



Solar Highways Benchmark Study

An overview and evaluation of existing photovoltaic noise barriers

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Introduction

In 2014, Rijkswaterstaat (RWS), ECN and SEAC started the project *Solar Highways: Solar Panels as integrated constructive elements in highway noise barriers*. The project aims to build a 450 m long photovoltaic noise barrier (PVNB) on a highway in the Netherlands in 2016. Most photovoltaic (PV) installations are oriented south and tilted around 30° to 50° to obtain the highest possible solar irradiation to maximize the amount of electricity that can be produced. Effectively half of the highways run north-south (and therefore face east or west). These highways form a huge additional potential for solar energy production. This project aims to demonstrate an optimized solution for highways (roads, railways, etc.) running north-south, based on a bifacial PV module concept using bifacial solar modules, which means these can capture sunlight falling on two sides of the module, resulting in a larger energy yield, compared to



Figure 1: The first PVNB, built in 1989, near Chur, Switzerland

a single sided installation. Opposed to conventional solar power installations, most of the energy will be produced in the morning and evening hours, and will show a minimum in production around noon. Furthermore, the solar modules should be a constructive element, in contrast to adding a standard solar module to a standard or slightly modified noise barrier. Over the last three decades, a number of PVNB have already been built. The first one, on a highway near Chur, Switzerland, was built in 1989. Since then, not only solar cell technology progressed towards higher solar cell efficiencies, also the price of solar cells and other solar installation components have dropped dramatically. Whereas the price for the Chur PVNB was €16.50 per Watt-peak (Wp), the system price for residential PV installations in the Netherlands was €1.48/Wp in early 2014 [1]. These two developments opened up a new range of opportunities for solar energy generation in general and for PVNBs in particular. Whereas the Chur PVNB was built as a pilot and demonstration project, new solar installations are now built worldwide on economic grounds, simply because, in certain circumstances, the price of solar electricity can compete with prices for conventional electricity.

In this document we present an overview of known initiatives for PVNBs, to be able to learn from past failures and successes. We will not only focus on technical aspects, but also provide background information on financial and organizational issues.

In this document, we will first make an overview of existing photovoltaic noise barriers in Europe. A number of these Installations have been studied in more detail in literature and by visiting the installations and the designer, builder or owner of the installation, of which you will find a more thorough description. In the chapter *Observations and lessons learned* we have grouped our gathered knowledge into different topics. The last chapter gives an overview and short descriptions of companies that build, design or perform consultancy work on PVNB.

Noise barriers

To protect civilians or nature reserves from excessive noise pollution, noise barriers are built in strategic places. Because space for building is limited, policy makers are forced to build closer to

roads and railways. If in these places excessive noise is present or particulate densities exceed the regulations, measures need to be taken. In practice, the exceeding of the regulations is quietly allowed ('gedoogd') and erecting a noise barrier is often postponed until large construction works are scheduled [2].

At present, several hundreds of kilometers are in use in the Netherlands. According to the *Vakgroep specialistische bouw of Bouwend Nederland*, every year 50 to 100 million euro is spent on noise barriers in the Netherlands alone. This does not include large projects like *de Betuwelijn* and *de HSL-zuid* [2].

Designs

Noise barriers are constructed from a variety of materials. Most often, the main structure is constructed from steel parts on a concrete foundation. As a sound absorbing or reflecting material, wood, concrete, glass, plastics or aluminium are used, or a combination of these materials. Some noise barriers are specifically designed to allow for vegetation to grow on the structure for aesthetic reasons. Some barriers are fitted with a T-top, which is a horizontal plate placed on top of the upright part of the barrier, for added noise reduction. In this way higher noise protection can be achieved or a lower noise barrier is necessary.

Lifespan

If a good foundation is constructed for the noise barrier and it is constructed from good quality materials, the expected life span for a noise barrier is at least 20 to 25 years [2].

Noise barriers and traffic

For construction or maintenance work on a noise barrier on a highway in the Netherlands, it is required to close the adjacent traffic lane or safety lane [3]. In certain cases it is needed to physically separate the working area from the traffic area, either with beacons or a solid barrier. A noise barrier that can be built quickly using a modular design will minimize traffic disturbance. Closing traffic lanes is not always possible, especially during peak hours. Therefore maintenance work is frequently carried out during the night.

For rail traffic, a physical separation between the rail traffic and work area is always required in the Netherlands.

The Dutch situation: The Modular Noise Barrier

In the document 'Modulaire Geluidsschermen: Handleiding configuratie en implementatie' from 2006 [4], we find guidelines from RWS for building modular noise barriers (MGS). The philosophy for this type of noise barrier is to use a limited number of elements to build a number of different types of noise barriers. Because several different techniques are now used for building noise barriers, maintenance and upgrading is relatively expensive. Furthermore, the noise barriers, as they are now, provide a messy appearance, because so many different designs are used. When for every new noise barrier a new design is made, no lessons can be learnt from previous projects. Therefore, RWS has designed a number of standard 'building blocks' which can be used when building a noise barrier in the MGS philosophy. Using these building blocks, different noise barriers can be built, according to the wishes of the architect or stakeholders. Height and tilt angle can be chosen within a specified range. The MGS design allows for a bend in the barrier, but this is not necessary. The building blocks can be arranged into foundation, standers, noise barrier modules, fastening materials and special

building blocks, such as safety doors. In the standard design there are four different types of noise barrier modules, two of which are sound reflecting and two are sound absorbing. Sound absorbing modules are made from rock wool or rock wool in a metal casing, whereas sound reflecting modules are made from concrete, glass or plastics. The specifications document [4] states that alternative modules can be designed, but they are required to have the same dimensions as the standard modules to ensure uniformity and scalability: 6 m wide and 1 m tall. Furthermore they need to adhere to the rules on safety and noise barrier effectiveness. Transparent modules are required to have at least 20% opaque area to avoid bird collisions [5].

For situations where space is limited, a number of special standers is designed, which are equally strong as the normal standers but have smaller dimensions. In PVNB where bifacial solar modules are used, these can be of interest because they will most likely produce less self-shading. Figure 2 shows the design of the normal standers (a), special standers (b) and a visualization of the different noise barrier modules in a MGS (c). Most existing MGS noise barriers are designed in such a way that they can be extended in height by adding modules [6]. This can be very interesting for PV, because it is arguably the best location to install PV in a noise barrier. In this way, an add-on PV-module can be designed that can be added to existing MGS noise barriers when extra noise protection is needed due to changed infrastructure or traffic loads.

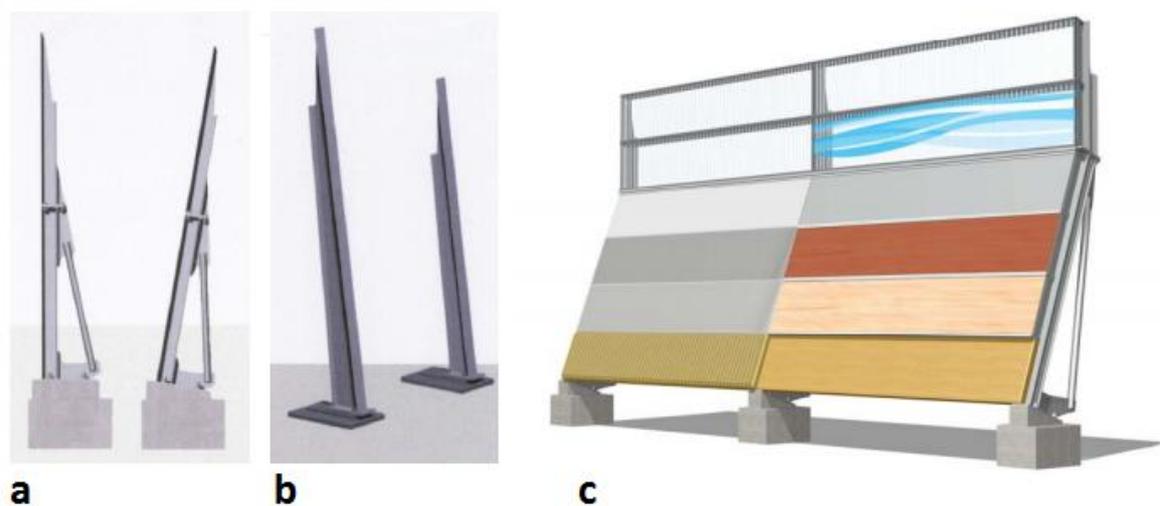


Figure 2: MGS standers (a), special standers (b) and a visualization of a MGS noise barrier (c). From [7] and [8].

The use of the MGS design is a guideline and not every noise barrier built since the introduction of the MGS adheres to the MGS guidelines.

Solar energy

PV systems

A PV module is a packaged assembly of solar cells. Usually a solar system contains a number of PV modules. To connect the modules to the grid, an inverter is used to transform the generated DC-power to AC power that can be fed to the grid. Electrical cables interconnect the modules and connect the modules to the inverter.

Standard PV modules

Most solar modules are based on crystalline silicon (c-Si) as a photo-active material. These panels are made by fixing an array of c-Si solar cells in an enclosure that keeps out moisture and hydrogen in a rigid casing that is easy to handle. Usually, these panels consist of 60 (6 x 10) or 72 (6 x 12) solar cells, which measure 156 mm x 156 mm each (6 x 6 inch), resulting in panels of roughly 1 m x 1.6 m or 1 m x 2 m, including casing. In most cases, these cells are laminated between two glass plates of 3 to 4 mm thick. For lamination, a thermoplastic is used, such as polyvinyl butyral (PVB) or ethylene-vinyl acetate (EVA). Both these materials are also used for laminating safety glass. If the glass shatters when it breaks, it is still held together by the thermoplastic. Most casings are made from aluminium for a rigid but light construction, although there are also frameless designs. A junction box is placed on the back of the module to connect cables. It also holds a number of by-pass diodes. Because of the light construction of a PV panel, it is not directly suited as a noise barrier, as it will not absorb or reflect enough sound.

