Highway Renewable Energy:
Photovoltaic Noise Barriers

Photo source: TNC Consulting

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Highway photovoltaic noise barriers (PVNBs) represent the combination of noise barrier systems and photovoltaic systems in order to mitigate traffic noise while simultaneously producing renewable energy. First deployed in Switzerland in 1989, PVNBs are now found in several countries where transportation agencies have sought ways to find multiple uses of their infrastructure. The PVNB experience documented in literature and supplemented through a series of interviews provides evidence suggesting that noise barriers can be designed to produce renewable energy without compromising their abilities to reduce noise, and do so safely. The business case for a PVNB often hinges on the availability of subsidies or other incentives that promote the renewable energy market. Although the first highway PVNB is yet to be constructed domestically, at least two State Departments of Transportation are currently working with partners to pursue PVNB pilots in the United States. Given the substantial extent of noise barriers in the country, the potential for solar energy production on American noise barriers is likely at least 400 Gigawatt hours annually, roughly equivalent to the annual electricity use of 37,000 homes, and perhaps much higher.

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- Solar Energy Application Center, the Netherlands
- The Ray C. Anderson Foundation
- TNC Consulting
- VicRoads, Victoria, Australia

Appendix A provides a full list.

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ACRONYMS AND ABBREVIATIONS

BASt	Bundesanstalt für Straßenwesen (Federal Highway Research Institute)
CFR	Code of Federal Regulation
CoRTN	Calculation of Road Traffic Noise
dB	Decibel
dBA	A-weighted Decibels
ECN	Energy Research Centre of the Netherlands
EEG	Erneuerbare-Energien-Gesetz (Renewable Energy Sources Act)
FEDRO	Swiss Federal Roads Office
FHWA	Federal Highway Administration
FIT	Feed-in Tariff
Foundation	The Ray C. Anderson Foundation
GDOT	Georgia Department of Transportation
GWh	Gigawatt hour
I-85	Interstate 85
ITC	Investment Tax Credit
kWh	kilowatt-hour
kW_p	Kilowatt-peak
LSC	Luminescent Solar Concentrator
MassDOT	Massachusetts Department of Transportation
MW	Megawatt
MWp	Megawatt-peak
PV	Photovoltaic
PVNB	Photovoltaic Noise Barrier
RFP	Request for Proposals
ROW	Right-of-way
RWS	Rijkswaterstaat (Ministry of Infrastructure and the Environment)
SDOT	State Department of Transportation
SEAC	Solar Energy Application Centre
SMART	Solar Massachusetts Renewable Target
The Ray	Section of Interstate 85 in Georgia
TNM	Traffic Noise Model
U.K.	United Kingdom
VicRoads	Roads Corporation of Australia

EXECUTIVE SUMMARY

Photovoltaic noise barriers (PVNBs) represent the combination of noise barrier systems and photovoltaic (PV) systems. Noise barriers are physical obstructions designed to lower noise levels between noise sources and sensitive receptors, such as hospitals, schools, and residential areas. Photovoltaic systems use solar cells to convert light energy directly into electricity. First deployed in Switzerland in 1989, PVNBs are now found in several countries where transportation agencies have sought to abate noise and produce renewable energy simultaneously.

The literature on PVNBs, most of which is several years old, generally agrees that there is great potential to use both existing and planned new noise barriers to produce solar power. Professionals from select transportation agencies who provided information to the project team echoed these views, especially when the integration of solar technologies is part of a holistic approach to design and construction. According to information collected, noise barriers can be designed to produce power without compromising their abilities to safely reduce noise, and in some cases may improve their performance. The business case for a PVNB is often contingent on the difference between marginal costs of constructing the infrastructure with and without energy generating capacity. Transportation agencies in countries with attractive subsidies or other incentives available to promote the renewable energy market will likely find PVNB implementation more feasible and economically self-sustaining than agencies in countries where the regulatory environment is not as favorable to renewable energy developers.

Although the first highway PVNB is yet to be constructed in the United States, at least two State Departments of Transportation are currently working with partners to pursue PVNB pilots on highways in the United States. Given the substantial extent of noise barriers in the U.S. (nearly 3,000 linear miles), coarse estimates done as a part of this study suggest that the potential for solar energy production on American noise barriers is at least 400 Gigawatt hours (GWh) annually, roughly equivalent to the annual electricity use of 37,000 homes, and perhaps much higher.

