or fire may lead to the release of hazardous substances (IEA Photovoltaic Power Systems Task Force, 1997). Work has been completed on the risks posed by cadmium telluride and copper indium sellenide units (Steinberger, 1997). These units contain more toxic elements than silica based units. Based on data from leaching experiments the research found that concentrations from heavy metals in water and soil as a result of module breakage posed no acute danger for human beings and the environment. It is important to note that this research was carried out for rooftop installations and did not rule out long term risks for the environment and human health. These results should be treated with caution.

It is generally accepted by the industry that amorphous cells are more damage proof than crystalline cells. This is important in an environment where stone chipping may be a problem.

#### *5.4.4 Wider educational benefits*

It is not possible to place a value on educational opportunities offered by the use of photovoltaic cells. The issue of education has two facets: education / skills and training of the workforce, and education and awareness of the public. Both serve different purposes.

Awareness raising of the public helps to raise the profile of photovoltaic systems and helps increase the demand for them and their development. The obvious presence of photovoltaic cells at the side of the road will not only raise awareness of renewable energy systems but may also increase awareness of energy saving issues and even wider environmental issues. This is, however, impossible to quantify.

Education of the workforce is vital in ensuring the supply by making sure there are enough trained staff to ensure that photovoltaics become more common place. Personnel trained in new technologies such as photovoltaics are in demand world-wide. Many schools, technical colleges and universities around the world are now beginning to offer renewable energy courses (IEA, 2001). However, it is recognised that there is currently a shortage of trained staff. When ranked against all factors considered important in the success of a photovoltaic system, the status of specialist knowledge was lowest in all areas (Groenendaal et al, 2001). If the Highways Agency does develop a renewable energy programme the opportunities to develop more trained staff should be seen as a positive externality.

### 5.5 Disposal

There are two issues regarding disposal that need consideration; the extent to which spent modules can be re-used or recycled, and any special considerations needed for disposal (whether the waste is considered hazardous).

Very little work has been carried out in the UK on designing for re-use and recycling of photovoltaic cells because the technology is relatively new. There is also a paucity of information available on general decommissioning and waste management issues connected with photovoltaic cells. The issue of waste management is one that needs further work to resolve. There are no commercial processes available for recycling of any type of photovoltaic module in the UK (personal communications: AEA Technology, Environment Agency). Recycling of the module cover glass should be possible if there is some way to separate it from the other components of the cell.

Given the large glass content of an amorphous cell, they can be recycled via standard glass recycling process (Alsema, 1996). Experiments carried out a few years ago indicated that the only restrictions are the modules should mainly be used for production of coloured packaging glass and that the fraction of module waste in the total feedstock should remain below 10%.

Alternatively, the active components could be etched away from the substrate and the substrate re-used. As the performance of modules with a re-used substrate may be similar or sometimes even better than with a virgin substrate this recycling technique would give benefits in terms of cost reduction. This is particularly the case as glass and other substrate material can make up 30-40% of the costs of the module (Alsema et al, 1997).

However, BP Solar state on their website that at present there is no demonstrated, cost and energy effective way to recover re-usable silicon cells or wafers from fully crystalline silicon modules. For the short term BP Solar will accept back all failed, end of life or unwanted silicon modules and ensure that all returned silicon modules will be logged, for control purposes, and then evaluated for the best path of recovery. This evaluation will take into account the best method to maximise recovered value, and the best environmental route to recycling. Modules that can be recovered and repaired into working modules will be so recovered. Modules that cannot be repaired into working modules will undergo a de-manufacturing process to recover aluminium frame material, and where possible recoverable materials. Specialised recyclers will then recycle materials appropriately. The remaining non-recoverable parts of the modules will be crushed and disposed of, according to all legislative requirements, in controlled landfill sites.

For the longer term, BP Solar is actively working on a regime to recycle completely all returned silicon solar modules and the thin film amorphous modules that they produce. This process will constitute part of a recycling strategy review to be finalised and introduced in the near future (www.bpsolar.com). Currently there is little data on the energy effects of recycling or other treatment of decommissioned systems as so little has been undertaken.

In terms of special disposal considerations, crystalline cells contain substances such as silver / gold, copper and lead which may lead to them being classed as hazardous waste. The European Waste Catalogue (EWC) contains a list of hazardous wastes. According to the Environment Agency (personal communication) the most appropriate waste classification code for the panels using the EWC is *electronic/electrical* material. Where the solar panels are disposed of separately from any other waste, chapter 20 is appropriate. The following is the appropriate reference to chapter 20:

| | |
|---|---|
| 20 01 35* | Discarded electrical and electronic equipment other than those mentioned in 20 01 21 and 20 01 23 containing hazardous components (this is a hazardous waste); |
| 20 01 36 | Discarded electrical and electronic equipment other than those mentioned in 20 01 21, 20 01 23 and 20 01 35 (this is a non-hazardous waste). |

However, if the panel were disposed of with other wastes, the appropriate code for the panels within the waste would be the following from chapter 16:

| | |
|---|---|
| 16 02 13* | Discarded equipment containing hazardous components other than those mentioned in 16 02 09 to 16 02 12 (this is a hazardous waste); |
| 16 02 14 | Discarded equipment other than those mentioned in 16 02 09 to 16 02 13 (this is a non-hazardous waste). |

*Both of these entries are what are termed *mirror entries*. This means that these wastes need to be assessed to determine whether they contain a hazardous component. This would apply to the lead solder used within crystalline photovoltaic cells. The limiting threshold for lead is 0.25%. Therefore, if the solder contains more than 0.25% lead then the solder would be hazardous. A similar determination would have to be made on the other components of the panels to determine whether they contain any dangerous substances. Several manufacturers have been contacted to try and ascertain the exact components of photovoltaic cells but no data has been forthcoming.

Amorphous cells contain little or no toxic materials and are not classed as hazardous waste.

# PART II. INTERSEASONAL HEAT TRANSFER SYSTEMS

## 6 Current state of the technology

### 6.1 Introduction

The use of interseasonal heat storage is at a critical stage of technical evolution. This is linked to the broader capability of building physicists to accurately model complex energy flows at the urban and infrastructure level, using computational techniques (Hewitt, Ford and Ritter, 2000). It is expected that the use of predictive techniques, (particularly computational fluid dynamics) will lead to a rapid expansion of applications of interseasonal heat transfer technology and its emergence as a significant renewable, non-carbon emitting energy source. There has been some research at a theoretical level, linked to particular product and application development (see Section 6.4), although surprisingly little. The most significant initiatives in the field appear to be practical projects, as yet at a relatively modest scale, undertaken by a number of commercial organisations, often with grant aid from governmental organisations.

Up to this point, the most frequent use of interseasonal heat technology has been for heating buildings: either as low temperature water heating (for space heating) or for space heating and water heating (in conjunction with a heat pump). Of the 65 largest solar heating plants in Europe (those with more than 500m$^2$ collecting area), only 15 use interseasonal heat (the remainder use summer/autumn seasonal solar water heating only). Interestingly, in these latter cases, 10 use water storage and 5 use ground storage (European Large Scale Solar Heating Network, 2002). Ground storage and water collectors are large, and involve expensive construction and insertion of vertical insulation.

A survey was made by the Fujita Research Company (1998) of current interseasonal storage technology in Europe that was based on analysis of applications for heating buildings, all of which use large insulated stores. They concluded “the development of interseasonal storage of solar energy in Europe is an important step in the development of sustainable communities and energy self-sufficient buildings. The projects mentioned in this report are mostly experimental systems, funded by Government Departments. However, the results of these pilot projects show that the technology works and is commercially viable. This, combined with the commitment of European governments to renewable energy suggests that such designs will become a major growth area in European construction over the next 10 to15 years.”

The largest solar heating plant in Europe, is the Munkegärde heating plant at Kungälv in Sweden (Munkegärde, 2002), with a solar collector array of 10,000m$^2$, installed in March 2001. In July 2001 the collectors produced an output of 600MWh at a cost of 50Euro/MWh (without subsidies). This plant is a mixed mode system, using wood chip burning and a 1000m$^3$ buffer storage (water tank). The prognosis for large scale applications which avoid the expense of enclosing large scale storage with vertical insulation or purpose-built tanks would seem to be even more promising. Results of modelling exercises on interseasonal heat storage implementation using horizontal insulation only are presented in this feasibility study.

It is worth noting that Directive 2002/91/EC of the European Parliament and the Council of the European Union requires administrative provisions on the energy performance of buildings to be in place by January 2006. Article 5 of this requires consideration, for new buildings with a floor area over 1000m$^2$, of the feasibility of alternative systems such as “decentralised energy supply systems based on renewable energy, CHP, district or block heating or cooling if available, heat pumps under certain conditions”.

### 6.2 Developments in the Netherlands

The work currently underway in the Netherlands in the field of interseasonal heat storage is at the leading edge of what can be discovered in the public domain (Carder, 2002). This is partly due to a tradition of engineering excellence and innovation in land management and drainage stretching back to the fifteenth century. The current work on interseasonal heat storage in the Netherlands is part of an ongoing tradition of large scale infrastructure engineering which is in turn yielding back the benefits of this technology. In particular, the recent work on providing heat sinks in aquifers accessed by deep bores builds on the long-term Dutch knowledge of underground water systems. Some particular projects are now described although it should be noted that all of these use uninsulated aquifer-based thermal energy stores, since this is appropriate to the predominant geological condition in the Netherlands.

### 6.2.1 Single structure projects

A good example of a single structure project recently constructed is the 28,000 seater Gelredome stadium (with an additional 22,000 seats for non-sporting events) built for the 2000 European Football championships in Arnhem. The main parties involved included the Arnhem City Council and the Province of Gelderland. A design consortium of energy provider NUON with project managers DHV, Tebodin and IF Technology used geothermal heat energy from water employing four boreholes (two warm and two cool aquifer sinks). The collected heat is transferred to and from the heat sinks via pipes using heat pumps. The resulting heat is used for space heating for the enclosed areas of the stadium, as well as for keeping the 11,000 tonne sliding pitch warm during winter. A £1.8 million EEC grant enabled the use of solar collecting photovoltaic arrays (and heat pump applications) to enhance the stadium as a demonstration project for new technological developments (Holdsworth, 1999).

### 6.2.2 Infrastructure projects

One of the first Dutch infrastructure projects in the transport sector employing interseasonal heat storage technology was the renewal of the bridge roads linking the Haringvliet locks in Zeeland (Holdsworth, 1998). In 1998 the demand was for a low cost, low maintenance refurbishment of the concrete road surface. At the time, the Dutch consultants Arcadis, road engineers Buro van den Boon, IF Technology and the Swedish under-surface heating specialist Velta formed a consortium to resolve the problem of winter ice and summer surface rutting and to seek ways of increasing road life. The developed solution was called “WinnerWay”. This involved the installation of an array of pipework, which was embedded in the concrete road surface at a depth of between 125mm and 175mm and linked to a heat store. The system has successfully evened out the extreme winter and summer time surface temperatures that were instrumental in exacerbating the wear on the surface. Although in this case the energy removed from the pavement surface is used only for winter de-icing, the measured performance of the system is sufficient to heat and (cool) 100 family houses per kilometre length. With current technology, such as the ModieSlab described below, this capacity has risen to 400 houses or the energy equivalent for other building types.

“WinnerWay” are not the only company developing interseasonal heat transfer solutions for road applications. In 1998 the Dutch company Ooms Avenhorn in conjunction with NOVEM installed a test section of road incorporating an array of pipe work used for de-icing and smoothing of surface temperature variations. Ooms Avenhorn are now marketing their collector to aquifer system under the trade name "Road Energy Systems ®." (Ooms Avenhorn, 2002).