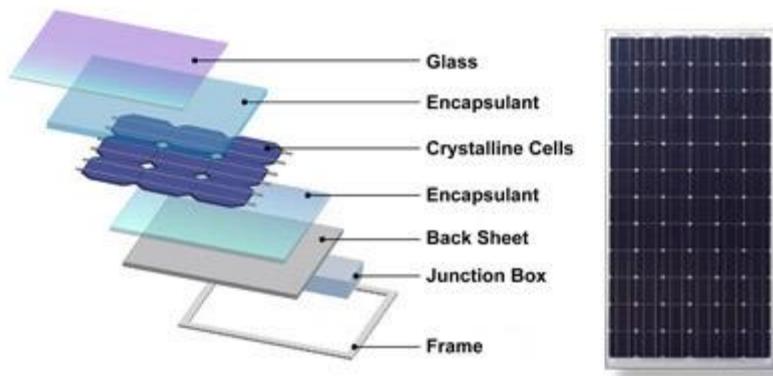


Figure 3: Schematic solar module build-up. From [9]

Inverters and cables

PV modules produce DC power. To connect the PV modules to the grid, an inverter is needed, which ensures maximum power output by presenting an electrical load to the system that is optimized for maximum efficiency, so called maximum power point tracking. Furthermore, the inverter converts the DC power to AC power and matches the frequency and phase to the grid. In this conversion step, power is lost. Most inverters have a maximum conversion efficiency near their maximum rated power. Therefore, to design a PV system that performs efficiently, it is important to match the inverter capacity to the expected power output of the PV modules. In most systems, PV modules are connected in series before they are connected to the inverter. As current carrying cables are prone to voltage losses, low resistance cabling is crucial.

Performance

Solar panels have a nameplate capacity or nominal performance, given in watt-peak (Wp). This number gives the electrical output in Watts under standard test conditions (STC), defined as 1000 W/m² illumination of a defined spectrum and a cell temperature of 25°C. Temperature is important because the performance of solar cells decreases with increasing temperature (and vice versa). Most standard PV modules are rated between 230 and 300 Wp. The AC performance of a PV system is not only influenced by the nominal power of the modules, but also by the irradiation on

the PV modules, weather conditions, shading conditions and electrical losses in cables and the inverter.

Loss mechanisms – from cell to system

There are a number of loss mechanisms in a PV system, which all have influence on the performance of the total system. These can roughly be divided into optical and electrical losses. Firstly, a PV module is an assembly of solar cells in a transparent casing, usually glass. Light that is reflected or absorbed by the glass cannot reach the solar cells and will not be converted to electricity. When these PV modules are placed in a carrying structure (as is the case in a PVNB), parts of the structure (horizontal and vertical supports, frames) may create shading on the PV during parts of the day, so called self-shading. When cells or modules are connected in series, the current of this string will be limited by the cell or module that produces the lowest current. Therefore, module and system design need to take self-shading into account. More optical losses can occur to external shading; trees, buildings or other constructions can block sunlight reaching the system. Also here the string-effect needs to be taken into account for a robust PV-system design. Electrical losses can occur in the cables and in the DC to AC conversion step. All of these factors need to be considered when a PV-system is designed.

Overview of existing PVNB systems

From different sources we have compiled an overview of existing PVNBs in Europe. As a starting point, PVNB overviews from [10],[11], [12] and [13] were used. More installations were found through internet search and cross-references. In Europe we found 34 existing projects, ranging from small-scale test setups to very large scale megawatt solar energy farms. Apart from the existing PVNBs, we identified a number of anticipated projects. All found installations are built near road or rail infrastructure or near industry. For all the existing systems we gathered publicly available technical information such as rated power, orientation, tilt, location, type of solar technology used, but also information on the builder, owner and operator of the system. This information is summarized in table 1. The smallest installation has a rated power of 7.5 kWp, whereas the largest has a rated power of more than 2 MWp (Aschaffenburg). There are plans to build a 5.5 km long 4.5 MWp PVNB in Michendorf, near Potsdam, Germany.

Most of the barriers are oriented south, with orientations ranging from 140° (south-east) to 220° (south-west). Most of these PV-surfaces are placed under an inclination, although a few are placed vertically (Zürich (Brütisellen), Emden and München). A number of installations are placed along roads that run north-south and therefore face either east or west. We found two of these systems (Zürich (Aubrugg) and Münsingen, both in Switzerland), that are both equipped with bi-facial solar cells, which enables solar energy harvesting from both sides of the barrier. These barriers are placed at a 90° tilt angle with respect to the horizontal. For the majority of the systems, c-Si cells are used. We identified 3 systems which use a-Si as a photoactive material for the solar cells.

Different PVNB designs

Although all found installations are advocated as photovoltaic noise barriers, the aim of the installations seems to differ substantially.

Solar parks near highways

Some of the installations found are clearly optimized for maximum solar energy harvesting, for which standard solar modules are used. For instance, the large (1 MWp) PVNB in Wallerdorf is built up in a rather uninhabited area, as shown in Figure 4. The placement of this system suggests that the noise barrier function of this installation is of low importance and that the side of the road is regarded as a good place to place a PV installation.

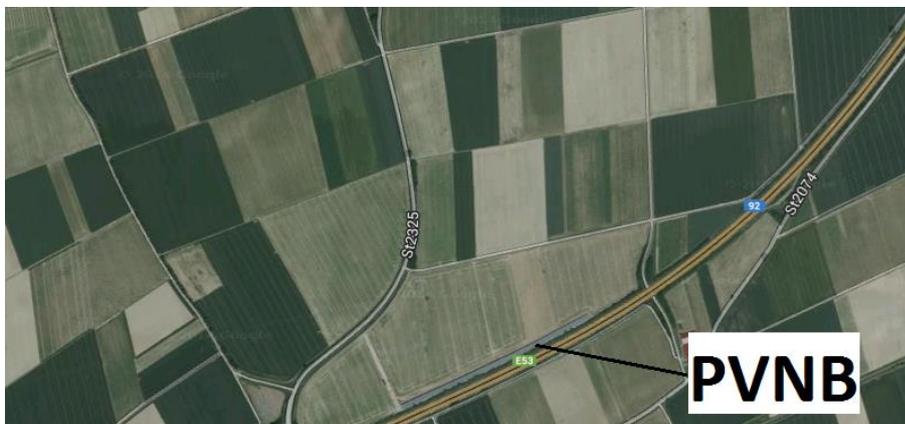


Figure 4: Area around PVNB in Wallerdorf, Germany (Source: Google Earth)

Noise barrier added PV

Other installations are merely standard noise barrier designs with solar modules fitted to it. For these installations no or very little adaptations were made to be able to add the PV. Examples of this type of installations are the PVNBs in Utrecht or Ouderkerk aan de Amstel, both in the Netherlands, where the PV panels were retrofitted to the noise barrier.



Figure 5: Noise barrier with add-on PV at Nieuwerkerk aan de Amstel, Netherlands (Source: Google Streetview)

PV integrated noise barriers

An integrated design for PVNB means that the building materials of the installation function both as a noise barrier and solar power generating device. This cannot be achieved by using standard PV modules alone, simply because these modules do not absorb or reflect enough sound. To achieve better sound absorption (or reflection), mass can be added to the noise barrier (PV)-modules. This can be done by laminating solar cells between thick glass plates or by adding standard PV modules to more massy materials or sound absorbing materials. An example of such a system can be seen in Figure 6, which shows solar cells laminated between two 5 mm thick glass plates. As a rule of thumb, the CROW states that the minimum mass per square meter must be at least 40 kg/m^2 [5].



Figure 6: Bifacial solar cells laminated between two 10 mm thick glass plates in a PVNB in Münsingen, Switzerland.



Figure 7: A map showing an overview of known photovoltaic noise barriers in Europe. An interactive version of this map can be found through <http://goo.gl/fMCAa0>.

Table 1: An overview of existing and planned PVNBs in Europe, including key characteristics. Estimations are *italic*.

Country	City	Road/Railway	Rated power (kWp)	Tilt	Azimuth	Year	Location known	Material	Owner/Builder
Switzerland	Chur	A13	100	45°		1989		c-Si	TNC AG
Austria	Seewalchen	A1	40		160°	1992			Oberösterreichische Kraftwerke
Germany	Rellingen	A23	30		200°	1992			TST (DASA)
Switzerland	Gordola	Rail	103		200°	1992	X		TNC AG
Germany	Saarbrücken	A620	60			1995			Stadtwerken Saarbrücken
Switzerland	Giebenach	A2	100	45°		1995			TNC AG/ Kanton Basel
Netherlands	Utrecht	A27	55	50°	245°	1995	X	c-Si	RWS
Netherlands	Ouderkerk a/d Amstel	A9	220	50°	200°	1996	X	c-Si	Shell & ENW / EU Commision
Germany	Inning am Ammersee	A96	30			1997			TNC GmbH, Bayernwerk, BMFT
Switzerland	Zurich (Aubrugg)	E41	10	90°	80°	1997	X	c-Si	Uitbreiding door TNC in 2004
Switzerland	Zurich (Walliselen)	Rail	9.6	45°	200°	1998	X	c-Si	TNC
Switzerland	Zurich (Brütisellen)	A1	10	90°	140°	1999	X	a-Si	TNC
France	Fouquières-lès-Lens	A21	63	45°	170°	1999	X	c-Si	
Germany	Sausenheim	A6	100			1999			
Austria	Gleisdorf	A2	101			2001			
Switzerland	Safenwil	A1	80	45°	170°	2001	X	c-Si	IG Solar Safenwil
Germany	Emden	A31	53	90°	180°	2003	X	multi	Straßenbauamt Aurich/Energievers
Germany	Freising (Munich)	A92	600	45°	180°	2003	X	c-Si	
Germany	Vaterstetten	Rail	180		210°	2004		a-Si	Phoenix Solar
Germany	Freiburg	B31	365			2006			TNC, aluminium: Van Campen
Germany	Großbettlingen	313	28			2006			
Australia	Melbourne	40	24	90°	180°	2007	X	a-Si	
Germany	Töging am Inn	A94	1000	45°	210°	2007	X		
Switzerland	Melide (Lugano)	A2/rail	123	45°	220°	2007	X	c-Si	Suntechnics Fabrisolar AG
Switzerland	Münsingen	Rail	14	90°	80°	2008	X	c-Si	TNC
Italy	Marano d'Isera (Trento)	A22	730	*	140°	2009	X	c-Si	IrisLab/Autobrennero A22
Germany	Aschaffenburg	A3	2065	45°	150°	2009	X	c-Si	Evergreen solar GmbH
Italy	Oppeano (Verona)	SS434	833	45°	210°	2010	X	c-Si	
Germany	Bürstadt	B47	283	60°	150°	2010	X		
Germany	Biessenhofen (Bayern)		90	45°	180°	2010	X		Rau Lärmschutzsysteme
Germany	Wallersdorf	A92	1000	45°	150°	2010	X		Apfelböck Ingenieurbüro GmbH
Germany	Polling	Rail	1200	45°	210°	2012	X	c-Si	Exaphi GmbH
Germany	München	Rail/road	7.5	90°		2013			Kohlauer
Switzerland	Zumikon	Road	90.8	45°		2014		c-Si	TNC
Systemens in preparation									
Netherlands	Bathmen	A1	1000		180°				RWS
Netherlands	Tiel	A15	300						
Germany	Michendorf	A10	4500		180°				
UK	Swindon	A419							
UK	Buckinghamshire	M40							
Netherlands	Rotterdam	A20							