1. INTRODUCTION

As defined by the Federal Highway Administration (FHWA), noise is any unwanted sound.[1] Although it can originate from many different sources, highway traffic noise is among the most pervasive and difficult to avoid.[2] In the U.S., highway traffic noise has been a concern among communities and all levels of government since the early 1960s when the first noise barrier was built in Washington State. Now, 48 states and the Commonwealth of Puerto Rico have constructed approximately 3,000 linear miles of highway traffic noise barriers.[3]

A highway noise barrier is a physical obstruction constructed between the highway noise source and the noise sensitive receptor(s) that attenuates the noise level near the receptor, as measured in decibels (dB). Noise barriers include stand-alone walls, berms, and combination berm/wall systems and are constructed from diverse materials, such as earth, wood, concrete, and metal, among others. They reduce noise by reflecting it back across the highway or forcing it to take a longer path over and around the barrier. Although they do not block all noise completely, noise barriers typically reduce overall noise levels by 5 to 10 dB, effectively cutting the loudness of traffic noise by up to one half.[4]

In most cases, noise barrier construction involves the multidisciplinary input of transportation planners, architects, landscape architects, and roadway, acoustical, and structural engineers. A general goal among noise barrier teams is to design cost-effective noise barriers that fit with the surroundings, while performing the intended noise abatement functions. In recent years, this goal has evolved to include finding innovative ways to merge noise abatement with sustainability concepts, such as stormwater retention,[5] air pollution reduction,[6] and electricity generation.

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[1] FHWA Noise Barrier Design Handbook. www.fhwa.dot.gov/environment/noise/noise_barriers/design_construction/design/design02.cfm

[2] Sullivan, J. Walls of Fame. Public Roads. May/June 2003. www.fhwa.dot.gov/publications/publicroads/03may/03.cfm

[3] FHWA Noise Barrier Inventory: www.fhwa.dot.gov/environment/noise/noise_barriers/inventory/

[4] *Ibid*.

[5] Personal conversation with Rijkswaterstaat staff during FHWA, Washington State DOT, and RWS peer exchange. April 10, 2017.

[6] Kotzen, B. and English, C. (2009).

1.1 Photovoltaic Noise Barriers: The Concept

The photovoltaic noise barrier (PVNB), or solar noise barrier, represents the combination of noise barrier systems with photovoltaic (PV) systems that use solar cells to convert light energy directly into electricity. PVNBs can either entail the retrofitting of existing noise barriers with PV modules (i.e., solar panels) or the integration of the PV modules into the design of new noise barriers. In both cases, the noise barrier serves as a substructure for PV modules. Top-mounted, retrofit designs that provide additional area to an existing noise barrier structure are currently the most common PVNB approach. Figure 1 shows some possible configurations of PVNB structures.