### 6.2.3 Building group projects: Appeldoorn

The “WinnerWay” system (Winnerway, 2002) is now being marketed by Velta and the Dutch road contractor KWS. An installation of an interseasonal heat storage system for a business park at Appeldoorn, which uses the feeder road as the solar collector surface, is now ready for use, but the associated industrial and office units will not be built until 2003. The solar heat energy collected from this project is transferred to a warm aquifer store. The heat energy transfer will be used for de-icing the road in winter, and for providing space heating and cooling for the units in the business park. Measured data from this installation shows a collection rate of 300KWh/$m^2$/year (Winnerway, 2001). The pipe collection array and storage aquifers are complete on this project, and the system will be complete following the installation of the utility building.

### 6.2.4 Roads to the Future project

The most significant investment of technical and financial resources in the field of interseasonal heat storage technology in the Netherlands has been in infrastructure (road) projects. This has been stimulated by the “Roads to the Future” project initiated by the Dutch Ministry of Transport, Public Works and Water Management in 2000. Four systems have been tested on a major motorway. The first results were announced in February 2002 and one of the leading edge developments was a prefabricated concrete modular intelligent road system known as ModieSlab. This was the result of detailed development work by the Dutch concrete manufacturer BetonSon with input from IF Technology and Arcadis consultants (Holdsworth, 2002).

The concept uses pre-fabricated sections of road with an integral pipe array, which is connected at each slab junction (Figure 6.1), with the potential for storing the solar induced energy in the tubes of supporting piling structures. The project has been in continuous development. The results are sufficiently promising that the original three year test period has been shortened and current findings are expected to be announced publicly during 2003. The indications are that the performance of the system has lived up to expectations, which will increase the likelihood of a large scale project being initiated soon in the Netherlands.

One proposal currently on the drawing board, resulting from the above Dutch developments, is for a project at Gasperdammersweg (Winnerway, 2001) linking a section of city ring road to the provision of heat for around 400 housing units. This link between roads as providers and buildings as users is likely to drive future developments in this technology area. The dual performance of the system, de-icing for the road, and heat energy surplus for other users is an important model.

Some preliminary costing information generated by the developers of ModieSlab is as follows:

- Construction, maintenance and amortisation based on a 5km stretch of a normal asphalted road and related to a 32 year life is calculated at £61 p.a./m$^2$.
- Construction, maintenance and amortisation based on a 5km stretch of ModieSlab, related to a 90 year life is calculated at £56 p.a./m$^2$.
- The business case for the system is stronger when other significant cost factors are included, eg. the cost of road accidents (£27,500 per person), traffic jams (£30,600/km), and an energy generation payback of £0.031 per 260 kWm$^2$. Taking these into account, the net benefit (as a credit) of the system is reported to be £27.50 p.a./m$^2$ (Holdsworth, 2002). The costs of de-icing vehicles or salts is a further small consideration which has not been taken into account.

Whilst the details of the costing framework needs further research, there are potentially large cost benefits to the use of interseasonal heat storage systems.

The success of the Netherlands in developing innovative solutions for interseasonal heat storage technology is accompanied and stimulated by significant Government funding for project development. More than 50% of the costs of the “Roads for the Future" developments (three other projects in addition to the ModieSlab) were met by the Ministry of Transport, Public Works and Water Management.

## 6.3 Developments in Japan

The most relevant project, which uses similar heat transfer technology, outside of the Netherlands is the Gaia snow-melting system at Ninohe in Japan (Morita and Tago, 2000). Detailed information on this is given on the web (Caddet, 2002) and is summarised below.

### *6.3.1 General description*

The National Institute for Resources and Environment of Japan has been involved in the development of the Gaia snow-melting system. The system consists of downhole coaxial heat exchangers , a heat pump and heating pipes buried under the pavement surface. The system is completely closed and thus does not contaminate formations or aquifers.

The main heat source of the system is the geothermal heat contained at shallow depths in the ground. The auxiliary source is stored summertime solar heat. In winter, heat extracted from the earth using the downhole heat exchangers is upgraded by a heat pump and passed to a network of heating pipes containing antifreeze and installed beneath the road surface. In summer, solar heat is recovered from the hot pavement and stored in the earth by circulating the antifreeze in a circuit formed by connecting the downhole heat exchangers directly to the heating pipes.

The first Gaia snow-melting system was installed in Ninohe (Iwata Prefecture) to prevent traffic accidents at the downhill section of a curved road. The system has been operating successfully since December 1995. This Gaia system demonstrated a reduction of 84% in annual energy consumption in comparison with systems using electric heating cables in the city. Numerical simulation codes were developed and used in the design of the system.

#### *6.3.2 Technical and performance data*

So far the Gaia system in Ninohe has functioned effectively and eliminated accidents due to snow and ice. In the winter of 1995/96 the average low temperature for the month of January was -7.1$^{o}$C and the total snowfall was 2.9m. The ground beneath the road consists of sandy tuff and the undisturbed temperature of the formation is 22.5$^{o}$C at depths of 150m.

The area covered by the snow-melting system is 4m wide and 65m long, covering a total area of 260m$^2$. Three downhole coaxial heat exchangers, each 8.9cm in outer diameter and 150m deep, and a 15kW (electric) pump are used. The heat supplied to heating pipes is approximately 50kW.

Coefficients of performance (COPs), defined as the ratio of energy delivered to the heat pump as electricity to the energy delivered from the heat pump as heat, were evaluated. For the winter of 1995/6 these were 4.1 for the heat pump and 3.4 for the whole system including circulating pumps and the control system. In the period from December 1995 to November 1996 the Gaia's annual electric energy consumption per unit area was 25.2kWh/m$^2$/year, only 16% of that used by the electric heating cable systems in the city.

Numerical simulations indicate that higher COPs, 4.6 for the heat pump and 4.4 for the systems, will be attained with the next Gaia system in Ninohe.

#### *6.3.3 Economic Data*

The running costs of Ninohe's Gaia system for the period from December 1995 to November 1996 were 760 JapaneseYen/m$^2$/year. This annual running cost is only 20% of that of Ninohe's electrical heating cable system and slightly lower than those of the snow-melting facilities using groundwater in Morioka, a major city in Iwata Prefecture. On the other hand the expensive installation costs of the downhole heat exchangers raise the construction cost of the Gaia system to levels about 40% higher than oil or gas fired systems and 60-70% higher than electrical heating systems. However the very low running costs and long service life of the system make the Gaia's total snow-melting cost, including depreciation and interest, cheaper than that of oil or gas fired systems in the long term (10 years or more).

### 6.4 Significant global IPR

Heat transfer and storage has been the subject of some patent claiming activity, particularly in the US, although the current built examples seem to be primarily in Northern Europe and Japan.

The following patents have significant components related to technical issues relevant to interseasonal heat storage:

- Interseasonal heat storage inventions for application in infrastructure and urban and building scale situations. [Patent Pending WO1/29320 A1 (World); PCT/GB000/0404 (UK)]
- A system for collecting heat from roadways and storing it in insulated tanks below the road. [Patent DE 3407927 A1 (Germany)]

- Heat shunt mechanism to insulated store with vertical insulation. [Patent 5069199 (US)]
- Geothermal energy (water) transferred by pipe work to utilise as heat source. [Patent 5204553 (US)]
- Geothermal heat energy from aquifer relayed to pipework in roads for de-icing. [Patent 04030005A (Japan)].

# 7 Costs of interseasonal heat storage in a highway situation

## 7.1 Estimate of construction costs

The cost estimates for the proposed demonstration project (100m long, 3.6m wide) are shown in Table 7.1. Some items are relevant to the trial only and would not occur if the system were adopted for general use. These have been highlighted in Table 7.1 and have not been included in the whole life cost analysis, which follows in Section 8. Some items such as that of a building management system and an under-floor heating system are also excluded from the whole life costing as they are considered the norm in new building construction.

Costs of construction activities such as excavation, backfilling and pavement construction will depend significantly on the length of pavement being considered. Costs from Spon (2002) have generally been used in estimating for these activities: for a limited length of road of 100m, their reliability must be treated with caution.

In addition to the installation costs given in Table 7.1, a proving trial of the ability of the high density cross-linked polyethylene pipes to withstand (without deformation) the temperatures during placement of the hot rolled asphalt is considered prudent. In previous installations in Europe, this perceived problem has been avoided either (a) by passing cooling water through the pipework, or (b) by installing the pipework in a thin layer of concrete beneath the asphalt surfacing, or (c) by using stainless steel coils in a plastic/cement-stabilised asphalt layer (Polydynamics Engineering, 2002). Of these options, the latter is probably less appropriate because of concerns about extra cost and possible corrosion. An additional contingency of £5k for this proving trial is considered appropriate.

## 7.2 Maintenance and running costs

The equipment will require nominal maintenance and it is anticipated that inspection and any maintenance would require visits by a heating engineer at approximately six monthly intervals. This cost is estimated at £400 per annum.

The electrical power consumption of the pumps (excluding any heat pump) during both the heat collection and winter heating season (a total of say 2000 hours) is estimated at 0.5kW. On this basis, if the electricity cost is 6p/kWh, the electricity costs amounts to £60 per annum.

Allowance should be made for the replacement of pumps and control valves every 25 years and renewal of all other plant every 50 years. The life of the pipe coils in the collection area and the heat store is expected to be at least that of the pavement. For example, Irish Agrement Board certificates are available for various cross-linked polyethylene pipes used in underfloor heating situations which indicate that they meet the requirements of prEN 12318-1 (1998) for a service life of 50 years. Furthermore, similar pipes have also been successfully used in more severe loading conditions under pavements in the Netherlands.

The cost in use of a heat pump and building management system would fall as part of the cost of a building since the scale and need is completely dependent on the building, its use and age. New well-insulated buildings would not require a heat pump although connection to an older building probably would. A heat pump is expected to operate at a coefficient of performance about 30% better than a

## Table 7.1. Estimate of costs of trial installation (100m long)

| ELEMENT | COST (£) | COMMENTS |
|---|---|---|
| **Design and supervision** | 10000 | Allowance for detailed design and supervision of all construction aspects of the work |
| **Infrastructure** | | |
| Plant room | 15000(1) | Allowance for a temporary building (16m$^2$) to contain the workstation and associated plant |
| Ground excavation and replacement | 8050 | Excavate all the insulated area to a depth of 1000mm; replace 290mm after laying with previously removed material. Gross area is 2300m$^2$ at minor works rate of £3.5/m$^2$ (Spon, 2002). |
| Supply and install insulation below ground | 20000 | Foam glass beneath road and extruded polystyrene (including waterproof layer of 1000g polythene) elsewhere. Gross area is 2000m$^2$ at rate of £10/m$^2$. |
| Telephone and datalinks to plant room | 1000 | Contingency for connection of local supply |
| Electricity supply(2) | 1000 | Contingency for connection of local supply |
| Construct pavement structure | 23000(3) | Estimated from Spon (2002) assuming 250mm capping, 150mm sub-base and 310 mm of asphalt. |
| **Mechanical installation** | | |
| Supply and install distribution pipework | 4000 | Distribution pipework to be high density polythene; building and store located within 10m of each other. |
| Supply and install collector and store pipework | 15000 | High density polyethylene |
| Supply and install pumps, valves, heat exchanger | 9000 | 6 variable speed pumps, 5 motorised valves and buffer storage cylinder. |
| Supply and install heat dump | 2000(4) | Passive radiators |
| Supply and install heat pump | 7000 | Water to water heat pump, using zero CFC refrigerants |
| Supply and install plant control system | 5000 | Further costs of about £5000 for a building heat management system are site specific |
| Testing and commissioning | 2000 | |
| **TOTAL** | **122,050** | ***Excludes contingency of £125,000 for control and monitoring of trial. [£80,000 is instrumentation during construction, monitoring and interpretation of performance of trial for one year from the first summer: £45,000 is designing the experimental protocols for controlling the two types of system and designing experiments.]*** |

**Notes:**

(1) This is for the demonstration project only. More usually, normal building practice would require provision of a plant room.