Detail studies

A number of PV noise barriers have been studied in more detail. From the list in table 1 we selected a number of PVNBs of special interest and contacted the companies involved in design, building and monitoring of these systems. Eventually, we visited two companies with an extensive portfolio in PVNB consultancy: TNC, based in Feldmeilen, Switzerland and IRIS Lab, based in Trento, Italy. More information on these companies can be found in the chapter *Companies*. The PVNBs that were visited in Switzerland and Italy will be described in more detail below. Furthermore, the PVNB situated on the A27 in Utrecht, the Netherlands, will be studied in more detail.

Switzerland

TNC has provided consultancy work for a number of PVNB in and outside Switzerland. Three PVNBs were visited and discussed with Thomas Nordmann and Thomas Vontobel from TNC.

Wallisellen

Building, operation and funding

The PVNB in Wallisellen near Zürich is built on a railway line, using a horizontal zigzag structure (see figure 13). Its orientation is south-west. Opposed to most PVNBs, the solar cells on the installations face away from the infrastructure. Many a times, cells facing towards the road or railway are built to utilize the open space of the road or railway, such that shading is limited. In this case, the cells face away from the infrastructure, in an urban environment. As a consequence, surrounding buildings cast shadows on the system, especially in winter.

The zigzag structure enables the solar cells on the barrier to have a 45° tilt angle while the barrier itself is placed vertical. Also, in the parts facing down, sound absorbing material is placed, such that the sound absorbing properties of the barrier are enhanced. The solar cells itself are laminated into panels of 3 x 8 cells, which are mounted on standard sound absorbing aluminium-plate cassettes that contain sound absorbing material, such as rock wool. The back sides (railway side) of the cassettes are perforated for better sound absorption. These cassettes are mounted on steel standers. These standers were specifically designed for this project and not a standard component for building noise barriers. It was built by ARGE Borra SA and Atlantis Energie AG.

The installation has a total length of 72 m, is 1.4 m high and has a rated PV power of 9.7 kWp.

The installation was built in 1998 as part of a competition for which (consortia) of companies were invited to submit a PVNB design. Six designs were eventually built, of which three in Switzerland: Aubrugg, Wallisellen and Brütisellen. The competition and the construction of the winning designs were financed by public bodies. A thorough report on the three Swiss installations within this project can be found in [14].

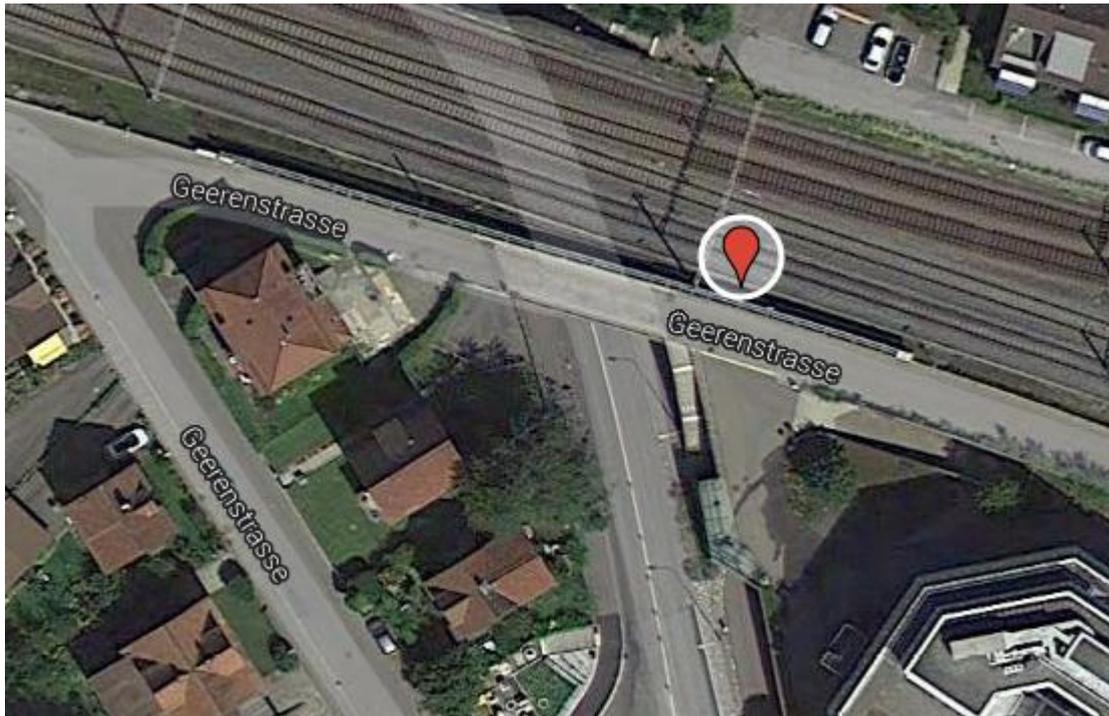


Figure 8: Wallisellen PVNB and its surroundings. Note that the PVNB is built on the south side of the infrastructure, facing away from the railroad. (Source: Google Streetview)

Monitoring, performance, pollution

The system is grid connected. The inverters are placed on the back of the barrier, on the railway side. Initially, the system was fitted with 45 inverters, all connected to three modules. In this way, the decrease in yield due to shadowing from nearby buildings can be mitigated, compared to a more traditional string inverter architecture. After several years, a number of inverters broke down. This was taken up as an opportunity to study the relative performance of different module level power management (MLPM) systems (power optimizers and micro-inverters) in comparison to string inverters in a real-life setup, including shadow. The system is fitted with three reference cells for monitoring of the local irradiation. Temperature was measured on three modules. Furthermore, the DC performance of the complete system was recorded. In 1999, 2000 and 2001, the installation produced 499 kWh/kWp, and had a performance ratio of 56%. This relatively low performance is addressed to a combination of factors: Shadow from trees and houses, self-shadowing of the bottom row of solar modules, high module temperature, a low inverter efficiency (86% average), and because the inverters consumed electricity at night from the grid. This last problem was solved by disconnecting the inverters from the grid at night using a timed switch. The adverse effect of the higher temperature of the modules was caused by the closed cassettes they were mounted on. The present performance is not known.

During our visit the system was being cleaned, because shortly before road works on the adjacent road were just finished. The cleaners were specifically instructed to use slow running water only (no high pressure cleaning). Furthermore, due to the 45° angle of the solar modules, normally the modules did not require any cleaning and natural rinsing by rain water was sufficient.

Vandalism and theft

Some of the cells were damaged over the years, either by vandalism or degradation due to the incorporation of moisture. Replacement of the panels proved difficult, because when the installation was built, solar cells based on 4-inch wafers were standard, but are now difficult to purchase. Therefore, a number of panels have been replaced by dark plates without solar cells. Because of the high degree of integration of the solar panels into the installation, no solar panels were stolen.

The inverters are fitted on the back of the installation, relatively easily accessible, with a simple metal sheet for rain protection, as can be seen in Figure 9. Also the cabling to the inverters was not hidden. Our host told us that in practice, this does not turn out to be a problem, mainly because the railway at the back of the system is not very welcoming to the public, although it is easy to access.



Figure 9: The Wallisellen PVNB, showing the panels, cleaning after roadworks and the backside of the barrier, where the inverters are mounted.

Aubrugg

Building, operation and funding

The PVNB in Aubrugg, near Zürich, was built by ASE GmbH within the same competition as the Wallisellen installation, organized by TNC. The competition and the construction of the winning designs was financed by public bodies. The bi-facial system was built late 1997 and is therefore the first PVNB using bifacial solar cells in use [14]. The solar modules used for this system are made by placing bifacial c-Si cells between two glass plates, which were laminated together, but more precise specifications for glass thickness and lamination materials are not known. These were retrofitted to a noise barrier originally built with corrugated fibre-cement plates ('Eternit'). The poles of this barrier could be reused, and the new bi-facial modules were placed in the existing structure. These modules were ready made by ASE GmbH and inserted into the existing pole structure using a crane, resulting in a 100 m long and 1.5 m high photovoltaic barrier. Cables for performance and measuring purposes are placed in cable trays on top and on the bottom of the barrier. The barrier is placed on a bridge near a road junction, where several roads run under and in parallel to the road on which the barrier is placed. Therefore this barrier is not only built for noise protection but also for safety reasons. Also for safety reasons, the modules are secured to the bridge using steel cables. This noise barrier only relies on reflection and does not absorb sound. In 2005 the plant was revised and expanded [15]: the availability of more efficient and larger bifacial cells was used to create a better performing bifacial PV noise barrier. Also new, more efficient inverters were installed.