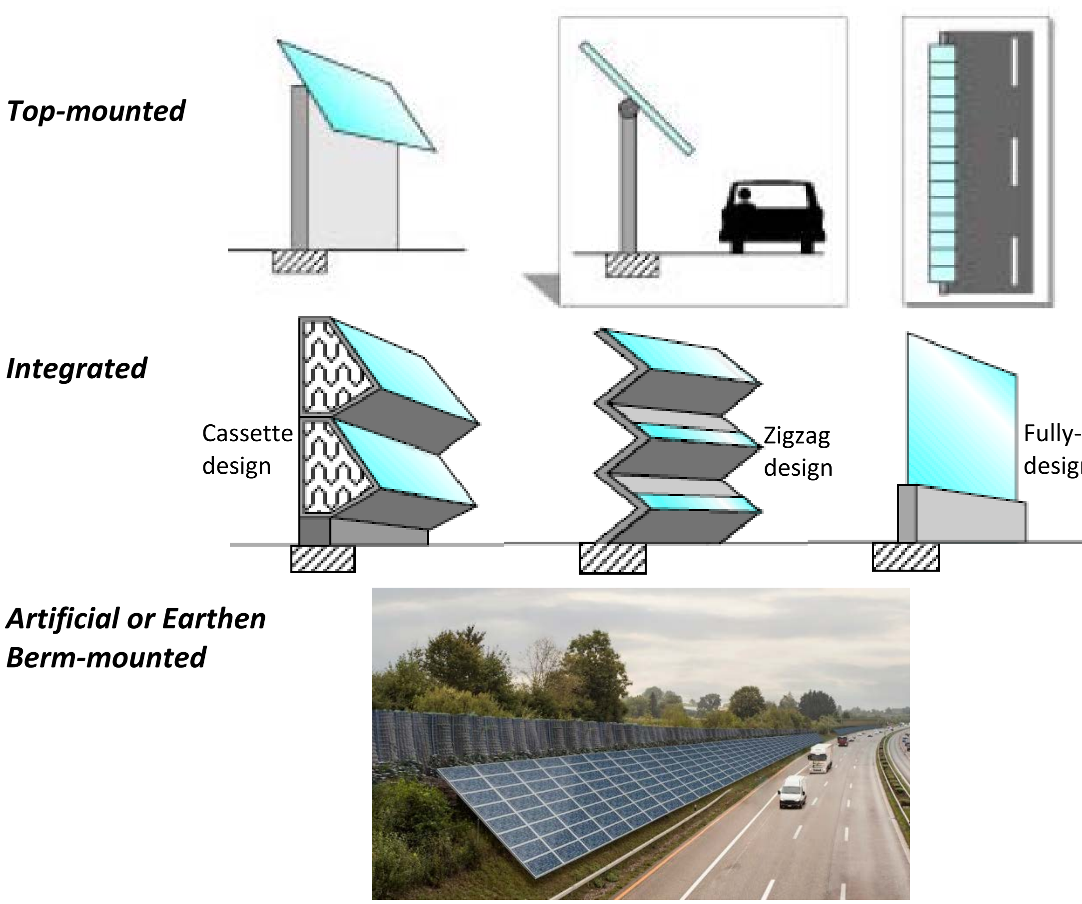


Figure 1. Different Possible PVNB Configurations.
Source: Adapted from Goetzberger et al. (1999) and Auerbach presentation

Generally, the degree to which PVNBs attenuate noise levels hinges on the proportion of the solar panels' glass surfaces to the noise barrier's other materials, as the glass surface of a PV module can only be applied for sound reflection. In many cases, sound absorption is not required for the noise barrier to achieve its intended acoustical function. Materials such as solid concrete, wood, or metal do not provide sound absorption, and PV panels are acoustically no less satisfactory provided that they are sufficiently dense. The top-mounted design offers greater PV surface area per linear meter of barrier wall, especially when configured in several rows as "shingles," but can only be used in situations where noise absorption is not necessary. Where noise absorption is required, an integrated cassette or zigzag design has to be applied, enabling a combination of sound reflection (off the PV glass) and sound absorption (via absorptive material in the non-PV areas); a drawback of the cassette or zigzag configurations from an energy perspective, however, is that the shape of the barriers encourage shading of the solar panels.[7]

Figure 2. The PVNB represents the combination of noise barrier systems with PV systems that use solar cells to convert light energy directly into electricity.
Photo source: TNC Consulting

Recently, technologies such as PV glass, thin film PV, semi-transparent PV, and luminescent solar concentrators (LSCs)[8] have been trialed in noise barrier applications in order to find new ways that solar PV might be combined with the built environment on a larger scale. These technologies are increasing freedom in colors and shapes possible because they are made of different materials than conventional PV cells. They can also be lighter in weight than conventional PV cells, potentially lowering installation costs.

PVNBs produce much less power than large-scale solar farms. For example, the current world's largest PV power station, completed in China in 2015, covers 14 km^2 and has an 850 megawatt-peak capacity (MW_p).[9] In comparison, a PVNB located near Töging, Germany, one of the largest PVNBs in the world, is approximately 1 km long and 6,000 m^2 in area, and has nearly a 2 MWp capacity. Nevertheless, since 1989 when the Swiss first retrofitted a highway noise barrier with PV modules, PVNBs have been installed in least 14 countries (Table 1) and are planned in others.