(2) For a relatively small installation such as proposed for this trial, electricity cost is not a major issue. For larger installations the use of photovoltaic power can be considered.

(3) The cost of pavement construction is only relevant to the trial installation, if interseasonal storage is installed as part of new construction this cost is inappropriate.

(4) The heat dump is only needed for demonstration project. In normal usage, an under-floor heating system would dispense the heat.

modern boiler system. Most new buildings would have a suitable building management system, although existing systems in old buildings would need upgrading.

# 8 Whole-life cost of interseasonal heat transfer system

A model has been developed to determine the effect of a number of factors on the whole-life cost of an interseasonal heat storage system of the type described above. As for the solar panel system, cost, performance and discount rate data are required.

## 8.1 Cost data

The following cost components have been considered for the heat storage system:

- design,
- installation of collector in pavement,
- installation of heat store, including insulation,
- pavement construction, including traffic management and traffic delay costs,
- installation of interconnecting pipework, heat pumps, circulating pumps and control system,
- installation of pipework to deliver heat to the point of use,
- heat supplied by the system (a benefit),
- operation and maintenance of the heat transfer system, including power for the heat and circulation pumps,
- pavement maintenance, including traffic management and traffic delay costs,
- decommissioning and salvage.

It has been assumed that heat would be stored during the summer months and used in winter for domestic heating.

As for the solar panel system, rather than determine the whole-life cost of a trial involving a collector area of 360m$^2$ within a 100m length of pavement, the whole-life cost of a larger installation with a length of 2000m has first been calculated. Then, for comparison purposes, the whole-life costs for the larger installation have been normalised so that they correspond to the same collector area as the trial installation, i.e. 360m$^2$.

## 8.2 Performance data

The performance data concerns all aspects of the performance of the heat storage system, as follows:

- the efficiency of the collector pipework, including the effects of damage,
- the service life of the collector pipework,
- the efficiency of the heat pumps and circulating pumps,
- the service life of the heat pumps and circulating pumps,
- the heat lost in storage and transmission,
- the service life of the interconnecting pipework and control system,
- the change in the service life of the pavement, i.e. any change in the time between maintenance treatments.

## 8.3 Discount rate data

As for the solar panels and in accordance with the current Treasury rules, an annual discount rate of 3.5% has been assumed in the model.

## 8.4 Cost and performance data assumed for interseasonal heat storage system

### *8.4.1 Design and installation costs for the heat storage system*

It has been assumed that the design and supervision costs for a large installation would be £5000 when calculated per 100m length, i.e. 50% of the cost given in Table 7.1 for the trial installation.

The cost of the plant room for a large installation has been assumed to be £7500, i.e. 50% of those listed in Table 7.1. The costs of the telephone and datalinks, and the electricity supply have been assumed to be £100 each, i.e. 10% of those listed in Table 7.1.

Icax™ Limited (2003) have indicated that the cost of the supply and installation of the collector and heat store pipework would be 50% of the cost given in Table 7.1, i.e. £7500. The cost of the supply and installation of a heat pump has been taken as £7000 as given in Table 7.1. One heat pump could be used to transfer heat from the collector pipes to the store while a second pump could transfer heat from the store to the domestic heating system. The most economic configuration would be dependent on the distances between the collector pipework, the heat store and the domestic heating system, and the heat losses in the connecting pipework. The latter would be lower at lower temperatures of heat transfer from one location to another. Losses may be lower if one heat pump was located near the store and a second pump was located near the domestic heating system. However, it is unlikely that the cost savings would offset the cost of a second heat pump. Therefore, without further site specific information on exactly how the system would operate, it has been assumed that only one heat pump would be required. The cost of the supply and installation of the pipework connecting the heat store and the domestic heating system has been assumed to be £3000.

The costs of the ground excavation and replacement, the supply and installation of the insulation, and the supply and installation of the pipework connecting the collector and heat store have been assumed to be £6000, £15000 and £3000 respectively, i.e. 75% of the costs given in Table 7.1 for a smaller trial installation. The costs of the supply and installation of the pumps, valves and heat exchanger have been assumed to equal £6000. The costs of the supply and installation of the control systems for heat transfer from the collector to the store and also from the store to the domestic heating system, have been assumed to be £5000. The cost assumed for testing and commissioning is £1000, 50% of the cost given in Table 7.1.

It has been assumed that the heat store pipework and the insulation for the store would be placed in the hard shoulder, verge and beyond the verge, and not under the carriageway. The cost of any additional land for the construction of the store has not been included.

It has been assumed that the heat storage system would be installed only during new construction or major reconstruction of a pavement. Additional costs would be incurred due to the extra time required to install the collector and heat store. The associated traffic delay and traffic management costs that have been estimated for three road classes are given in Table 8.1. The costs were calculated using HA's whole-life cost model for pavement maintenance schemes, Scheme Analysis System 2003, for installation lengths of 4km on a long-life motorway pavement and 2km on a determinate-life trunk road pavement, and normalised for an installation of length 100m. It has been assumed that it would take an additional 2 days to install the collector pipes and heat store along one kilometre of road, the collector pipes being installed in lane 1 only.

**Table 8.1 Cost of pavement and heat store construction during new construction or major reconstruction of the pavement**

| ROAD CLASS | DESCRIPTION | TRAFFIC DELAY COSTS (£) | TRAFFIC MANAGEMENT COSTS (£) |
|---|---|---|---|
| 1 | Long-life motorway pavement D3<br>100,000 AADT – 15% HGVs | 44,500 | 400 |
| 2 | Long-life motorway pavement D3<br>45,000 AADT – 10% HGVs | 2,100 | 400 |
| 3 | Determinate-life trunk road pavement D2<br>40,000 AADT – 10% HGV | 5,850 | 130 |

**Note:** (1) AADT is the annual average daily traffic (two way).

(2) For new construction these costs are still relevant, as delays in opening to traffic will occur. However with careful scheduling on a large scheme these costs might be avoided.

### *8.4.2 Heat supplied to end users*

The heat supplied to the domestic heating system is dependent on a number of factors, including:

- the temperature of the pavement at the depth of the collector pipes,
- the temperature of the heat store,
- the heat loss in storage,
- the temperature at which the heat is supplied to the domestic heating system,
- the energy required to operate the heat pump system.

It has not been possible to determine precise operational factors as they are site specific, for this reason estimates of the heat supplied and power required have been based on experience in other countries.

#### *8.4.2.1 The power required to operate the heat pump system*

The heat supplied by a heat pump is, theoretically, the sum of the heat extracted from the heat source and the energy required for operating the pump. As mentioned above, the measure of heat pump performance is the coefficient of performance, COP, which is defined as the ratio of the heat supplied by the heat pump and the energy supplied to the compressor. For the reversed Carnot cycle, the COP is calculated as the ratio of the temperature of the heat store in °K and the temperature rise.

*Transfer of heat from collector to store*

The temperature of the store is expected to rise to about 27°C. In theory, it would not be necessary to use a heat pump to transfer heat from the collector to the heat store when the temperature of the collector was higher than the temperature of the store. However, temperature data obtained from the A1 in Cambridgeshire from March 1989 until February 1990 show that the temperature at a depth of 102mm was above 27°C for only approximately 6% of the time (Croney and Croney, 1991). The temperature was above 15°C for approximately 40% of the time, but it would be necessary to use a heat pump to transfer heat to the store when the temperature of the store was greater than the temperature of the collector. For example, if heat was transferred when the temperatures of the collector and heat store were 21°C and 24°C, respectively, the COP of the heat pump is calculated, in theory, to be 99. In practice, the power required to run the circulating pumps and the control system, and the inefficiency of the heat pump would reduce the COP for the whole system somewhat.

However, without further data, it has been assumed that the difference in costs of the power required to operate the pumps and the additional heat supplied to the domestic heating system would be negligible.

*Transfer of heat from store to domestic heating system*

For the heat in the store to be used for domestic heating, it should be supplied at a temperature of approximately 55°C. Some of the heat stored will be lost during the time it is stored and during transmission through the connecting pipework, resulting in a decrease in the effective temperature of the store. If the average temperature of the heat supplied from the store to the heat pump was 20°C, the COP of the heat pump would be, in theory, 9.4. Most domestic ground source heat pump systems claim a COP of 4, and this would be consistent with a lower temperature heat store (uninsulated, unheated ground) and take into account the additional power required to run the pumps, control system etc. Furthermore, as the heat was removed from the store, the temperature of the store would decrease, and the COP would reduce accordingly. If the COP of the heat pump was 5.0, and half the heat stored was lost in the store itself or during the transmission of the heat to the end-users, the power required to operate the pump system would be 13.5MWh/year and the heat supplied would be 67.5MWh/year (108/2 + 13.5). The power consumption of the Gaia system in Ninohe was 25.2kWh/m$^2$/annum, equivalent to 9.07MWh for an installation of area 360m$^2$, but it is not known at what temperature the heat was supplied. Therefore, the heat supplied and power consumption figures shown above for a COP of 5.0 for the heat pump and the whole system have been assumed. Note that icax$^{TM}$ Limited (2003) estimated that the power required to operate the (circulating) pumps would be 1MWh/year.

#### 8.4.2.2 The effect of damage to and a change in performance of the collector pipes

Some of the collector pipes may fail in service. As periodic replacement of the pipes would be uneconomical, a reduction in the heat supplied and power required has been assumed equivalent to the loss of 2% of the pipes every 10 years, starting after 5 years.

The heat transfer characteristics of the collector pipework, heat exchanger and heat store pipework may decrease if they become scaled. The efficiency of the heat pump may also decrease with time. The rate of decrease for both these factors has been assumed to be constant over 30 years and equivalent to a reduction in the heat supplied and power required of 1%/year.

#### 8.4.2.3 The effect of reducing heat losses in storage

If the amount of heat that was lost in the store was reduced, temperature of the heat supplied to the heat pump would be higher, so the COP of the heat pump system would increase. Therefore, more heat could be supplied, and the ratio of the heat supplied to the power required would be lower. Dependent on the temperature and the COP, more or less than a maximum of 13.5MWh may be required to supply the additional heat. However, without further data, it has been assumed that no additional power would be required to supply the additional heat that would be supplied if less was lost in storage.

#### 8.4.2.4 The effect of an increase in the depth of the collector pipes

Some of the pavement maintenance options (eg. addition of an overlay) can increase the depth of the collector pipes by up to 100mm, thereby reducing the temperatures that they will reach. The temperature data in Croney and Croney (1991) indicates that, at a depth of 356mm, the temperature was above 27°C and 15°C for approximately 0.8% and 39% of the time. Therefore, increasing the depth from 102mm to 356mm, would change very little the time when the temperature was above 15°C, but it would decrease significantly the time when the temperature was above 27°C when, presumably, much heat would be transferred to the store.

The net effect of the increase in depth would be to decrease the temperature of the store, decrease the heat stored and decrease the ratio of the heat supplied to the power needed to supply the heat at the required temperature. Without further data, it has been assumed that for each increase in depth of the collector by 50mm, the heat supplied would decrease by 10% and there would be no decrease in the power required.