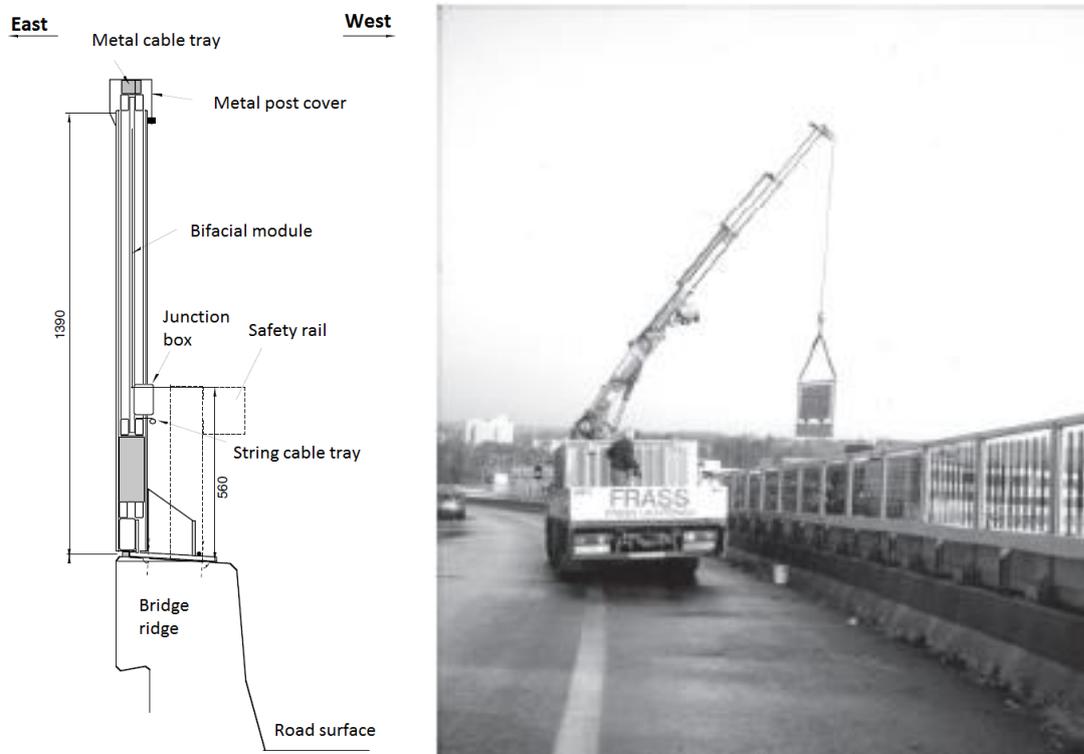


Figure 10: Intersection drawing of the Aubrugg PVNB (translated) and the PVNB during construction. Both from [14].

Monitoring, performance, pollution

The bridge runs north-south, which means that the active faces of the bifacial cells face east and west. The cells have a nominal power at STC of 14% on the front side and 11.3% on the back-side. Because of this unequal efficiency, the faces with the highest efficiency face eastwards, away from the road, because on this side there are no shading sources and this side is expected to get less polluted than the road-facing side, because of passing traffic. The complete system has a nominal power of 8.95 kWp on the east side and 7.25 kWp on the west side. The system was originally fitted with one Sputnik Engineering AG string inverter, which takes five strings.

TNC collects data from every string every 10 minutes. The current is measured using Hall-sensors, together with voltage and AC power generation. Also this PVNB is fitted with four reference cells: two facing east and two facing west in plane with the solar cells. Although pyranometers will give you a physically more correct measurement, TNC chooses to use reference cells because in this way the results are easier to compare between different locations, seasons and weather types because changes in the spectrum are automatically 'corrected' by the reference cell.

TNC defines the performance ratio (PR) of a bifacial system as

$$PR_{\text{bifacial}} = \frac{G_{\text{STC}}}{G_{\text{front}} + G_{\text{back}}} \frac{P_{\text{measured}}}{(P_{\text{STC,front}} + P_{\text{STC,back}})/2} \quad (1)$$

By using this definition, the PR is averaged over the performance of the two sides of the cells. As in-plane radiation, the radiation on both sides of the system is added. Furthermore, the temperature of the modules is measured.

The inverters and measurement equipment are located in a municipality-owned industrial dwelling, which is not closed to the public. The cabinets that hold the equipment can be opened by anyone.

Due to the bifaciality of the system, together with the east-west orientation, the system has a very different daily yield profile from a south-oriented system, on a typical day. Whereas a south oriented system has a maximum power output at midday, a bifacial system will have maximum yield during morning and afternoon hours. This will result in a 'double maximum' type of profile as illustrated in Figure 11. This figure shows the global irradiance, in-plane irradiance and the DC performance of the first generation Aubrugg system on a mainly clear winter day, a few months after the plant started operation. The energy values represent the normalized integrated energies under the profiles. The graph clearly shows that the cells do not show full bifacial behavior. Although irradiance in the morning and evening are similar, the east facing side generates more electricity than the west facing side. Using more symmetric (higher bifaciality factor) bifacial cells will therefore give a more symmetric yield profile. From 1998 to 2001, the system shows an average performance of 693 kWh/kWp, resulting in a PR of 58% [14]. This relatively low PR is attributed to a lower efficiency of the cells than expected and a relatively low irradiation in winter due to fog. Later studies reveal a rather low inverter efficiency. After the system was upgraded in 2005, the system performed better, leading to a rise in PR [15].

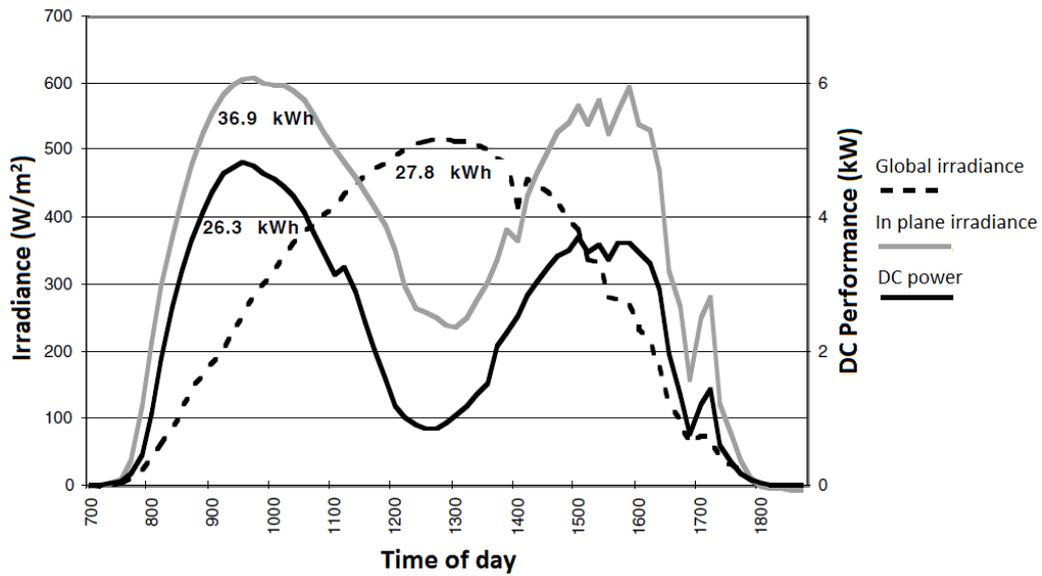


Figure 11: Irradiation and PV performance for the Aubrugg bifacial PVNB. From [14] (translated).

Vandalism and theft

No vandalism or theft was reported, which can be attributed to the fact that the installation is very difficult to reach, as it is located on a bridge that is only accessible through the highway. Although the inverters and measuring equipment are easily accessible, no vandalism or theft was reported.



Figure 12: Impression of the Aubrugg PVNB from the outside, from the road (from Google Street View) and the inverter housing.

Münsingen

Building, operation and funding

The Münsingen bifacial PVNB installation was built in 2008 along a railway line very close to the railway station of Münsingen, near Bern [16]. The building of the noise barrier specific parts was commissioned by Schweizerische Bundesbahnen SBB, while the solar installation was the responsibility of the municipality of Münsingen. This also means that the noise barrier is owned by the Swiss railway company, while the PV and the produced electricity are owned by the municipality of Münsingen. The overall design and the organization of the tendering processes were done by TNC. The plant is 115 m long and about 2 m high. The PV modules are specially designed and built for this installation and measure 2.5 or 2.1 m by 1 m. A part of the barrier is built on a bridge that crosses a road that runs under the tracks. There is a break in the barrier to allow for travelers to cross to the train platform.

Many of the parts of the installation are standard noise barrier parts. The building foundation and the plinth are concrete. The only difference between this foundation and a standard noise barrier foundation is that at strategic places, plastic tubing was put in the concrete when it was poured, to allow for cabling to run through, to the inverters and passing the break in the barrier. The rest of the concrete parts are identical to standard noise barrier elements. Also the steel poles are not PV-specific. These poles are H-type beams. The PV cassettes are inserted into the space in the H-beams and then bolted into place. The cabling between the modules runs through a cable tray at the top of the barrier, which is closed with a (loose) linear lid. The modules are interconnected using standard solar MC4 connectors. On the ends of the barrier the cables run through the empty space of an H-beam, closed with a lid, down to the tubes in the foundation. From there the cables are led underground to a closed weatherproof cabinet that holds the inverter and the monitoring equipment. The PV-cassettes were installed by a team of the building company that also built the noise barrier foundation, without specific knowledge on PV-installation.