[7] Nordmann and Clavadetscher (2004).
[8] LSCs are technologies that guide sunlight in a concentrated form to traditional solar cells. They may come in a variety of colors, shapes, and transparencies. LSCs are not yet commercialized. For more information, see Debije, M. Renewable energy: Better luminescent solar panels in prospect. *Nature* 519. 298-299. March 19, 2015. Doi: 10.1038/519298a and the four universities of technology in the Netherlands at www.4tu.nl/bouw/en/PDEng/Luminescent%20Solar%20Concentrator/.
[9] www.theguardian.com/environment/2017/jan/19/china-builds-worlds-biggest-solar-farm-in-journey-to-become-green-superpower

Table 1. Compiled Highway PVNB Counts*

Country	Earliest Implementation	Count (at least)
Australia	2007	2
Austria	1992	3
Croatia	2010	1
Denmark	1991	2
France	1999	2
Italy	2006	2
Germany	1992	18
The Netherlands [a]	1995	4
Slovenia	2012	1
Sweden	2014	1
Switzerland	1989	9
United Kingdom (U.K.)	2006	3

* *Confirmed by available documentation; planned not included*

[a] *Includes luminescent solar concentrator pilot*

Sources[10]

Transportation agencies in these countries have documented a number of benefits of using PVNBs. First, the PVNBs allow for multiple uses of the same road space and thus consume a limited amount of land, avoiding a common drawback of solar arrays not mounted on roofs or integrated with buildings. Trials have shown PVNBs to be safe and relatively low-maintenance. The potential for renewable energy generation, especially when considered cumulatively across a country, is often high. Furthermore, the costs to install solar PV in the residential, commercial, and utility-scale sectors have continued to decline over recent years making novel applications potentially more feasible.[11]

[10] Data sources are: *http://sunenergysite.eu/* , *https://cppc.gov.pl/wp-content/uploads/I.Kacafura_GOLEA_Slovenia.pdf* , *www.noisun.se/*, *http://ibtta.org/awards/noise-barrier-integrated-photovoltaic-plant*, *www.vdpsrl.it/public/files//noise-barriers-2007.pdf*, *Literature review (see Bibliography), and electronic correspondence.*

[11] U.S. Department of Energy, National Renewable Energy Laboratory www.nrel.gov/news/press/2016/37745

2. LITERATURE REVIEW

The earliest literature on PVNBs evaluated the potential of a large grid-connected PV installation along motorways and railways in Switzerland, including an analysis of the economic parameters that would make PVNBs viable in the future (Nordmann et al. 1989). Nearly 10 years passed before additional literature on PVNBs was published. In the late 1990s, researchers began reporting on the performance of PVNB technology options available at the time, as well as the renewable energy potential of such systems when considered at a national level. Nordmann et al. (1998) compared the noise dampening and electricity generation characteristics of six different concepts deployed as part of an international competition on PVNBs. The researchers presented detailed findings from the construction, operations, and monitoring phases of three demonstration projects in Switzerland and three in Germany, including labor hours required to install the PV modules and electricity output by season.

Results indicated that it was possible to design barriers as "high absorbing" systems by German standards, while also producing electricity. Other early studies that calculated the renewable energy potential from PVNBs for European Union countries reported PVNBs to represent one of the least expensive ways to implement large scale grid-connected PV installations (Goetzberger et al. [1999] and Nordmann et al. [2000]). These studies also discussed the attitudes of various stakeholders, including road authorities, toward PVNBs. At the time, road authorities expressed concerns about the costs and quality of the walls.

Later research has provided additional results on subsequent years of monitoring PVNBs (e.g., Grottke, Voigt, and Hartl 2010) or refined country-specific estimates for PVNB feasibility, with both generally finding that noise barriers offer good opportunities for electricity production (e.g., Bellucci et al. 2003, de Schepper et al. 2012, and Nordmann, Vontobel, and Lingel 2012) even in locations with regular cloud cover (Meppelink 2015). Forthcoming research from Michigan Technological University estimates the total U.S. energy potential from PV modules on existing noise barriers to be approximately 815 GWh/yr (Wadhawan and Pearce 2017).