*8.4.2.5 The price of the heat supplied and power required*

The heat supplied would reduce the heat that domestic users would need to purchase from elsewhere. The cheapest form of domestic heating to most users is currently natural gas. The price of natural gas to domestic users is now about £15/MWh. However, a price of £18/MWh has been assumed to allow for the thermal efficiency of gas boilers. The cost of electricity for the heat and circulating pumps has been assumed to be £25/MWh. Higher prices of £28.8/MWh and £40/MWh have been assumed for gas and electricity, respectively, for some analyses in order to investigate the effect of the price on the whole-life cost.

It is likely that the price of natural gas and electricity will increase in real terms over the next few years when reserves become limited and alternative sources of heating become more expensive. However, it is unlikely that increases above the rate of inflation can be sustained in the long term. For the purposes of this study, the changes in the prices of natural gas and electricity that are shown in Table 8.2 have been assumed. They correspond to those assumed for solar panels in Section 4, i.e.

- no increase above the rate of inflation,
- increasing by a factor of 2 over the first 10 years (equivalent to 7.2% annual increase), then no further increase,
- increasing by a factor of 4 over the first 10 years (equivalent to 14.9% annual increase), then no further increase.

**Table 8.2. Assumed variation in price of natural gas and electricity above rate of inflation**

| GAS / POWER PRICE CASE | PERCENTAGE INCREASE FROM YEAR 1 TO YEAR 11 | PRICE OF MWh OF GAS (£) | | PRICE OF MWh OF ELECTRICITY (£) | |
|---|---|---|---|---|---|
| | | YEAR 1 | YEAR 11 TO YEAR 30 | YEAR 1 | YEAR 11 TO YEAR 30 |
| 1 | 0 | 18 | 18 | 25 | 25 |
| 2 | 7.177 | 18 | 36 | 25 | 50 |
| 3 | 14.87 | 18 | 72 | 25 | 100 |
| 4 | 0 | 28.8 | 28.8 | 40 | 40 |
| 5 | 7.177 | 28.8 | 57.6 | 40 | 80 |
| 6 | 14.87 | 28.8 | 115.2 | 40 | 160 |

#### *8.4.3 Operation and maintenance costs*

Operation and maintenance costs would be incurred for:

- routine maintenance of the heat pump system,
- routine electrical testing,
- pavement maintenance,
- replacement of heat and circulating pumps, control valves and heat exchanger at end of useful life,
- replacement of control system at end of useful life,
- replacement of connecting pipework, cabling and data link at end of useful life,
- replacement/maintenance of plant room at end of useful life.

*Maintenance of heat pumps etc.*

It has been assumed that the heat pumps, circulating pumps, control vales, control system etc. would require maintenance by a heating engineer at a cost of £300 per annum, i.e. £100 less than for the trial. It has been assumed that the time taken for maintenance would not decrease the heat supplied.

*Electrical testing*

The cost of electrical testing has been assumed to be £50 every 3 years for short inspections, and an extra £50 every 6 years for more detailed inspections. It has been assumed that the time taken for electrical testing would not decrease the heat supplied.

*Pavement maintenance*

The whole-life cost (net present value) of typical maintenance treatments for the three road classes described above, normalised for an installation length of 100m, are given in Tables 8.3 to 8.5. The whole-life costs include traffic management and traffic delay costs.

The base options correspond to the treatments that would apply if there were no collector pipes in the carriageway. The same treatments have been assumed for Option 1, but some treatments would increase the depth of the collector pipes or remove them during planing operations. The loss of heat associated with the treatments is given in the last column of the tables, as discussed above. Option 2 assumes that an overlay would be laid which would increase the depth of the collector pipework but, generally, would delay the time before it would be removed by planing. Options 3 and 4 assume that the collector pipework would weaken the pavement so the time between maintenance treatments would be reduced and, in some cases, additional interventions would be required within the accounting period of 30 years.

The whole-life costs of the four alternative maintenance profiles that have been assumed in the analyses correspond to the differences in the costs of the particular options and the base options. For example, the change in whole-life cost assumed for Option 2 for Road Class 1 is £5750, i.e. £173,250-£167,500.

*Replacing components of heat storage system*

It has been assumed that the heat and circulating pumps would be replaced after 25 years, provided the collector pipes have not been removed during pavement maintenance. It has been estimated that the time taken to replace the heat pumps and circulating pumps would result in a loss of heat supplied equivalent to the heat supplied in one week. A similar reduction in the power required has been assumed.

It has been assumed that the service life of the heat store pipework and the insulation would be 30 years.

It has been assumed that the service life of the heat exchanger, the interconnecting pipework and the control system would be 50 years.

*Replacing/maintaining plant room, cabling and data links*

It has been assumed that the useful life of the plant room would be 100 years, and that no maintenance would be required during the accounting period.

It has been assumed that the useful life of the cabling and data links would be 60 years, and that no maintenance would be required during the accounting period.

**Table 8.3 Whole-life cost of pavement maintenance for Road Class 1 (per 100m)**

| MAINTENANCE OPTION | | | | | NET PRESENT VALUE (£) | CHANGE IN NET PRESENT VALUE (£) | DECREASE IN POWER OUTPUT (%) |
|---|---|---|---|---|---|---|---|
| No. | Year | Lane(s) | Depth planed off (–mm)<br>Depth replaced (+mm) | Increase in depth of collector (mm) | | | |
| Base, 1 | 10 | 1, 2, 3 | –50 +50 | 0 | 167,500 | 0 | 0 |
| | 19 | 1 | –100 +100 | Collector removed | | | 100 |
| | | 2, 3 | –50 +50 | | | | |
| | 27 | 1, 2, 3 | –50 +50 | | | | 100 |
| 2 | 10 | 1, 2, 3 | –50 +50 | 0 | 173,250 | +5,750 | 0 |
| | 19 | 1 | –50 +100 | 50 | | | 10 |
| | | 2, 3 | +50 | | | | |
| | 27 | 1, 2, 3 | –50 +50 | | | | 10 |
| 3 | 9 | 1, 2, 3 | –50 +50 | 0 | 177,500 | +10,000 | 0 |
| | 17 | 1 | –50 +100 | 50 | | | 10 |
| | | 2, 3 | +50 | | | | |
| | 24 | 1, 2, 3 | –50 +50 | | | | 10 |
| 4 | 8 | 1, 2, 3 | –50 +50 | 0 | 237,500 | +70,000 | 0 |
| | 15 | 1 | –50 +100 | 50 | | | 10 |
| | | 2, 3 | +50 | | | | |
| | 24 | 1, 2, 3 | –50 +50 | | | | 10 |
| | 27 | 1 | –100 +100 | Collector removed | | | 100 |
| | | 2, 3 | –50 +50 | | | | |

**Table 8.4 Whole -life cost of pavement maintenance for Road Class 2 (per 100m)**

| MAINTENANCE OPTION | | | | | NET PRESENT VALUE (£) | CHANGE IN NET PRESENT VALUE (£) | DECREASE IN POWER OUTPUT (%) |
|---|---|---|---|---|---|---|---|
| No. | Year | Lane(s) | Depth planed off (–mm) Depth replaced (+mm) | Increase in depth of collector (mm) | | | |
| Base, 1 | 12 | 1, 2, 3 | –50 +50 | 0 | 22,175 | 0 | 0 |
| | 24 | 1 | –100 +100 | Collector removed | | | 100 |
| | | 2, 3 | –50 +50 | | | | |
| 2 | 12 | 1, 2, 3 | –50 +50 | 0 | 23,550 | +1,375 | 0 |
| | 24 | 1, 2, 3 | +25 | 25 | | | 5 |
| | 28 | 1 | –100 +100 | Collector removed | | | 100 |
| | | 2, 3 | –50 +50 | | | | |
| 3 | 11 | 1, 2, 3 | –50 +50 | 0 | 26,300 | +4,125 | 0 |
| | 22 | 1, 2, 3 | +25 | 25 | | | 5 |
| | 26 | 1 | –100 +100 | Collector removed | | | 100 |
| | | 2, 3 | –50 +50 | | | | |
| 4 | 10 | 1, 2, 3 | –50 +50 | 0 | 30,000 | +7,825 | 0 |
| | 20 | 1, 2, 3 | +25 | 25 | | | 5 |
| | 24 | 1 | –100 +100 | Collector removed | | | 100 |
| | | 2, 3 | –50 +50 | | | | |

**Table 8.5 Whole -life cost of pavement maintenance for Road Class 3 (per 100m)**

| MAINTENANCE OPTION | | | | | NET PRESENT VALUE (£) | CHANGE IN NET PRESENT VALUE (£) | DECREASE IN POWER OUTPUT (%) |
|---|---|---|---|---|---|---|---|
| No. | Year | Lane(s) | Depth planed off (–mm) Depth replaced (+mm) | Increase in depth of collector (mm) | | | |
| Base, 1 | 11 | 1, 2 | –30 +30 | 0 | 40,200 | 0 | 0 |
| | 22 | 1, 2 | +50 | 50 | | | 10 |
| 2 | 11 | 1, 2 | –30 +30 | 0 | 40,650 | +450 | 0 |
| | 22 | 1, 2 | +100 | 100 | | | 20 |
| 3 | 10 | 1, 2 | –30 +30 | 0 | 65,000 | +24,800 | 0 |
| | 20 | 1, 2 | +50 | 50 | | | 10 |
| | 30 | 1, 2 | +100 | 150 | | | 30 |
| 4 | 9 | 1, 2 | –30 +30 | 0 | 70,000 | +29,800 | 0 |
| | 18 | 1, 2 | +50 | 50 | | | 10 |
| | 28 | 1, 2 | +100 | 150 | | | 30 |

### *8.4.4 Decommissioning and salvage*

An end-of-use cost has been calculated for the components of the heat storage system that have useful years of service at the end of the accounting period. A linear decrease in their value has been assumed over their assumed service life.

For the pavement maintenance options that would remove the collector pipework, the end-of use costs for the circulating and heat pumps have been calculated assuming that the remaining life would be the service life less the time actually used. For example, if the collector pipework was removed by planing after 19 years, it has been assumed that the remaining life of the pumps would be 6 years. However, the remaining life of the other components has been calculated assuming that the remaining life would be the service life less the accounting period.

### *8.4.5 Summary*

The heat supplied, power required, operation and maintenance, and end-of-use costs, and the performance data described above are summarised in Table 8.6.

### *8.4.6 Results*

Tables 8.7 to 8.9 show whole-life costs for the three road classes described in Table 8.1. They were calculated for an accounting period of 30 years by assuming the cost and performance data described above. The installation costs for the three road classes, including traffic management and traffic delay costs, are £111,100, £68,700 and £72,200, respectively.

Rows 1 to 6 correspond to the gas and electricity price cases defined in Table 8.2. The figures in Row 1 were calculated assuming present day prices and no future increases above the rate of inflation.

The figures in Columns 2 to 5 and in Columns 6 to 9 were calculated assuming that 50% and 35%, respectively, of the heat stored (108MWh) were lost. Columns 2 to 5 and Columns 6 to 9 correspond to the four pavement maintenance options described in Tables 8.3 to 8.5.