The solar cells used are Hitachi c-Si bifacial cells and these are laminated between two 10 mm tempered glass plates with 2 mm of PVB in between. Every module contains 6x12 cells, divided into three substrings placed horizontally side by side, and three bypass diodes. These diodes are not placed in a junction box but mounted on top of the module. In this way they can be reached by opening the cable tray on top of the barrier and don't produce any shade. The transparent area of the modules is almost 50%. To avoid self-shadowing, the cells are placed around 15 cm away from the upper and side edges of the modules.

In the case of the Münsingen PVNB, a new strategy for financing was found. The main philosophy for this was to separate the costs for the noise barrier and the PV as much as possible. In this way, a clear view on the extra costs for a PVNB can be established, compared to a conventional noise barrier. In this strategy several procurements are issued, because TNC estimates that when all parts of the PVNB are in the same procurement, there will not be enough response from the market. Therefore it is split into several parts: The building foundation and noise barrier specific parts, bifacial cells, manufacturing of the modules, and the manufacturing of the cassettes were all carried out by different contractors. The cooperation between the different contractors was led by TNC. For the procurement of the noise-barrier, it was demanded that the costs for the noise barrier with and without glass element was specified. The 'saved costs' for not placing the glass elements then could

be transferred to fund the PV elements. In short, the railway company paid for the noise barrier as if it were a conventional noise barrier. The extra costs for the PV-functionality were carried by the municipality of Münsingen.

Monitoring, performance, pollution

The PVNB runs parallel to the railway line, resulting in an orientation of roughly 80° for the east facing side of the panels and 260° for the west facing side and the modules are placed vertical. The barrier is built up in an urban and industrial area. Some of the buildings cast shadows in the early morning or close to sunset. Also the constructions that hold the railway overhead wires cast shadows on the installation. The Hitachi cells in this barrier had a rated STC efficiency of 15% on the front side and 11% on the back side [16]. The total system has a total rated power of 7.25 kWp on the front side and 5.6 kWp on the back. The modules are connected to three string inverters with a total power of 4.7 kW, which is substantially lower than the nominal power of the system. Because of the east-west orientation of the bifacial system, it will never generate the STC power. A lower inverter power will give a better overall performance because generally inverters have a higher efficiency when they operate close to their maximum rated power. For this same reason it is beneficial to use cells that have a very similar performance for the front and the back side.

The installation is equipped with three reference cells: One facing east, one facing west and one facing south on a 45° inclination. From April 2011 to March 2012, the overall annual yield reached 832 kWh/kWp, calculated on an average for a year. The inverter efficiency is measured on a monthly average of slightly below 80% to slightly above 90%, but always below nominal efficiency. In comparison to the bifacial installation in Aubrugg, the Münsingen plant performs much better. A PR of 84% was reached during June 2011 for one of the three sections of the plant which has least issues with shading because it is located on a bridge [15].

The installation suffers from quite some shadowing from vegetation. During our visit, quite some large plants were growing right next to the barrier on the east side. Also the reference cells suffer from shadow from large leaves.

Vandalism and theft

For the Münsingen plant, no theft was reported. Stealing these modules does not seem to be very attractive: the modules are fixed within the noise barrier and are purpose-made for this project. They are quite heavy and the fact that they are custom made makes it difficult to reuse or resell them. Some of the panels were damaged, showing impact marks and cracks in the glass on the east side of the glass, as can be seen in figure 13. Our host told us that this is caused by firearms. There have also been occurrences of graffiti, but this is relatively easy to clean from the glass modules. According to our host, the Swiss railways check all their noise barriers for graffiti twice a year, and are cleaned if necessary.

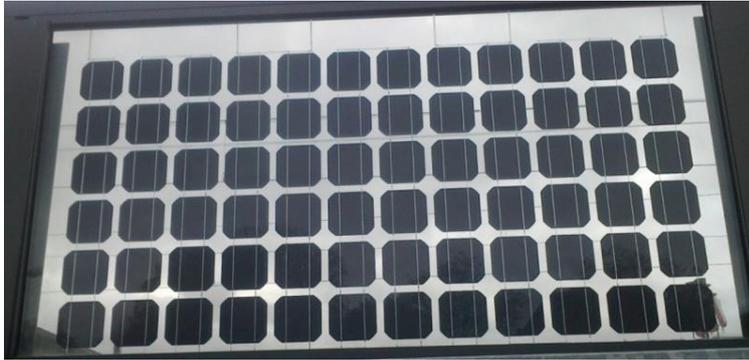


Figure 13: Photographs of the Münsingen bifacial PVNB, showing the barrier as a whole, module layout, vegetation near the barrier, the inverter cabinet, the effects of vandalism, the module interconnections in the top cable tray, hiding of the cables in an H-beam and shadowing of the reference cells.

Italy

During our visit to IRIS Lab, our hosts wanted to show us their 'evolution of PVNBs'. The order in which we visited the three installations is preserved in this report and in their view it symbolizes their progressing view in designing and building PVNBs. An important change is the change of the aim of the PVNB from a PV plant built near a road towards a fully functioning noise barrier with PV functionality.

Marano d'Isera

Building, operation and funding

The first PVNB we visited was the installation in Marano d'Isera, roughly 25 km south of Trento on the A22, which is a commercially exploited highway. The plant is built in 2009 and is owned by Autostrada del Brennero SpA, the company that operates the A22. The installation was designed by IRIS Lab and commissioned by and paid for by Autostrada del Brennero SpA. According to IRIS Lab, the company has 'a deal' with a neighboring village that uses the electricity. The main aim of this installation seems to be the production of solar electricity. Behind the barrier there are not very many buildings: mainly vineyards and a small village. Opposite the barrier is a small town. Since the barrier was built, inhabitants are exposed to more noise: the surface of the PVNB reflects a part of the noise, such that more sound reaches the town. There is no noise barrier on the side of the town. It has a total length of 1067 m and an average height of 5.6 m.

The PV modules fitted to this noise barrier are standard c-Si panels, mounted on a carrying structure which holds sound absorbing modules but only in the lower part of the barrier: perforated aluminium encasings holding a sound absorbing material such as rock wool. The back side of the PVNB can be reached through an emergency door, where we find an unpaved corridor large enough to allow maintenance vehicles to reach the installation.

Monitoring, performance, pollution

The installation contains 3944 PV modules. The orientation of the plant is roughly 140°, and around two thirds of the modules are tilted 60°, while the rest, the top part, is tilted 35°. According to the specifications it is rated 730 kWp and produces 690 MWh per year. The generated electricity is fed into the medium-voltage 20 kV grid. The design of the photovoltaic noise barrier is composed of 6 subfields. Each subfield has 657 photovoltaic panels, 19 6-kWp Aurora inverters and one 20kV substation [17]. Unfortunately, no performance data is available.

Vandalism and theft

On the top part of the installation the modules are interconnected by standard PV-cabling, which hangs loose from one panel to the next, but are difficult to reach because of the height. The inverters are mounted on the back of the plant, but not enclosed. Also the cables entering the inverters are exposed. The AC-cables from the inverters run through a cable tray on the bottom of the system towards a concrete electricity building, where it is connected to the grid.

On the back of the installation a number of cameras were mounted. No theft or vandalism on the inverters or cabling was reported, but a few of the cameras were broken or missing. We also spotted

one PV module of which the glass was shattered but still in place. Unclear is if this was caused by vandalism.

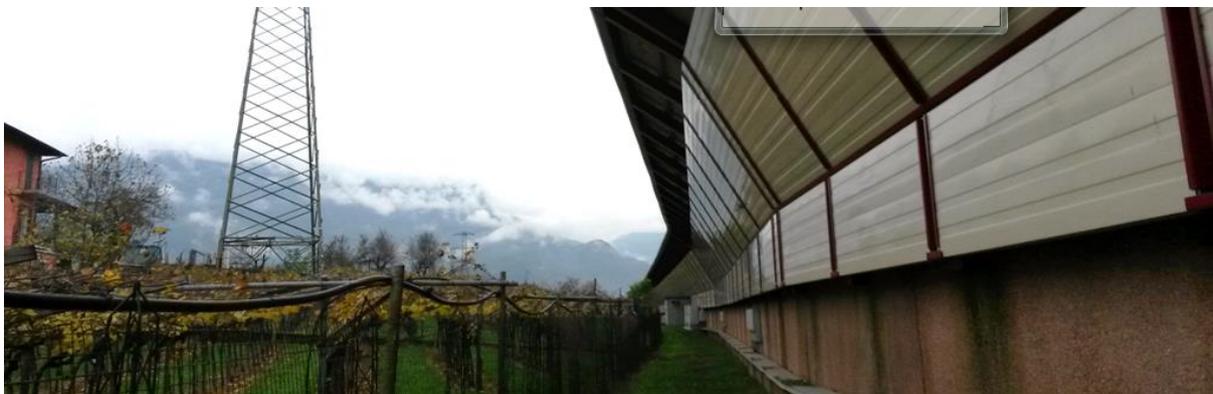


Figure 14: Marano d'Isera PV Noise Barrier, showing the barrier from the road side, from the back side, the top part of the back side, including loose hanging wires, (vandalized) safety camera's, damage to one of the modules, the concrete medium voltage connection enclosure and the emergency door embedded in the PVNB.

Oppeano

Unfortunately, we could only inspect the Oppeano PVNB from our car. There was no safe place to pull over.

Building, operation and funding

The PVNB in Oppeano, near Verona is the largest one we visited: 820 Wp. It is designed by IRIS lab and built by FAR Systems SpA. It was commissioned by ANAS, the Italian public road authority, which also operates and exploits the installation. The barrier is constructed as a test case for lowering the cost of building noise barriers by using the revenues generated from the PV installed on it [18].

The PVNB consists of two parts, both stretching almost 1 km long. The first part resembles the Marano d'Isera PVNB, showing two sections above each other, but the Oppeano barrier is lower. The bottom part is tilted 60°, while the top part is tilted 35°. The PV modules are standard monocrystalline silicon panels, mounted on a structure holding aluminium sound absorbing cassettes.