Solar Efficiency

In terms of solar efficiency, monitoring has shown that accumulated traffic dust (Van der Borg and Jansen 2001) or graffiti on modules can cause energy losses, especially if the modules are mounted too low, near the surface of the road (Nordmann and Clavadetscher 2004). Self-shading can also reduce PV module performance. However, rain has been observed to be effective at cleaning PVNBs (Carder and Barker 2006), and the systems can be designed to minimize shading (De Jong et al. 2016).

Since road orientation dictates noise barrier orientation, it also can also affect the solar efficiency of PVNBs. East-west oriented roads were initially viewed as the only roads suitable for PNVBs, but the emergence of bifacial panel technology has presented a potentially attractive option given their ability to produce electricity in any orientation—particularly on north-south oriented highways

(Figure 3). Bifacial PNVBs, which allow light to enter from both sides, were first deployed in a highway setting in Aubrugg, near Zürich Airport in Switzerland in 1997; that system was later expanded in 2005, and several others have been constructed since, with the technology having shown substantial improvements from standpoints of physical size and cell efficiency (Nordmann et al. 2012). The noise barrier support structures for bifacial PVNB systems likely need to be larger than the ideal size for the solar modules since the noise barriers must be designed to maintain their noise blocking functionality (i.e., be large and of a certain mass) and to withstand high wind loads (De Jong et al. 2016).

The angle of the PV panels on the noise barrier is also important. A 30° PV panel tilt position and east-west orientation has been shown to be ideal in terms of capturing solar irradiation (Wadhawan and Pearce 2017), although optimal tilt angles depends on latitude and local weather conditions. The same research notes, however, that panels tilted at 90° – which is suboptimal from an energy production perspective – are less susceptible to soiling along highways, less expensive to install, and generally have more area available for PV cells. This suggests a large potential for PVNB regardless of road orientation (Wadhawan and Pearce 2017).[12]

Figure 3. Bifacial PNVBs allow light to enter from both sides.
Photo source: TNC Consulting

Noise Attenuation

[12] Measurements in Switzerland have shown that the combined annual solar irradiation of two vertical planes, one facing east and one facing west (bifacial), is 108 percent of the annual irradiation of a south-facing plane at a 45 degree orientation (Goetzberger and Nordmann et al.).

From a noise perspective, research results suggest that PVNBs produce a quiet zone, or noise shadow, similar in depth and effect to that of a solid noise barrier of similar height (Highways Agency 2013). A PVNB pilot project in the U.K. that included simultaneous sound measurements at a control site found that the minimal increase in noise levels opposite the PVNB site (0.3 dBA)[13] would not be expected to cause any change in the disturbance from road traffic noise (Carder and Barker 2006). Other studies have observed that a PNVB can result in a slight increase in noise on the side of the road opposite the PV installation, but one that is likely unnoticeable to abutters, and potentially minimized by the careful positioning of the PV modules or use of select vegetation behind or opposite the barrier (Corfield 2012).

Safety Performance

The current literature does not often speak to the safety performance of PVNBs specifically. One exception (Carder and Barker 2006) describes a study that the Highways Agency (now "Highways England") conducted in order to address a concern that the PVNB might be a source of distraction for drivers and as a result lead to a reduction in safe driving at the site. The study involved two cameras that filmed vehicles from the front and rear as they approached the PVNB site. The team did not see any differences in vehicle speed, brake application, or lateral displacement between the site before and after installation of the array under similar road and weather conditions, nor was any driver behavior that might indicate driver distraction observed. It was noted that an unused access road separated the PVNB from the highway and that the array may have been more distracting if closer to the highway.

Information on the Australian experience that was provided to the project team indicated that PV panels inclined at approximately 60 degrees from horizontal caused complaints from drivers about glare. Complaints were sufficient enough to prompt the coating of those PV panels with non-reflective film, which slightly compromised their performance generating electricity.