**Table 8.6. Summary of assumed heat, power, operation and maintenance, and salvage costs**

| ELEMENT | COST (£) | FREQUENCY |
|---|---|---|
| **Heat supplied and power consumption** | | |
| Heat supplied to domestic heating system | 67.5MWh if 50% of heat stored is lost<br>83.7MWh if 35% of heat stored is lost | Annually, but decreasing due to loss of performance and damage to collector pipework<br>Loss due to performance: 1% each year<br>Loss due to damage: 2% every 10 years after 5 years<br>Loss due to pavement maintenance: 10% for every 50mm increase in depth of collector pipework, 100% when collector pipework removed by planing<br>Loss due to heat and circulating pump replacement: = 1 week |
| Power required to operate pumps, valves, etc. | 13.5MWh | Annually, but decreasing due to loss of performance, damage to collector pipework and heating and circulating pump replacement as above for heat supplied<br>Decrease due to pavement maintenance: 0% when depth of collector pipework increased, 100% when collector pipework removed by planing |
| **Routine maintenance** | | |
| Maintenance on heat pumps, circulating pumps etc. | 300 | Annually |
| Basic electrical inspection | 50 | 3 years |
| Detailed electrical inspection | 100 | 6 years |
| **Replacing components** | | |
| Pavement maintenance | See Tables 8.2 to 8.4 | |
| Circulating pumps and valves | 5000 | 25 years |
| Heat pump | 7000 | 25 years |
| Collector pipework | 3750 | 30 years |
| Heat store pipework, including insulation | 24750 | 30 years |
| Connecting pipework from collector to heat store etc. | 3000 | 50 years |
| Connecting pipework from heat store to domestic heating system. | 3000 | 50 years |
| Heat exchanger | 1000 | 50 years |
| Control system | 5000 | 50 years |
| Cabling | 100 | 60 years |
| Data links | 100 | 60 years |
| Plant room | 7500 | 100 years |

**Table 8.7. Variation in whole -life cost with price of gas and electricity, percentage of heat lost, and additional pavement maintenance for installations in Road Class 1 (per 100m)**

| GAS / POWER PRICE CASE | INSTALLATION COST = £111,100<br>HEAT LOST = 50%<br>WHOLE LIFE COST (£) | | | | INSTALLATION COST = £111,100<br>HEAT LOST = 35%<br>WHOLE LIFE COST (£) | | | |
|---|---|---|---|---|---|---|---|---|
| | PAVEMENT MAINTENANCE OPTION | | | | PAVEMENT MAINTENANCE OPTION | | | |
| | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| 1 | 99,800 | 107,100 | 111,400 | 171,300 | 96,000 | 102,400 | 106,800 | 166,800 |
| 2 | 93,100 | 97,800 | 102,200 | 162,700 | 87,100 | 90,000 | 94,500 | 155,500 |
| 3 | 80,900 | 80,200 | 84,900 | 146,800 | 70,900 | 66,500 | 71,300 | 134,200 |
| 4 | 93,000 | 98,700 | 103,100 | 163,400 | 87,000 | 91,200 | 95,700 | 156,300 |
| 5 | 82,300 | 83,800 | 88,400 | 149,800 | 72,800 | 71,300 | 76,000 | 138,100 |
| 6 | 62,800 | 55,800 | 60,700 | 124,300 | 46,800 | 33,800 | 38,900 | 104,000 |

**Note:** £44,900 could be deducted from the above figures if traffic delay and traffic management costs are not incurred for new motorway construction (see Table 8.1).

**Table 8.8. Variation in whole -life cost with price of gas and electricity, percentage of heat lost, and additional pavement maintenance for installations in Road Class 2 (per 100m)**

| GAS / POWER PRICE CASE | INSTALLATION COST = £68,700<br>HEAT LOST = 50%<br>WHOLE LIFE COST (£) | | | | INSTALLATION COST = £68,700<br>HEAT LOST = 35%<br>WHOLE LIFE COST (£) | | | |
|---|---|---|---|---|---|---|---|---|
| | PAVEMENT MAINTENANCE OPTION | | | | PAVEMENT MAINTENANCE OPTION | | | |
| | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| 1 | 57,300 | 59,800 | 62,500 | 65,300 | 53,100 | 55,200 | 58,000 | 61,000 |
| 2 | 49,100 | 50,600 | 53,700 | 57,100 | 42,000 | 42,900 | 46,400 | 50,100 |
| 3 | 33,600 | 33,200 | 37,400 | 41,800 | 21,500 | 19,800 | 24,600 | 29,700 |
| 4 | 49,600 | 51,500 | 54,500 | 57,600 | 42,700 | 44,100 | 47,300 | 50,700 |
| 5 | 36,400 | 36,700 | 40,500 | 44,500 | 25,100 | 24,500 | 28,700 | 33,300 |
| 6 | 11,700 | 9,000 | 14,300 | 20,000 | (7,800) | (12,600) | (6,200) | 700 |

**Note:** £2,500 could be deducted from the above figures if traffic delay and traffic management costs are not incurred for new motorway construction (see Table 8.1).

**Table 8.9. Variation in whole-life cost with price of gas and electricity, percentage of heat lost, and additional pavement maintenance for installations in Road Class 3 (per 100m)**

| GAS / POWER PRICE CASE | INSTALLATION COST = £72,200 HEAT LOST = 50% WHOLE LIFE COST (£) | | | | INSTALLATION COST = £72,200 HEAT LOST = 35% WHOLE LIFE COST (£) | | | |
|---|---|---|---|---|---|---|---|---|
| | PAVEMENT MAINTENANCE OPTION | | | | PAVEMENT MAINTENANCE OPTION | | | |
| | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| 1 | 62,300 | 63,000 | 87,200 | 92,400 | 57,600 | 58,400 | 82,500 | 87,800 |
| 2 | 52,800 | 53,800 | 77,800 | 83,200 | 44,900 | 46,100 | 70,000 | 75,500 |
| 3 | 35,000 | 36,600 | 60,200 | 66,100 | 21,200 | 23,000 | 46,400 | 52,500 |
| 4 | 53,800 | 54,700 | 78,800 | 84,100 | 46,300 | 47,300 | 71,300 | 76,700 |
| 5 | 38,700 | 40,100 | 63,800 | 69,500 | 26,100 | 27,700 | 51,300 | 57,100 |
| 6 | 10,200 | 12,500 | 35,600 | 42,000 | (12,000) | (9,200) | 13,600 | 20,300 |

**Note:** £5,980 could be deducted from the above figures if traffic delay and traffic management costs are not incurred for new trunk road construction (see Table 8.1).

### *8.4.7 Discussion*

Installation of a heat transfer system in Road Class 2 gave the lowest whole-life costs. This is mainly because traffic delay costs are lower for Road Class 2 than the other two classes. It must be noted that traffic delay and traffic management costs are particularly significant for Road Class 1 (see footnote to Table 8.7) and with careful scheduling on a large new construction scheme it is possible that these may be avoided.

The whole-life costs for Road Class 2 are relatively insensitive to the pavement maintenance option. In other words, the whole-life cost does not increase significantly if the collector pipework increases the rate of damage of the pavement. The main reason for this is because the number of maintenance treatments required during the accounting period is the same for all four options.

Comparison of rows 1 and 4 in Table 8.8 shows that, if the price of gas and electricity is increased by 60% and there are no future increases above the rate of inflation, the whole-life cost decreases by approximately £8,000 and £11,000 when the heat lost is 50% and 35%, respectively. Comparison of columns 2 to 5 with columns 6 to 9 in row 1 shows that, assuming present day gas and electricity prices and no future increases above the rate of inflation, the whole-life cost decreases by only approximately £4,000 when the heat lost reduces from 50% to 35%. Row 4 shows that the decrease is approximately £7,000 if the price of gas and electricity is 60% higher than present day prices and there are no future increases above inflation.

Comparison of row 1 with rows 2, 3, 5 and 6 shows that the whole-life cost decreases significantly only if future increases the price of gas and electricity are well above the rate of inflation. Furthermore, the reduction in the heat lost becomes more significant. A benefit (negative whole-life cost) was calculated for Options 1 to 3 of Road Class 2 (row 6 of Table 8.8) and Options 1 and 2 of Road Class 3 (row 6 of Table 8.9) when the heat lost is 35% and future increases in the price of gas and electricity are significantly above the rate of inflation.

It is unlikely that future increases the price of gas and electricity will be as high those assumed in row 6 of Tables 8.8 and 8.9. Therefore, it is concluded that an investment in an interseasonal heat storage system is only likely to give any significant financial benefits if the costs of the system and its maintenance were considerably lower than those assumed in these analyses and/or there were significant environmental cost benefits that have not been taken into account in this section.

It must be noted that these analyses have been undertaken assuming that the collector pipework is buried at a depth of between 50 and 100mm below the carriageway surface. Although a greater depth can be used the efficiency of the system will then be reduced because pavement temperatures will be lower at this depth which will necessitate an increased usage of the heat pump, although this will be compensated for by reduced pavement maintenance costs.

# 9 Environmental life cycle assessment of interseasonal heat transfer

## 9.1 Introduction

Interseasonal heat transfer is a relatively new technology when compared to photovoltaic cells. As a result, the research available concerning the life cycle environmental impacts of interseasonal heat transfer is less detailed. Therefore, a different approach has been taken in this section which concentrates more on significant impacts of the technology and utilises more case study data to compare buildings heated by interseasonal heat transfer to buildings heated by a conventional heating system.

## 9.2 Production

The production of the components of the interseasonal heat transfer system is the stage of the life cycle with the most significant environmental impact. This section will examine the significant aspects of the production cycle.

The main components of an interseasonal heat transfer system are (over and above a normal pavement):

- distribution pipework made of high density polyethylene,
- antifreeze solution (ethylene glycol) within the pipes,
- variable speed pumps,
- water to water heat pump using zero CFC refrigerants.

There is not enough readily available information to consider in detail the materials and energy used to produce each of these components and the harmful by products released by their production. What is clear, however, is that infrastructure is also required in a conventional heating system and these conventional systems also have the added impact of burning fossil fuel to create heat.

Probably the most significant aspect of production of the technology is the production of the pipe arrays. These are made from durable high density polyethylene which is manufactured from crude oil, a finite non-renewable resource. A simplified life cycle assessment study carried has been carried out by the City of Portland in the USA to examine the impacts of different types of sewer pipes (Environmental Services, City of Portland, no date given). Table 9.1 is taken from this report and details the main impacts associated with high density polyethylene pipes.

It has been argued that the use of polyethylene pipes is preferable to alternatives such as PVC because the production of polyethylene does not involve the use of chlorine as a base material, last longer, typically 70 years rather then 50 years and can be 100% recycled.

**Table 9.1. The environmental impacts of polyethylene pipes**

| | |
|---|---|
| **Fuels** | Natural gas, crude oil |
| **Key inputs** | Ethylene, synthetic organic chemicals |
| **Energy consumed per lb. of pipe** | No conclusive data |
| **Emissions to water (g/kg)** | Little water used in process (primarily in cleaning equipment). |
| **Stabilisers** | Lead and cadmium (very low quantities) |

## 9.3 Installation

### *9.3.1 Energy emissions and pollution associated with transportation*

It is not feasible to measure what the detailed impacts associated with the transport of the units would be without knowing:

- the location of the trial site,
- the location of the plant manufacturing different elements of the system,
- the number and type of vehicles used for transport,
- the routing of the vehicles.

With this information it would be possible to predict:

- noise and air emissions of the vehicles,
- fuel used by the vehicles,
- effects on sensitive environments that may be affected by the vehicle routing.

However, in the absence of this information, it has been assumed that relative to existing transport movements the transport required to install the system is likely to be negligible. It is also assumed that disruption to traffic would be the same as with normal pavement construction or maintenance so impacts on traffic using the highway over and above this would also be minimal.

There may also be impacts relating to the installation of equipment for the use of the heat but again these cannot be ascertained at this stage.