The second part is built according to the Solar Sound Panel (SSP) design by IRIS Lab. This design, a zigzag or shingled design, has tilted PV modules, around 45°, mounted on a vertical barrier, on the lowest part of the barrier. The barrier holds aluminium cassettes that have good sound absorbing properties. On the top part standard PV modules are mounted.



Figure 15: Oppeano PV Noise Barrier

Lodi

The last Italian installation we visited was built by Edil Valpar S.R.L. in Lodi, near Milan, situated on the SS9. It was commissioned by Exportclean S.R.L., which is a real estate company from Lodi. During our visit, the company was building a luxurious apartment complex near the road. By installing a noise barrier, the noise pollution at the complex diminishes, which raises the prices for the apartments. After the barrier was built, the ownership of the noise barrier was transferred to the public Italian road authority ANAS.

The barrier is based on the SSP design by IRIS Lab, and according to the company, this design resembles the third step in the evolution of PVNBs. With this shingled or zigzag design, tilted PV-panels can be mounted on a vertical sound wall. A technical drawing of the design is shown in figure 16.

A SSP-based noise barrier is made by inserting multiple SSP modules into vertical standing H-beams. By using the side facing down as sound absorbing area, these modules do not only reflect but also absorb sound. The shingles prevent the sound from deflecting over the barrier. The noise barrier modules are made of bent steel sheets and assembled using rivets. The parts that will eventually hold the PV-modules are strategically bent to allow for room for the junction boxes and for the cabling. The PV modules that fit the SSP barrier are specially designed for this purpose and therefore not standard off-the-shelf PV panels. The hollow SSP modules are filled with sound absorbing mineral wool for sound absorption. Where possible, the steel sheets are perforated to allow the sound to reach the absorbing material.

The barrier standers hold 8 SSP building blocks stacked on top of each other, resulting in a total height of a little more than 5 meters, including concrete plinth. To the untrained observer, the noise barrier function is remarkable: The sound of a passing truck almost disappears when it goes behind the barrier. According to the company, the noise barrier function of this design is outstanding.

At present no PV-modules are installed. The spaces that are design to hold the specially designed PV modules are now filled with PMMA plates. It is intended that in the near future, these modules will be placed and that the generated electricity is used by the new apartments. By using sustainable energy, the energy rating of the houses increases, increasing their market value.

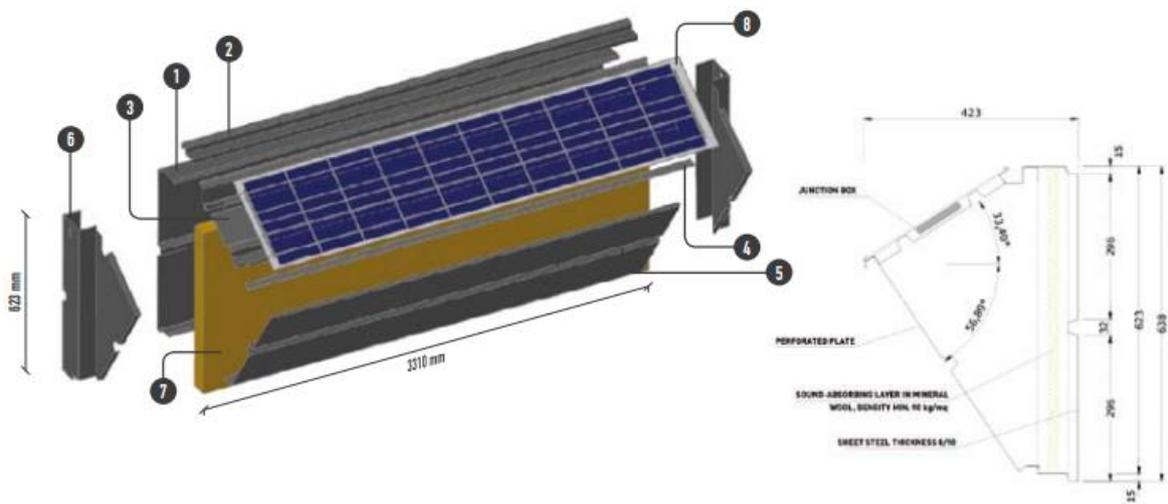


Figure 16: Lodi (PV) Noise Barrier, showing the complete barrier seen from the apartment complex, the side from the road, the PMMA plates that will be replaced by PV modules and an exploded view of the SSP design (from [19]).

The Netherlands

Utrecht

In the spring of 1995 a photovoltaic system consisting of 1116 modules, with a total nominal power of 48.5 kWp was installed on an existing noise barrier on the A27 highway near De Bilt. The modules were placed on top of the barrier with a tilt angle of 50°, while the orientation of the system was 236° to 254° (south-west), showing a shallow bend. The total length of the system was 590 m. The system was arranged into 6 substrings each consisting of 10 to 12 arrays, each containing 18 modules, which were all fed into one large inverter (SMA), which was placed in a purpose-built concrete housing, which also houses the monitoring equipment. Metal plates were attached to the back of the modules.

Building, operation and funding

The PVNB was commissioned by the 'Ministerie van Verkeer en Waterstaat', designed by Holland Scherm, Aveco and Intersec and built by Holland Scherm and R&S. The total cost of the PV-project was € 1.106.094, of which € 544.536 was for the PV-system. Novem (now RVO) contributed € 299.495. The REMU (Utrecht energy company, now Eneco) contributed € 64.610. Both the PV and the Noise barrier were owned by the Dutch state, but the PV was operated by REMU [20].

Monitoring, performance, pollution

For cabling, thick 16 mm² copper cables were used to transport the energy from the substrings to the inverter. For the substring furthest away, 445 m, this resulted in 0.47 Ω cable resistance. The system was monitored by recording the DC yield of every subarray, the temperature of two modules, two reference cells and the total power fed into the grid. Global irradiance data was obtained from Utrecht University, about 1 km away. Compared to an 'ideal' orientation and tilt, the irradiation in the plane of the A27 PVNB was 18% less.

Betcke et al. [21] have analyzed the monitoring data from this system from October 1995 to September 1997. This analysis shows a performance ratio of 72% in the first year and 70% in the second year. A road sign that crosses the road casts a shadow on one of the subarrays, resulting in a reduction in performance, but was not studied in detail. It was estimated that the metal sheets on the backside of the modules cause them to heat up more than free-standing modules. This extra heating led to a 1 to 2% lower yield of the modules.

To analyze the influence of pollution due to traffic, ECN measured the performance of the reference cells before and after cleaning after a year of operation along the A27. Due to the pollution, the performance of the reference cells was 5.5% lower.

Betcke et al. [21] state that after September 1997 the system was still monitored but the data was not analyzed. REMU gathered monthly production data to assess the overall performance and performed visual inspections. At present, the system is no longer operational and no more data is collected or analyzed.

Vandalism and theft

While the PV was installed, one module was stolen. Within two weeks after the monitoring had started, the two reference cells were stolen, along with a module [21]. In the first two years graffiti

was found only on the concrete parts of the installation, but not on the PV. Visual inspection from the highway side shows several solar modules missing. At present, the system is no longer connected to the grid. Many panels were stolen and replaced with dummy panels. Even at present, the panels get stolen. The installation is easy to access from the back side. By using 3 m ladder and standard tools, the metal sheet on the back can be removed and the panels can be taken. Also, the panels have a very convenient size for carrying and are therefore easy to steal.



Figure 17: Utrecht A27 photovoltaic noise barrier, showing the exposed cabling on the back side of the barrier, the back side of the barrier showing the steel plate encasing, the grid connection housing and the installation as seen from the road, with several modules missing.

Observations and lessons learned

In this chapter, we will take the PVNB overview and the detail studies of the PVNBs of the preceding chapters as input for lessons for future design and application of PVNBs. The lessons are grouped together by topic.

Design choices

Noise barriers

Noise barriers rely on two principles: sound reflection and sound absorption. Most PV enclosures are made from glass, which doesn't absorb sound but does reflect it, but also transmits sound. To ensure a good noise barrier, guidelines from the CROW [5] require the barrier to have a minimum mass density of 40 kg/m^2 . For glass panels, this means that the total glass thickness needs to be at least 16 mm. Standard PV modules do not fulfill this requirement. For this reason, if standard modules are used, an additional sound reflecting or absorbing material is needed. The PVNBs in Marano d'Isera and Oppeano (partly) rely on this design. In the case of the Lodi, installation, the side of the barrier facing the sound source is partly covered by glass PV-modules, and a part of this area consists of sound absorbing material. IRIS Lab, which designed the Lodi installation, claims this to be the best noise barrier strategy in combination with PV. When bifacial cells in a glass-glass sandwich are used, no extra (opaque) material can be added. Therefore the PV modules need to be sufficiently heavy.

In the Netherlands, reflecting noise barriers are mostly tilted away from the road, because then the reflected sound is pointed upwards. In the case of noise barriers along railways, most noise barriers tilt towards the railway, because in this case the sound is reflected towards the rail ballast, which is a very good sound absorber.

In the case of Marano d'Isera, Italy, the erection of the PVNB led to more noise pressure in a village opposite the noise barrier, because of the reflecting sound from the barrier was added to the initial sound pressure.

Solar energy

Most PVNBs rely on c-Si as a photoactive material, although a few can be found that use different types, such as the PVNBs in Vaterstetten, Germany, which uses a-Si cells or Emden, Germany, which uses a multi-junction thin film silicon cell design. In the case of Brüttsellen, Switzerland, a-Si panels were glued to thicker glass plates that were integrated into the noise barrier. Most large installations use standard PV modules under a 30° to 50° inclination angle. The mounting structure of these installations is under the installation. Most probably, the main aim of these installations is to harvest solar energy, while the noise barrier function is of minor importance.