Economic Feasibility

Findings regarding economic feasibility of PVNBs are mixed. One important economic factor is that the efficiency of solar cells is increasing while the cost for PV systems is decreasing. Now, payback horizons largely depending on factors such as PVNB size, noise barrier maintenance schedules, the availability of renewable energy incentives, and electricity prices—the latter of which have continued to decline since much of the literature was published. For example, a decade ago researchers estimated that electricity generated over 30 years by a project in the U.K. would not pay for the cost of installation unless the price of electricity was many times its current value (Carder and Barker 2006). That analysis could not account for the feed-in tariffs (FIT) that the U.K.'s Energy Act of 2008 introduced and that took effect in April 2010. In the U.K., FITs are payments to

[13] dBA is shorthand for A-weighted noise measurements. It denotes the use of a weighting filter to approximate the relative loudness of sounds to the human ear.

people and organizations that generate renewable energy up to 5 Megawatts (MW).[14] More recent studies have estimated that the installation costs of a series of proposed PVNBs in the U.K. could possibly be offset by their electricity generation revenue over 20 to 25 years (Highways 2013 and Giles 2015). Finally, researchers in Belgium who monetized the ecological benefits of PVNBs found that a PVNB investment in that country could be recuperated after 12 years (Schepper et al. 2012).[15]

Most recently, researchers in the Netherlands have monitored the first two years of performance of two LSC noise barriers at a test site in Den Bosch, the Netherlands—the largest deployment of the prototype technology to date (Kanellis et al. [2017] and Sloof et al. [2016]). Although the LSC technology may not currently be ready for widespread use in noise barrier settings, researchers have made observations that may help transportation agencies deploy future LSC noise barrier systems, such as ways to design LSC structure frames to avoid self-shading.

[14] Currently, seven states in the U.S. have FIT programs that are mandated by law or regulation. FIT programs are similar to net metering programs but differ significantly in one key aspect: the power a utility customer's system generates is compensated at the rate set the FIT sets rather than the retail electricity rate. This generation is treated independently from the customer's own electricity use, which is billed at the utility's regular retail rates. In a net metering program, a utility customer is effectively paid the retail rate for any generation that is fed back into the grid. www.eia.gov/todayinenergy/detail.php?id=11471

[15] The shortest time needed to offset PVNB construction costs that the project team could find in the literature was for a system installed along a railway in China. Researchers there found the payback period to be 5.4 years, factoring the potential air quality improvements possible from avoided emissions (Gu *et al*. 2012).

3. EXAMPLES FROM THE INTERNATIONAL EXPERIENCE

During spring 2017, the project team conducted interviews and corresponded with transportation professionals with experience with PNVBs abroad, including experts at select agencies that have implemented and monitored successful PNVB systems. Experts were identified by networking with existing professional contacts. An interview guide (Appendix B) was used to provide consistency across communications while allowing for follow-up questions and sidebar conversations where appropriate.

3.1 Switzerland

Switzerland's Federal Council directs the administration of Switzerland. The leaders of the country's seven federal executive departments comprise the council, which serves as a collective head of state. An important objective of the Federal Council is to use resources, such as land, water, and energy, in a sustainable manner. Viewing PVNBs as compatible with this objective as well as facing legislative requirements to build noise barriers along roads and railways in developed areas, stakeholders in Switzerland worked with the Swiss Federal Roads Office (FEDRO) to install the world's first highway PVNB in December 1989. The solar panels at the site are affixed to a 2-meter tall structure that is top-mounted at an optimal tilt angle given the site's latitude and cover the length of the noise barrier's 800 linear meters of road. The polycrystalline PV modules added approximately 970 square meters to the surface area of the noise barrier and have netted approximately 108,000 kilowatt-hours (kWh) per year after deducting the electricity needed to power the PVNB's monitoring system and inverter (Prasad and Snow 2005).

Figure 4. PVNBs were first deployed in Switzerland in 1989. *Photo source: TNC Consulting*

Six years after the first highway PNVB, an international ideas competition on PVNBs created an impetus to demonstrate alternative PVNB configurations. As a result, between 1997 and 1999, six additional installations of 10 kWp each were built (three in Switzerland and three in Germany), including the introduction of integrated PV noise barrier concepts. One goal of the trials was to show typical advantages of a variety of technologies in different situations.

Since then, other highway PVNBs have been constructed across the country (Figure 5). FEDRO indicated that it generally supports multiple uses of road space, as long as road safety can be ensured. FEDRO can help to implement PVNBs on Swiss National Roads by conducting feasibility studies, but the agency does not operate the facilities or sell the energy generated. Since there is no direct relation to the maintenance and exploitation of the National Roads, the FEDRO solely provides the infrastructure for PVNBs if the infrastructure is available and road safety will not be compromised; the agency does not finance PVNBs, and thus investors are responsible for project planning, implementation costs, as well as costs of any feasibility studies undertaken. The investor then ensures the economic viability of PVNB operation.