### *9.3.2 Energy emissions and pollution associated with installation*

The assumption has been made that the installation of the system is likely to have a relatively minor impact compared to other stages of the life cycle, especially as the system is installed as part of normal pavement construction or maintenance. The building of a plant room will have some impacts but it is difficult to judge what they would be without knowing the sensitivity of the receiving environment.

### *9.3.3 Health and safety risk to installation staff*

As well as the normal risks associated with civil engineering projects there is also the risk associated with the chemicals used within the pipe array. Ethylene glycol will be used which is standard antifreeze and is toxic when ingested. Acute poisoning with ethylene glycol can be associated with effects on the nervous system, heart, lung and kidneys. The likelihood of this arising is considered to be very slim. What may be more of a risk is eye and skin contact and inhalation. Exposure of the eye and skin can cause minimal irritation. Incidental exposures, such as skin exposure to antifreeze, do not cause harm, however, prolonged and repeated contact should be avoided. The low vapour pressure of ethylene glycol makes it unlikely that exposure by breathing would cause adverse effects either from single or repeated exposures to high vapour concentrations.

## 9.4 Use / Maintenance

### *9.4.1 Maintenance issues – frequency and type of maintenance needed*

The maintenance of the system will be minimal with a visit by a heating engineer at six monthly intervals. The impact of maintenance on the environment is expected to be minimal.

### *9.4.2 Visual impact*

There will be no visual impact from the collector array and heat store as it becomes an integral part of the pavement. There will be a visual impact from the plant room although this will be within the existing footprint of the highway. The wider educational benefits to the public are perhaps less with this technology than with photovoltaic cells, which are very obvious from the side of the road. What is important is that the Highways Agency does all it can to raise the profile of renewable energy issues and make links to wider environmental issues. This is perhaps less important with a more visible technology (such as photovoltaic cells) than it would be with interseasonal heat transfer.

### *9.4.3 Emissions*

In terms of negative accidental emissions, when properly installed, there is a low probability of antifreeze solution polluting ground water sources. The fluid in the ground-loop heat exchanger is enclosed within a closed system but it is possible for accidental releases to occur. However, an analysis by the United States Environmental Protection Agency (US EPA, 1998), found that the human health risk from ingesting groundwater contaminated by an antifreeze leak is low. Presumably this is due to the small amounts that are likely to leak out in an accidental release.

Ethylene glycol is a standard antifreeze and de-icing solution. Because of its reactivity, it breaks down within several days to a week in water and soil. Data indicate that ethylene glycol is readily biodegradable, and thus will not persist or accumulate in the environment. In terms of effects on aquatic life, on an acute level, ethylene glycol is considered of a low toxicity level to fish and aquatic invertebrates. Large accidental releases into the environment, however, have the potential to rapidly deplete oxygen in confined surface waters. In such cases, oxygen depletion is due to the rapid degradation characteristics of both chemicals, which may cause localised fish kills and pose a threat to other aquatic life in the immediate area (taken from the Dow Chemicals website http://www.dow.com/dog/safe/ehs3.htm).

Heat pump systems are also thought to be safer to householders than conventional heating systems as there are no combustion flames, no flues, and no odours associated with heat pump systems as there is with conventional boiler systems.

Non chlorofluorocarbon (CFC) refrigerants are to be used within the water to water heat pump. It has been assumed that this a hydrofluorocarbon (HFC) refrigerant. Although HFC does not harm the ozone layer, it is a gas with a high global warming potential. It has not been possible to ascertain the probability of the gas entering the atmosphere. However, more environmentally benign substitutes should be examined if possible.

#### 9.4.4 Energy produced / $CO_2$ emissions

The United States Environmental Protection Agency has carried out a significant amount of research on the provision of heat from heat pump systems and the environmental benefits. Their report *Space Conditioning: The Next Frontier* (US EPA, 1993) found that ground heat pump systems are the most energy efficient, environmentally clean, and cost-effective space-conditioning systems available.

The report also found that heat pump systems offer the lowest carbon dioxide emissions and lowest overall environmental cost of all the residential space-conditioning technology readily available at the time. According to the same report, heat pump systems can reduce energy consumption (and corresponding emissions) by up to 44% compared to air-source heat pumps and by up to 72% compared to electric resistance heating with standard air-conditioning equipment for residential applications.

A report prepared for the International Sustainable Energy Organisation for Renewable Energy and Energy Efficiency (Wittwer, 2000) compared the environmental impact of an electric heat pump applied in a building as compared with a conventional boiler. It found that the most important $CO_2$ emission source is the local combustion of oil or gas in a boiler and the generation of electricity for driving the heat pump compressor. The emission rates of a boiler and a electric heat pump depend on the energy efficiency of the equipment, and on the fuel mix and efficiency of electricity generation.

Within this report the relative $CO_2$ emissions of conventional heating systems were compared with different types of heat pumps. Assumed is an average European $CO_2$ emission for electricity of 0.55 kg $CO_2$/kWh. The result shows that the electric driven heat pump reduces the CO2 emissions by 45% compared to an oil boiler, or 33% compared to a gas fired boiler. Gas heat pumps have reduction rates of the same amount.

**Case Study – UK Energy Efficiency Best Practice Programme**

The case study examined a heat pump that was installed to supply an underfloor heating system for a large private dwelling. The figures shown are indicative only as the study points out that environmental performance should be planned on a project by project basis. Table 9.2 shows some comparisons between different heating systems and their energy used and annual $CO_2$ emissions.

**Table 9.2. Energy consumption and $CO_2$ emissions of the ground pump system versus conventional heating systems**

| System | Energy consumed (kWh) | Annual $CO_2$ emissions ($kgCO_2$)* |
|---|---|---|
| Ground source heat pump | 7,825 | 3,600 |
| Regular oil fired boiler post 1998 | 23,646 | 6,390 |
| Gas fired condensing boiler | 21,976 | 4,260 |

** assumed $CO_2$ emission: oil 2.7kg/kWh; gas 0.194kg/kWh; electricity 0.46kg/kWh.*

**Case Study—Fort Polk Army Base, USA**

An example of a large-scale application of heat pump technology is the project at Fort Polk, Louisiana, where 4,003 US Army housing units were converted to heat pump systems. Since the new systems were installed, service calls on hot summer days have dropped from 90 per day to almost zero, testifying to the reliability of heat pump systems.

Data were collected on the utility feeders serving the housing area, and on a sample of apartments before, during, and after the retrofits. The heat pump systems and other efficiency measures reduced electrical consumption by 26 million kWh (average of 6,445 kWh per housing unit) or 32% of the pre-retrofit consumption, as well as 100% of natural gas consumption. It also reduced summer peak demand by 7.5 megawatts, which is 43% of the pre-retrofit electrical consumption in family housing. These energy savings correspond to an estimated reduction in carbon dioxide emissions of 22,400 tons per year.

### 9.5 Disposal

Because the technology is relatively new and untested it is difficult to ascertain what the end of life issues may be in terms of recyclability of components and special disposal requirements. The issue of waste management is one that needs further work to resolve. However, the system is expected to have a long life (with certain components being replaced every 25 or 50 years). Issues that are more important at this stage, therefore are designing for this durability.

## 10 Summary

### 10.1 General

(i) Renewable energy technologies are likely to become more important as other energy sources become depleted and the cost of power generation using fossil fuels rises. Renewable sources of energy have considerable potential for increasing security of supply although, in most cases, they require significant initial investment.

(ii) Both technologies studied represent ways to generate heat or power without directly burning fossil fuels. They both have different benefits and disbenefits and impacts at different stages of their life cycle. However, it is not possible to directly compare the two technologies as they are providing different services to each other. Photovoltaic systems provide electricity to feed into the HA grid to power signs, lighting and equipment or into the national grid for more general use, whereas interseasonal heat transfer provides heat to replace conventional heating systems in nearby buildings. In the latter case this heat could also be used for road de-icing purposes if required.

(iii) It is important that the Highways Agency does all it can to help meet government targets, raise the profile of renewable energy issues and make links to wider environmental issues. This is perhaps less important with a more visible technology (such as photovoltaic cells) than it would be with interseasonal heat transfer.

(iv) The UK Government actively supports the use of renewable energy by various grant schemes and intends using Renewable Obligation Certificates to ensure the best price for energy from renewable sources. These factors have not been taken into account in the whole-life costing undertaken in this report as they can be viewed as subsidies of uncertain magnitude and duration.

### 10.2 Photovoltaic systems

(v) One of the most promising sites for mounting photovoltaic systems is onto highway noise barriers particularly as a significant infrastructure of noise barriers already exists on UK highways. Unshaded areas of south facing barrier provide a convenient mounting for solar panels which has little environmental impact. A compromise in the optimum angle of tilt for the solar panels may however be necessary to maintain noise reducing capabilities.

(vi) Various demonstration projects using photovoltaic panels on highway noise barriers have been undertaken in Europe and outputs from systems in the UK are expected to be similar to those in the Netherlands. A demonstration trial in the UK is expected to provide HA with experience in using these systems and in particular with an assessment of environmental impacts and experience with grid-connection problems on the highway network. Possible trial sites in the UK are identified in the appendix to this report.

(vii) Initial costings have been established assuming the output from the system will be synchronised with either the HA private grid or the national grid using inverters. In this way the power generated will be used immediately with no requirement for battery or generator back-up. The solar array would therefore be better placed near to where there is a daytime power demand (eg. tunnel, maintenance depot, highway junction) to avoid transmission losses in the cables. In remote localities where there is no existing grid, a stand alone system will be needed. In this latter case, the cost of routing the grid to the location will be an important factor in deciding on its financial merits.

(viii) Electricity produced by photovoltaic cells when compared to electricity generated by fossil fuels produces less greenhouse gases including $CO_2$. Extensive studies have also shown that their energy pay back period has decreased, as technology has become more sophisticated. They have minimal impacts on the environment when in use and minimal risk to maintenance staff and the public. However, there are some issues relating to their manufacture and disposal that are of concern and will need to be further considered in the future. The production of cells requires small quantities of scarce resources such as silver and gold. End of life is also a concern as although in theory large elements of the modules can be recycled, little work has progressed to make this a reality and there is currently no recycling plant that commercially recycles photovoltaic cells in the UK. The major production companies are, however, working on improved recycling regimes. Another end of life issue with photovoltaic cells is the fact that the modules may constitute special or hazardous waste. The exact composition of the modules is needed to assess this further.

(ix) The whole-life cost analyses have shown that, for the assumptions made, the costs associated with the installation and maintenance of the assumed solar panel system are far greater than the cost of the power generated by the panels. This is the case even assuming increases in the price of electricity significantly above the rate of inflation, and either significant reductions in the costs of the components or significant subsidies. It is concluded that it is unlikely that an investment in a solar panel system would give any financial benefits unless the costs of the system and its maintenance were considerably lower than those assumed and/or there were significant environmental cost benefits that have not been taken into account in these analyses. Nevertheless for the reasons given in (v), a demonstration trial on the highway network is appropriate given that the Department of Trade and Industry are currently encouraging photovoltaic installations by grants of up to 65% for public bodies.

### 10.3 Interseasonal heat transfer systems

(x) Up to the current time, the most frequent use of interseasonal heat technology has been for heating buildings: either as low temperature water heating (for space heating) or for space heating and water heating (in conjunction with a heat pump). Most of these systems have used either deep ground storage or heat storage in the aquifer. More recently the possibility of shallow earth stores, which are thermally insulated, has emerged. The development of interseasonal storage of solar thermal energy is an important step in the development of sustainable communities and energy self-sufficient buildings.

(xi) In many ways installing the collector pipe arrays below black asphaltic surfaces appears an innovative use of the highway network. The direct heat collected and stored can then be used to heat adjoining buildings or, if significant continuous stretches were modified, for de-icing purposes.