Monofacial BIPV installations are usually built to face south for optimal solar energy harvesting. Therefore most PVNBs have an orientation ranging from 140° to 220° , 180° being south. For bifacial installations, the calculations show that the best yield is obtained for a north-south orientation, in combination with vertical module placement.

Self-shading

Self-shading is the effect that part of the structure (horizontal and vertical supports, frames etc.) create shading on the PV during parts of the day. For bifacial systems that run north-south, self-shading can be a significant problem, especially for high barriers, as they will generally need larger supports, that can cast large shadows around noon, when the sun aligns with the barrier. The known bifacial PVNBs are all relatively low and built using H-type beams as standers, which are relatively narrow. The PV modules are inserted into the H-beams. For higher PVNBs this might not be possible because of the needed strength, but it is very important to minimize support dimensions to minimize self-shading. Also to avoid self-shading, the bifacial cells in the PVNBs in Aubrugg and Münsingen are placed away from the top and side edges of the module as these parts of the modules are most effected by self-shadowing.

Cabling

The challenges for a good design of the cabling are to minimize cable losses, optimize safety and robustness, and minimize opportunities for vandalism and theft. For PVNB built from standard PV modules that we have investigated, the cabling is mostly standard cabling. In the case of the Marano d'Isera, we saw cables hanging freely from one panel to the next, as can be seen in figure 14. Because these were very difficult to reach, this does not seem to give problems. In the case of the Lodi PVNB, the cables run under the panels in specially design cable canals that are pre-formed in the steel sheets under the panels, as can be seen in figure 16. In the case of Aubrugg and Münsingen, the cables run through cable canals on top of the barrier. This is also where the modules were connected to strings, using standard solar component. In Marano d'Isera, a central cable tray mounted along the complete barrier carried the AC cables from the inverters to the grid connection. As most glass or plastic noise barrier modules have some sort of steel or aluminium frame, solutions for hiding the cables can be found.

In the case of the Utrecht PVNB, the module interconnection cables were put behind the panels in a sheet metal enclosure. In special cases, where the barrier crosses to a bridge, the cables are exposed. This has led to cables being stolen or vandalized. For this reason, it is very important that easy to reach exposed cabling is avoided.

Because noise barriers can be long stretched, cabling can be a major cost. In some cases it can be beneficial to use aluminium instead of copper wiring, because it is less expensive. A downside of this choice could be that these cables do not bend easily and that these are thicker.

Safety aspects

Glass

For noise barrier applications, also without PV, tempered glass is used. When it breaks, this type of glass does not break into large shards that could be dangerous, but crumbles into small pieces. It is also common practice to use glass-glass sandwiches, bonded together with a flexible plastic in the middle, such as PVB, also used for laminating bifacial cells.

Glare

PV modules do not produce more glare than normal glass noise barriers. Also, the reflection can never be brighter than the source. Nevertheless, glare can be regarded as a problem by decision makers. When the first PVNB was built in 1989 in Chur, Switzerland, road authorities were

concerned that glare would cause safety issues and that this might lead to the need to close the roads for certain sun positions. TNC, responsible for the project, responded by stating that this would mean that the road needed to be closed at sunrise and sunset, because the road runs east-west. After that, the road authorities no longer objected.

Operational aspect

Ownership and responsibilities

Because in an integrated PVNB the noise barrier and the PV cannot be separated, it is not always clear who owns the PVNB, or part or aspect of it, and which party is responsible for damaged parts, maintenance or repairs. We have come across different constructions.

- In some cases, the complete PVNB is owned by the same party. The Utrecht PVNB was completely owned by RWS, but REMU owned the generated electricity. A number of modules were replaced after they were stolen, but it is not clear who paid for this.

In case of de Marano d'Isera PVNB, the whole system is paid for and owned by A22 Autostrada del Brennero, a private road company. It is clear that this company is also responsible for all aspects of the PVNB.

- In Münsingen, the cost of the PVNB was split into costs for the noise barrier and the added cost for the PV. To be able to distinguish between these costs, in the tender it was specifically demanded to have a specification for a noise barrier with glass (non-PV) modules and without the glass, so that the added cost for PV could be determined. The Swiss railway company owns the noise barrier, but the Münsingen municipality owns the PV-functionality, and the generated electricity. Equal to other noise barriers owned by the Swiss railways, the PVNB is checked every six months for graffiti or damage. The Münsingen installation suffers from vandalism which affects the PV performance, but not the noise barrier function. At present no efforts are made for repairs, and it is unclear which party is responsible. Also the installation suffers from quite some shadowing from vegetation. Although the municipality would directly benefit from removing these plants (because more electricity would be generated), no efforts seemed to be made to do this.
- The Lodi SS9 (PV)NB was paid for by a building company that was also building luxury apartments near this road. By reducing the sound received from the road by building the noise barrier, the apartments could be sold for a higher price. After the barrier was built, the ownership was transferred to ANAS, the Italian road authority. The noise barrier is prepared for placing PV-panels, but these were not placed yet during our visit. The goal was to add the PV panels, which then would be owned by the owner of the apartment complex. By connecting the PV to the apartment complex, these apartments obtain a higher energy rating, which increases their price.

Pollution and cleaning

Only for the Utrecht PVNB we have a quantitative measurement for a decrease in power generation due to pollution: Due to pollution, reference cells performed 5.5% less after one year of operation alongside the A27. In other cases we have seen substantial pollution, but no data on performance

changes. In Lodi, the dummy panels had a much polluted appearance. In Wallisellen, the installation was being cleaned during our visit using low pressure water.

Vandalism and theft

Vandalism, graffiti and theft can be major problems. We have seen many occurrences. In Utrecht, theft of the modules was a large problem, although we do not have exact number, quite a lot of modules were stolen. This was made easy by using small and light modules and by the fact that the back side of the installation is easy to reach, but relatively quiet. Using standard tools and a ladder, it was relatively easy to take the panels without being seen. Also exposed cables were stolen and vandalized.

For the large systems in Italy: Oppeano and Marano d'Isera, no theft was reported, although the modules were standard PV modules. The plant in Marano d'Isera has cameras (or dummies?) placed on the back side of the barrier. Some of these were missing or damaged. Unclear is whether this was caused by vandalism or theft. Also we identified one module of which the glass was shattered but still in place.

The plant in Münsingen showed clear signs of vandalism: large holes in one side of the installation, caused by firearms. No theft was reported. This was also the case of the Aubrugg system. For both these systems holds that the modules are very heavy and customized equipment and therefore difficult to take, reuse and resell. Also they are fully integrated into to noise barrier, so difficult to take away.

Graffiti is a widely spread problem for noise barriers. This is also the case for PVNB. Graffiti is relatively easily removed from glass, but also temporary graffiti can negatively influence the electricity production, especially when the modules are placed in series electrically. In the case of the PVNB in Brütisellen, near Zürich, heavy graffiti pollution was one of the reasons to 'give up' and disconnect the system.

In general, standard modules are stolen more often than customized modules. Furthermore, exposed wires can easily get damaged or thieved. The best protection from theft seems to be using purpose made, heavy, fully integrated solar modules.

Electricity production

Inverters

For different systems, different types of inverters have been used. The first PVNB in Chur used one central inverter for the complete 100 kWp system. The system in Ouderkerk aan de Amstel was fitted with micro inverters, one inverter per module. Most installations use standard string inverters. In the case of the Wallisellen installation, failure of some of the inverters was taken up as an opportunity to set up a module level power management (MLPM) setup. In this setup different inverter systems are tested side by side: string inverters, power optimizers and micro inverters.

In the case of bifacial systems, the dimensioning of the inverters requires special attention. Because of the different generation profile of such a system, the rated nominal power for such a system will not likely be reached. As most inverters work more efficient close to their maximum rated power,

overdimensioning of the inverter will lead to a lower production. Therefore a thorough analysis of the expected system power output curve is advisable. According to TNC, also the maximum power point tracking system for a bifacial system needs special attention, because inverters are not designed for the behavior of such systems. Especially the behavior around noon can cause problems.

In a number of cases, the inverters were not placed in an enclosure, but simply placed on the back of the installation: Wallisellen, Marano d'Isera. In other cases (Utrecht, Münsingen), the equipment was placed in strong weatherproof cabinets to avoid theft and vandalism and for safety reasons. In the cases in which no enclosure was used, no theft or vandalism was reported on the inverters.

Monitoring

To know whether your system performs well, adequate monitoring is necessary. For the installations that we studied in detail, a few different approaches were found. The three TNC installations that we visited were all monitored. These systems are equipped with a number of reference cells for irradiation measurements. For all systems the total DC and AC yield is measured, which gives information on the inverter performance, based on the AC/DC production ratio. Furthermore, for a few of the modules, the temperature was measured. In the case of the Utrecht PVNB, the total DC yield, total AC yield, the temperature for a small number of modules, and in-plane irradiation were measured. These were compared to the weather measurement station nearby at the Utrecht University. For the large-scale PVNB we visited in Italy, we do not have performance or monitoring data. In contrast to the other installations we studied in detail, these are not experimental or pilot projects and no performance data is publicly available.

Electricity production performance

Figures of merit for the performance of a PV system are usually the amount of electricity generated per kWp installed capacity (kWh/kWp) per year or the performance ratio. In the case of the Wallisellen, Aubrugg, Münsingen, and Utrecht plants, we have this information available. In Utrecht an analysis was made for the period from October 1995 to September 1997, starting half a year after system startup, showing a PR of 72% in the first year and 70% in the second year. The installation in Wallisellen produced 499 kWh/kWp in the first three years, on average, which leads to a performance ratio of 56%. This relatively low PR was attributed to several causes. In Aubrugg, the bifacial system generated 693 kWh/kWp, resulting in a PR of 58% in the first three years. The lessons learned from the Aubrugg installation were used to improve the Münsingen installation. In the first year, this installation produced 832 kWh/kWp. The main losses were attributed to a low inverter efficiency.