Figure 5. The Swiss Federal Roads Office can help to implement PVNBs on Swiss National Roads by conducting feasibility studies. *Photo source: TNC Consulting*

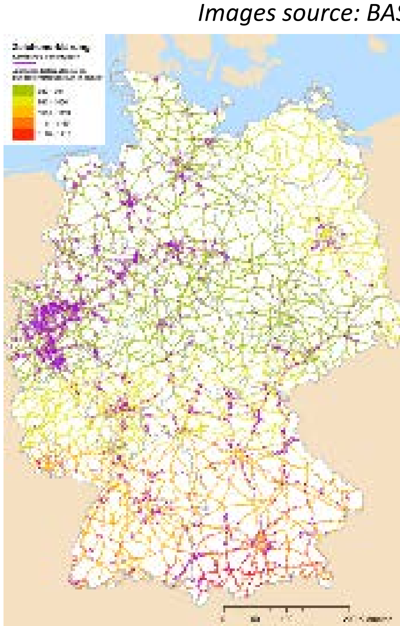
3.2 Germany

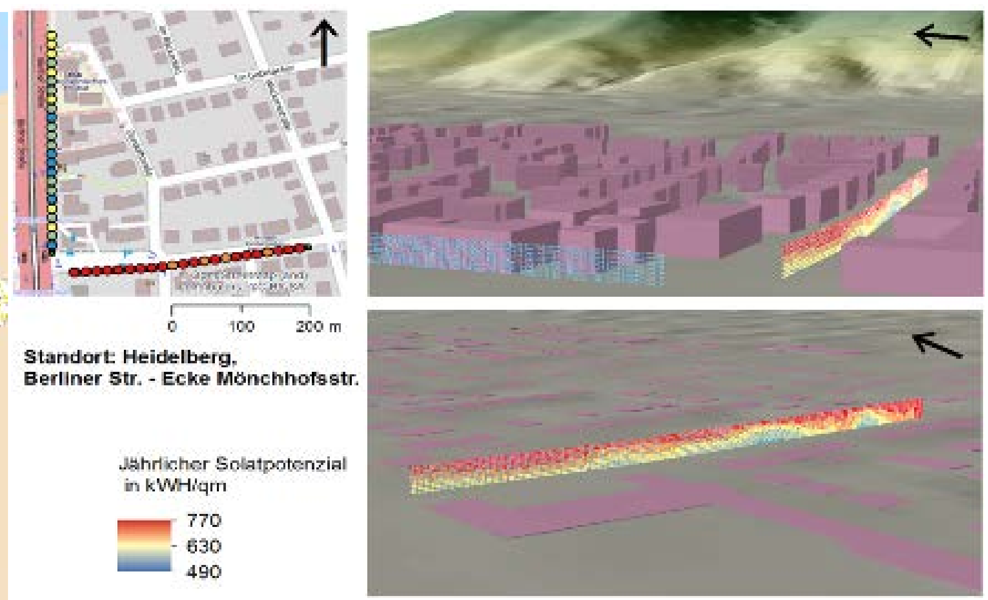
The first PVNB in Germany was constructed in 1992, and since then a variety of PVNBs have been built across the country, coinciding with the increasingly commonplace practice in Germany of considering options for using highway right-of-way (ROW) for energy generation. This has been due in part to declining PV costs that the country's *Renewable Energy Sources Act (Erneuerbare-*

Energien-Gesetz or EEG)[16] and *Energiewende*[17] policy helped set in motion. Together, the EEG, which introduced a feed-in tariff for renewable energy, and *Energiewende*, a policy that promotes a transition to an environmentally sound, reliable, and affordable low-carbon energy supply, have successfully incentivized renewable energy development across Germany. As subsidies have been lowered over time, costs to install PV have also gone down, preserving the economic viability of solar installations. Additionally, in summer 2016, the German government adopted a 29-point "Integrated Energy and Climate Programme," the first of its kind in Germany. The program aims to help reduce greenhouse gas emissions by 36 percent from 1990 levels by 2020. This has provided further impetus for agencies to expand the utilization of renewable energy technologies.