(xii) Durability of the pavement surface may be improved as the heat transfer system will act to lower pavement temperature during the summer. However this needs to be proven and trafficking trials need to be carried out to ensure that the presence of the collector pipe array does not have any deleterious effects on pavement performance. Trials of the ability of the high density cross-linked polyethylene pipes to withstand (without deformation) the temperatures during placement of the hot rolled asphalt are also considered prudent. In previous installations in Europe, this perceived problem has been avoided either by passing cooling water through the pipework, by installing the pipework in a thin layer of concrete beneath the asphalt surfacing, or by using stainless steel coils in a plastic/cement-stabilised asphalt layer.

(xiii) Heat produced by interseasonal heat transfer when compared to heat generated by conventional boiler systems produces less greenhouse gases including $CO_2$. The technology also has minimal risks to installation staff and the public as well as reducing the risk to householders of conventional boiler systems. However, the production of the components does have some environmental impacts, as the production of the pipe arrays requires the use of fossil fuels. Certain chemicals are also used within the process such as zero CFC refrigerants and ethylene glycol. More environmentally benign alternatives to non CFC refrigerants may become available in the future. End of life issues are also important although no information has been found on this issue due to the technology being relatively new and untested.

(xiv) On the basis of whole-life costing which assumes large increases in the price of gas and electricity in the future, it is concluded that an investment in an interseasonal heat storage system is only likely to give any significant financial benefits in certain situations. These are if (a) the costs of the system and its maintenance were considerably lower than those assumed in these analyses, (b) there were significant environmental cost benefits that have not been taken into account, or (c) the high costs of traffic delay and traffic management assumed during system installation were inapplicable. The latter may be the case on a large motorway or trunk road construction scheme or in the construction of local roads for a new housing estate. The effect of installing the collector pipework at a greater depth than 100mm below the carriageway surface needs further investigation.

(xv) The use of interseasonal heat transfer systems is currently innovative and at the forefront of technology. There is therefore merit in carrying out a demonstration trial as system costs are likely to reduce when more data are available. Possible locations of trial sites are identified in the appendix to the report.

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# 13 Appendix. Location of sites for demonstration trials

### 13.1 Photovoltaic systems on highway noise barriers

The next possible phase of the study is a demonstration trial on the network. For the purpose of this trial, it is proposed to mount solar panels on the traffic face of one approximately 100m long stretch of existing noise barrier. The panels will be mounted either vertically or at an angle of about $60^o$ to $70^o$ to the horizontal (with the toe of the barrier nearer to the highway) on a south facing barrier. Mounting in this way will minimise interference with the existing structure in terms of its wind resistance and noise reducing capacity. It is accepted that some annual loss of power will result because this angle is not the optimum, although winter power production may be enhanced.

Data was obtained from the CONFIRM database on the location and extent of noise barriers on the motorway and trunk road network and this is presented in Table 13.1. It should be noted that entries are not included in the database for all motorways and trunk roads.

**Table 13.1. Orientation of existing noise barriers on the motorway and trunk road network**

| Eastbound/westbound | | Northbound/southbound | |
|---|---|---|---|
| **Motorway / Trunk road** | **Length of noise barrier (m)** | **Motorway / Trunk road** | **Length of noise barrier (m)** |
| M20 | 21,933 | M271 | 7,865 |
| A27 | 3,498 | A1 | 1,067 |
| M27 | 63,551 | A1(M) | 7,441 |
| M4 | 14,332 | A606 | 1,798 |
| A31 | 154 | M1 | 48,340 |
| A616 | 2,534 | M18 | 7,005 |
| M62 | 15,300 | | |
| **Total** | **121,302** | **Total** | **73,516** |

**Notes:**

(1) Data were obtained from the CONFIRM database which is part of the HAPMS system.

(2) Details on noise barriers are not contained in the database for all motorway/trunk roads, notably the M25 for example.

(3) A total length of 3,324m of noise barrier (at various orientations) is also documented for the orbital M621.

Table 13.1 illustrates the resource of noise barriers that exist on which photovoltaic panels could theoretically be mounted. However it must be noted that many of these barriers may be shaded by vegetation, unsuitably oriented, or so close to the carriageway to preclude photovoltaic panel installation without traffic management. The need for costly traffic management makes the installation of photovoltaic panels untenable in whole life cost terms.

For this purpose of this study it was arbitrarily decided to confine the search for trial locations to the M27 as the majority of the noise barriers on one side of this motorway are south facing. Two apparently suitable locations have been identified within Area 3 on south facing barriers of the M27. In both cases, the barriers are at the top of cutting slopes with front and rear access being available without the need for traffic management.

#### *13.1.1 Preferred site A near marker post 33/0*

This barrier is about 400m long and 2m high, and is constructed using galvanised steel I-beams and wooden panels. It is located to the east of Junction 9 (M27/A27) and before the Whiteley Lane overbridge, and backs onto Lady Betty's Drive. A map of the location is shown in Figure 13.1.

A photograph of the traffic face of the barrier is given in Figure 13.2. The slope has been recently planted with small saplings, although it is not envisaged that these will provide any significant shading of the panels for many years. Access to the traffic face of the barrier is facilitated by the existence of an old disused two lane road separated from the main carriageway by a safety barrier (Figure 13.3). Use of the nearside lane for transporting items to site should therefore not present a problem.

A lane runs behind the barrier (Figure 13.4) so there is also good access by that means.

There is a post carrying overhead cables at the site and property on the other side of the lane, so that connection to the national grid should be feasible. No information is currently available on the nearest junction point to the HA private grid.

#### *13.1.2 Reserve site B near marker post 11/6*

This barrier is about 200m long and 2m high, and is constructed using concrete posts with wooden battens. It is located to the east of Junction 3 (M27/M271) and just after the Romsey Road bridge. A map of the location is shown in Figure 13.5.

Figure 13.6 shows a photograph of the cutting slope. The slope has been recently planted with small saplings, although it is not envisaged that these will provide any significant shading of the panels for many years. The first 40m of the barrier is unshaded however there is some light shading over the next 10m or so. Access should be possible without traffic management over the top part of the slope and there is good access to the rear from a track.

There is nearby property and HT overhead cables so that connection to the national grid should be feasible. There is a HA electricity box (11/6A RMTV) on the slope near to the steps, which might provide access to the HA grid.

### 13.2 Interseasonal heat transfer trial

In view of the prohibitive cost both in terms of construction and disruption to traffic, installation of a heat transfer system as a proving trial on a motorway or trunk road is not appropriate at this time. The use of slip roads and/or road systems at motorway service areas is recommended as a first stage.

This would seem to have the following advantages:

- costs will be far lower than on a motorway or trunk road,
- disruption to the public will be minimised,
- land alongside the road system could potentially be utilised to construct the trial,
- traffic could easily be routed over the trial length to investigate durability issues,
- the service area could utilise some or all of the heat stored,
- instrumentation and performance monitoring of the trial would be simpler.

A survey of motorway service areas within a distance of about 100miles from TRL has therefore been carried out. This survey involved the use of aerial photographs and maps, no site visits were undertaken.

Fifteen service areas were considered. Table 13.2 gives the location of each service area and brief comments as to their suitability. No aerial photographs of the new Winchester services on the M3 were available. This site is relatively close to TRL and should be visited before a decision is made.

From the photographs two sites on the M4 and M40 appeared to be the most suitable as shown in Table 13.2. However aerial photographs do not necessarily give the complete picture and visits to these selected sites may reveal other unforeseen problems.

The service area on the M4 south of Reading is a relatively new service area and does not appear to have much in the way of mature trees to cause shading of the trial length. The westbound entry road has two reasonable straight sections of road that all traffic uses before splitting into its various categories, i.e. cars, HGVs, etc. There appears to be land within the boundary of the services adjacent to the road on which the trial could be constructed. The two straight lengths also have different aspects, i.e. one runs roughly north/south, the other east/west. This site is also only 16miles from TRL. The west bound entry slip road and eastbound exit slip outside the service area boundary would not be ideal as they pass under an over-bridge that would cause some shading.

The second likely site is the M40 services at Warwick, which appears to have a reasonable length of road at both north and southbound entrances. The northbound road is adjacent to some dense woodland but this appears to be at a sufficient distance not to give rise to serious shading. The southbound entry road appears un-shaded. The slip roads outside the service area boundaries also appear suitable though it is not possible to determine from the photographs if sufficient land is available along side of them. The site is about 90 miles from TRL.

Several other sites appeared to be potentially suitable and these are shown separately in Table 13.2. Of these sites the M1 services at Toddington has a Highways Agency maintenance depot on the northbound side of the site. The road system appears to offer some suitable lengths of road with the further advantage that HA might be able to utilise the heat in its own buildings.

**Table 13.2. Possible sites for the interseasonal heat transfer trial**

| Service station location | Comments |
|---|---|
| ***(a) Most suitable*** | |
| M4 Reading | A relatively new service area with few mature trees to cause shading. Fairly extensive road system so land adjacent to roads is probably available. |
| M40 Warwick | Long entry road northbound with land to either side. Some trees but too far away to provide serious shade to slip road. Long entry road entering southbound which also is unshaded and has land to either side. |
| ***(b) Potentially suitable*** | |
| M4 Membury | Long unshaded slip roads with land adjacent. Reasonable distance from TRL worth visiting if closer sites prove unsuitable. |
| M4/A34 Junction | Has a long exit slip road with possible space adjacent to build trial on. Does not appear shaded. Reasonable distance from TRL |
| M40 Cherwell Valley (nr Bicester) | Some mature trees but the exit road looks to be to the south of them. Some adjacent land by roads. |
| M27 Rownams | Close to TRL, and near to possible photovoltaic trial site. Westbound entry road looks clear of shading. |
| M1 Toddington | Northbound entrance road looks suitable. There is also a Highways Agency works depot on the northbound side of the site. There may therefore be potential to use the stored heat at an adjacent HA facility. |
| M1 Rothersthorpe | Both access roads look possible with no obvious sign of heavy shading though there are some trees about. |
| ***(c) Unsuitable*** | |
| M3 Fleet | Far too many trees on this site likely to cause serious shading this is not a promising location. |
| M3 Winchester | A new service area so heavy shading is unlikely. No aerial photos were available since construction. The site is close to TRL and should be visited before decisions are made. |
| M25 South Mimms | The road system looks short and congested, with little free land available. The location does not look promising. |
| M25 Clacket Lane | No aerial pictures available. This site is potentially time consuming to get to as the M25 can be very busy. |
| M4 Leigh Delamere | Looks to have significant tree cover that could give a serious shading problems. This site appears unlikely to be suitable. There are potentially better sites available nearer to TRL. |
| M40 Oxford Jnct 8 | Relatively new service area. Cannot see any heavy vegetation. The road system does not look ideal but site is reasonable close to TRL. |
| M1 Watford Gap | This site does not look suitable. |