Bifacial cell performance

A bifacial PVNB that is placed on road or railway running north-south will have cells facing both east and west, resulting in a very different yield profile from a south-oriented system on a typical day. On a clear day, a south oriented system has a maximum in electricity output at midday, whereas a bifacial system produces very little around noon, but will show a maximum in production in the morning and evening hours. This will result in a 'double maximum' type of profile as illustrated in Figure 11. This figure shows the global irradiance, in-plane irradiance and the DC performance of the first generation Aubrugg system on a mainly clear winter day. Combining south-oriented PV-plants with bi-facial systems can result in a rather flat generation profile during the day.

For monofacial cells, the performance ratio is defined as

$$PR_{\text{monofacial}} = \frac{G_{\text{STC}}}{G_{\text{measured}}} \frac{P_{\text{measured}}}{P_{\text{STC}}} \quad (2)$$

in which G_{STC} = is the irradiance under standard test conditions, defined as 1000 W/m^2 at a specified spectrum, G_{measured} is the measured irradiance in the plane of the solar cell, P_{measured} is the measured electrical output of the system and P_{STC} is the tested performance of the cell under standard test conditions (G_{STC} and a cell temperature of 25°C).

This definition cannot be used for bifacial cells, as the P_{STC} is only defined under one-sided illumination. A solution could be to characterize both sides of the bifacial cell as if it were two separate cells. Now the PR can be defined by

$$PR_{\text{bifacial}} = \frac{G_{\text{STC}}}{G_{\text{front}} + G_{\text{back}}} \frac{P_{\text{measured}}}{(P_{\text{STC,front}} + P_{\text{STC,back}})/2} \quad (3)$$

This definition divides the generated solar electricity (from both sides of the cell, as it is the same system) over the added STC performance from both sides. As irradiation, the irradiation on both sides of the cell is measured. This is the definition that TNC uses when reporting the performance of their systems. An alternative is to scale the measured electrical output to the STC performance of the best performing side of the cell, resulting in the following expression for PR_{bifacial}

$$PR_{\text{bifacial}} = \frac{G_{\text{STC}}}{G_{\text{front}} + G_{\text{back}}} \frac{P_{\text{measured}}}{P_{\text{STC,front}}} \quad (4)$$

in which 'front' is the face with the highest conversion efficiency. By using this definition, the PR is directly influenced by the 'bifaciality' of the cells, which is the ratio of the front and back STC efficiency of the cells, because it is based on the irradiation on both sides, but scaled for the STC performance of the best side. Therefore asymmetric cells will have a lower PR.

To effectively measure the irradiation on both sides of the system, pyranometers (or reference cells) need to be installed in-plane on both sides of the system.

Traffic and dynamic shading

We do not have data on the effect of dynamic shading on the performance of PVNBs. These shadows can be avoided by a high placement of the PV modules. Generally speaking, north-south running PVNB are prone to suffer more from shadows from traffic than installations facing south, because these systems generate most of the electricity in the morning and evening hours, when the sun has a low position. When the PV installation faces away from the road or railway, there is no shading from traffic.

Organisational aspects

Procurement strategy

A large risk for a public tendering process is that there will be very few proposals or not sufficient proposals of good quality. According to TNC, this the largest risk. According to their view, a procurement for a complete PVNB system should be split into several smaller ones: One for the

noise barrier foundations and standers, one for the PV modules, and one for fabricating noise barrier modules (framed PV-modules). Ideally, a specification is made for a noise barrier with and without sound modules, so that the budget difference for these parts can be used for the procurement of the PV-related parts. Also, in this way the added cost for PV can be calculated, compared to a noise barrier without PV.

In the view of IRIS Lab, the tendering procedure should be as open as you can afford. By allowing as much freedom as possible for design choices for the participating companies, you will get the best proposals. Therefore you should not demand certain properties for the PVNB, but specify ranges and define a system for rating the proposals. In their view, freedom for engineers to make use of their creativity will lead to the best proposals. It is very important that the tender is correct from the start. If the requirements in the tender change during the process, possible contenders will lose interest.

Both companies stress that it is essential to start early with informing and 'warming up' potential contenders. This will certainly lead to a higher number of proposals. Because most building companies are not familiar with PVNB, participating in a tender will need a lot of design work. Therefore it should be clear that the Solar Highways project is a pilot project. If executed successfully, it will open a new market, which of course is encouraging for participation.

Both companies show interest for performing consultancy work for setting up the procurement strategy.

Stakeholder acceptance

The acceptance of two PVNB stakeholder (groups) is essential: road authorities, in the case of the Solar Highways project this is Rijkswaterstaat, and civilians living nearby. Very generally speaking, road authorities have no interest in becoming electricity producers. Only a lower cost for the noise barrier or a better stakeholder acceptance is of added value. Therefore, other parties will be asked to operate the PVNB.

Nearby living civilians will be more involved in a project such as Solar Highways, if the produced electricity is used for a purpose that 'speaks' to the public, such as charging electric cars or street lamps for a public park.

Other

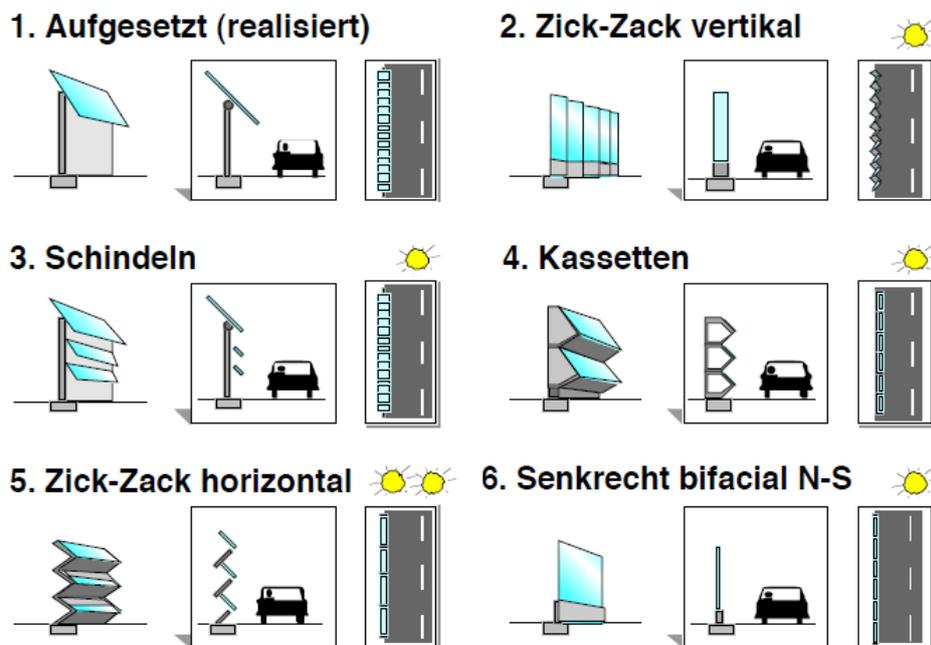
Constructing companies and PV installation companies think in different time scales. For a large construction company, a project horizon of 10 years is not very awkward, but in the PV business, this is a very long time. Especially in the last few years, PV prices have dropped so quickly that a PV installer cannot afford to have a long time interval between buying and installing PV.

Companies

There are a number of companies that have developed, sell or have experience on consultancy work for photovoltaic noise barriers. In this chapter you will find an overview of companies that are presently active in this field, including a short description.

TNC

TNC (Thomas Nordmann Consultancy) is a consultancy company that focusses on energy saving technology, with its headquarters in Feldmeilen, Switzerland. It also has branches in Zürich, Switzerland and Freiburg, Germany. The company has a vast experience in PV projects, including the first PVNB installation in Chur, Switzerland in 1989. Other projects focus on complex PV concepts such as their design for floating PV tracker systems for hydro-power lakes. In 1993 TNC opened a competition for companies or consortia of companies to design a PVNB. More than 30 designs were submitted and 6 were chosen to be tested in an outside real-life test setup, with a rated PV capacity of 10 kWp. Three installations were built in Switzerland in different locations in and around Zürich and also three installations were built in Germany, of which in total 5 systems are still running. Figure 18 shows the six different prototype designs. More information can be found on their website [22].



Grafik © 2002 TNC Consulting AG, Erlenbach

Figure 18: TNC: Six designs for PVNBs (source: [14])

IRIS Lab

IRIS Lab is a company active in research and development focused on the study and realization of sustainable transport infrastructure. Examples of their work include wooden guard rails and scales for weighing trucks while in motion. The company works on design, development, and performs consultancy work. The company was founded in 2007 and has 10 employees. It is located just south of Trento, Italy. IRIS Lab is responsible for the design of the PVNBs in Marano d'Isere, Oppeano and Lodi. The PVNBs in Oppeano and Lodi are based on the Solar Sound Panel (SSP) design as illustrated in figure 16. In 2014, IRIS Lab won the section "Moscow is seeking cost-effective solutions to cut

excessive traffic noise” in the Citymart competition for their SSP design for PVNB. More information can be found on their website [23].

Heijmans, Van Campen and the SONOB project

Van Campen Industries is a company that designs, develops, and constructs aluminium installations, with a large part of their work focusing on noise barriers. Heijmans is a very large construction company that builds houses, commercial buildings but also executes infrastructural projects.

Heijmans and van Campen, together with SEAC, Dutch Space, ECN and the TU/e collaborate on the Solar Noise Barrier (SONOB) project. In this project we design, build and monitor a bifacial PVNB as a prototype that uses the luminescent solar concentrator (LSC) concept. A prototype will be tested in a ‘Living Lab’ environment in Den Bosch. The PVNB will be tested for photovoltaic performance and stakeholder perception. On top of that, a techno-financial analysis will be made for a large-scale roll out of such a technique. More information can be found on the company websites [24], [25].

Other companies

There are a number of companies that have experience in designing or building PVNB including R. Kohlhauer GmbH [26], Rau Lärmschutzwände GmbH [27], Solar Sky GmbH [28], Exaphi GmbH [29] and Solar World Wide Solutions [30].

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