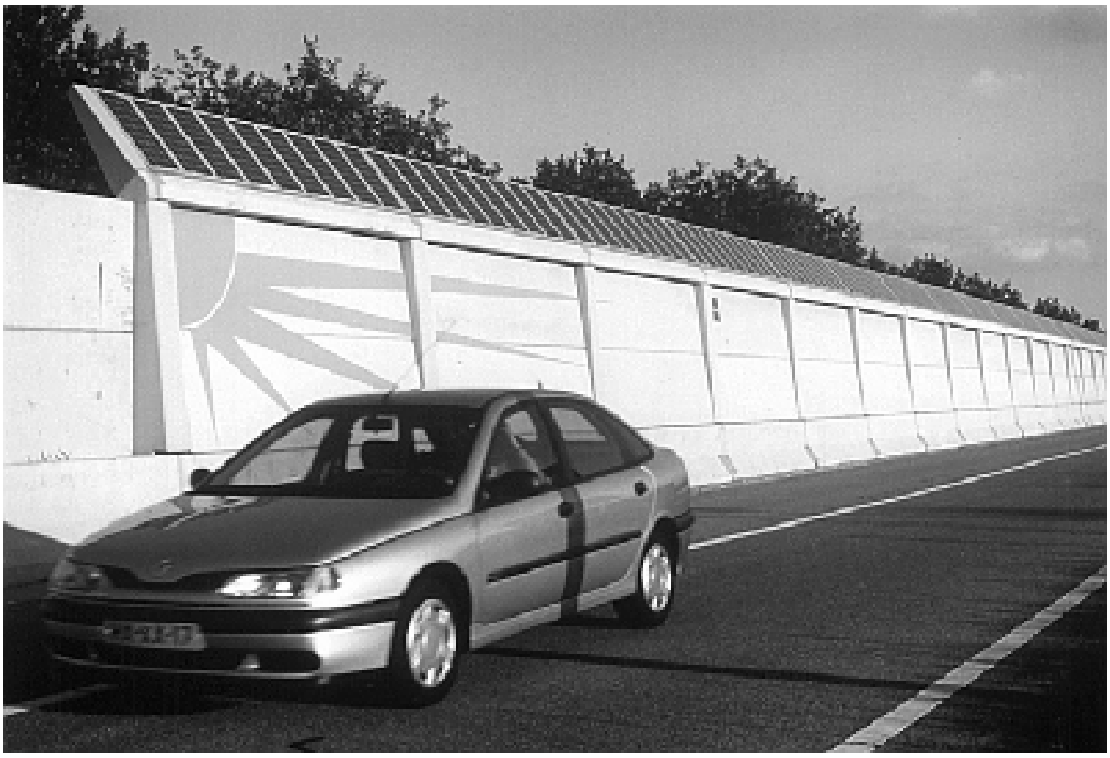

**Figure 2.1. Solar panels fitted onto noise barriers**
(from www.caddet-re.org, by courtesy of CADDET Dutch National Team)

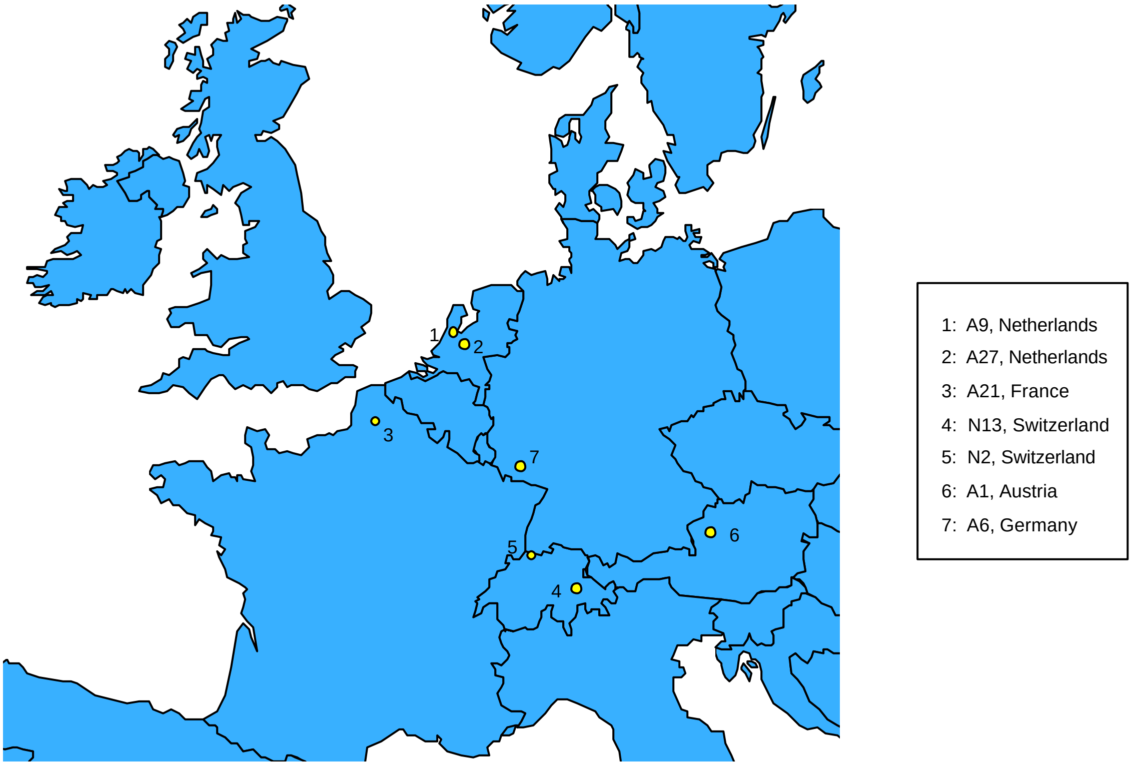


**Figure 2.2. Location of some European PV noise barriers**

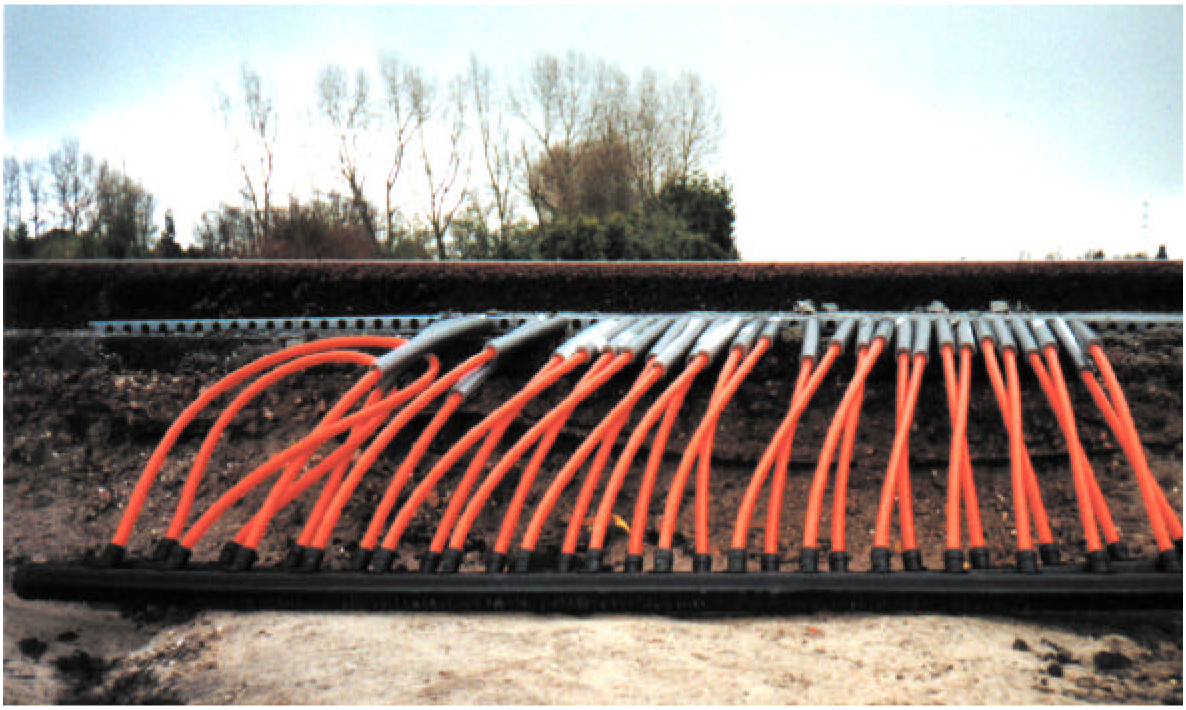

**Figure 6.1. Connections of integral pipe array**
(By courtesy of *i*cax™ Limited)

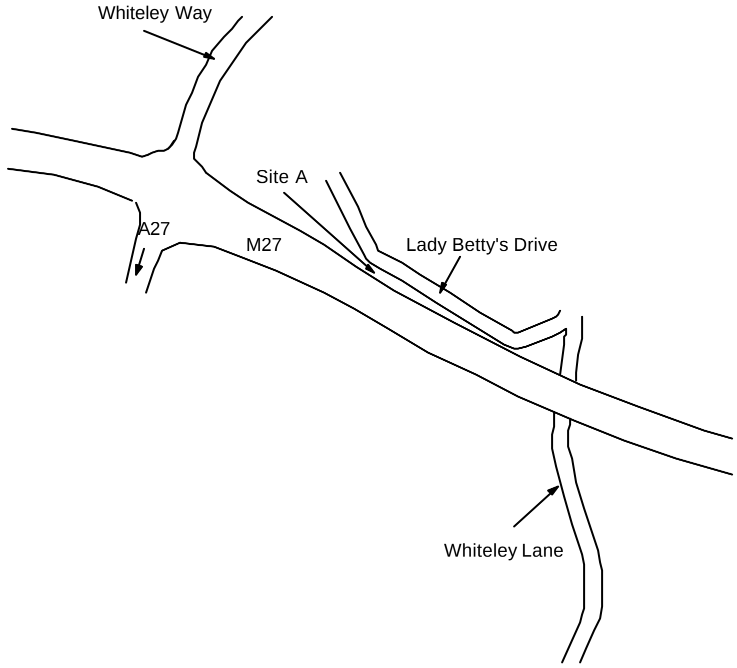


**Figure 13.1. Location of Site A**

**Figure 13.2. Photograph of barrier (Site A)**

**Figure 13.3. Photograph of barrier showing disused road (Site A)**

**Figure 13.4. Photograph of rear of barrier (Site A)**

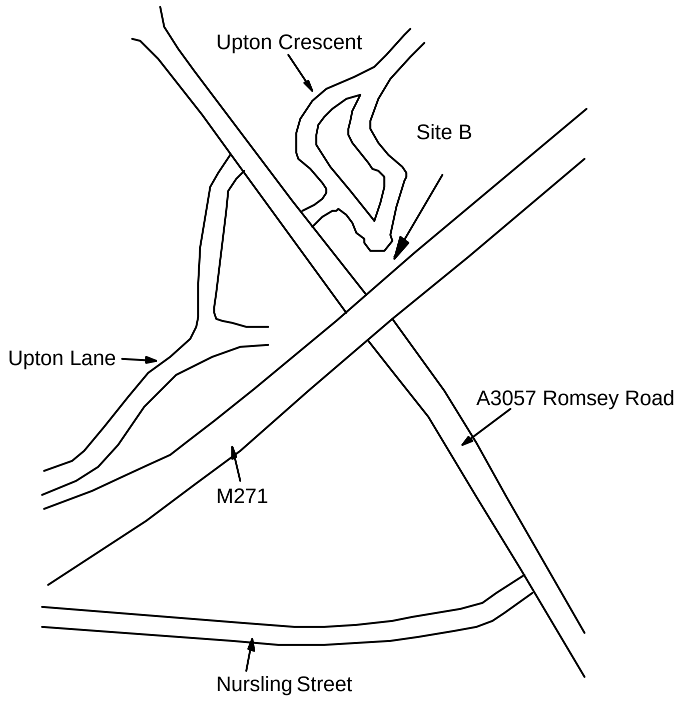


**Figure 13.5. Location of Site B**

**Figure 13.6. Photograph of slope and noise barrier (Site B)**