The first generation PVNBs in Germany were retrofit installations located on top of existing noise barriers. Now, opportunities to use noise barriers for renewable energy generation are assessed from the outset of planning for new noise barriers. Nevertheless, existing noise barriers continue to provide significant potential for renewable energy generation. The Federal Highway Research Institute (BASt) identified prospective sites across the country through a GIS analysis that merged information on the location and orientation of existing infrastructure, such as noise barriers, roads, buildings, and levees, with natural characteristics, such as topography, land cover, and solar irradiance (Figures 6-7). Local 3D modeling was then used to further refine where embankments and infrastructure provide the most solar potential.

Figure 6. (left) GIS analysis helped identify prospective PVNB sites across Germany.
Figure 7. (right) Local 3D modeling further refined the assessment of potential sites.
Images source: BASt





[16] www.erneuerbare-energien.de/EE/Navigation/DE/Recht-Politik/Das_EEG/das_eeg.html;jsessionid=C771A2CF7BB1A22175E9C8E0AD9A9FDC
[17] www.germany.info/contentblob/3043402/Daten/3903429/BMUBMWi_Energy_Concept_DD.pdf

In most cases when a feasible PVNB site is found, a private developer who is willing to pay the upfront costs is needed to finance and complete construction.[18] The developer will also typically pay a fee to the road authority in order to be able to use the property, and the electricity generated will feed the grid. Construction of retrofit PVNB will usually entail mounting the solar panels using theft-proof equipment, such as counter-sunk screws and attaching cameras to the barriers to dissuade vandalism. (This issue, however, is becoming less of a concern as the use of integrated PVNBs grows.) The time needed to recuperate these costs will depend on the price of electricity and subsidy amount, but in sunnier regions, such as southwest Germany, PVNBs have proven particularly cost-effective. BASt developed a guidebook describing how public and private stakeholders might best collaborate to make PVNB applications economically viable, including providing an overview of effective design and construction practices and sample contracts for public-private partnerships.

To German road authorities, PVNBs typically do not present technical problems in terms of noise reduction or safety. Off-the-shelf PV technologies made specifically for noise reducing devices meet or exceed German regulatory guidelines for noise reduction, and assuming the PV components are properly oriented given a site's characteristics, the addition of PV to noise barrier is not expected to cause new noise complaints. The same has been true for safety issues: noise barriers in Germany have to comply with all relevant regulations and safety standards, regardless of whether they include solar panels. They are typically located behind guard rails and have not been associated with glare or driver distraction problems.

PVNB maintenance normally involves visual inspection, but the panels are typically not cleaned given that the cleaning effort can be more expensive than savings possible from minimal efficiency gains (Figure 8).

Figure 8. This and similar PVNBs in Germany are typically expected to be self-cleaning. *Photo source: BASt*

One challenge has been periodic complaints from abutters about the visual aesthetics of the PVNB or that PVs extending above an existing noise barrier disturb the view. In the future, stakeholders

[18] In some cases, utilities companies have been willing to finance construction. German utilities have been supportive of the effort to find innovative locations for renewable energy technologies.

plan to involve abutters in the PVNB planning and development process more in order to help ensure abutters' acceptance of the projects.

3.3 The Netherlands

Noise barrier construction is relatively common in the Netherlands. The country's high population density means that highways, railways, houses, and businesses are often in close proximity, sometimes necessitating noise barriers (Figure 9). In the early 1990s, the Dutch began trialing the concept of retrofitting concrete noise barriers with PV panels, and in 1998 built one of the longest and largest PVNB installations in existence at the time, stretching 1.6 km along a highway near Amsterdam. It still generates approximately 176,000 kWh of electricity annually. When it was constructed, however, renewable energy was much more expensive per watt to install than it is now, and implementing a solar noise barrier in the Netherlands showed "green" ambitions but did not necessarily generate a profit. As costs have come down, similar projects now can be both environmentally friendly and economical.

Figure 9. The Dutch began trialing the concept of retrofitting concrete noise barriers with PV panels in the early 1990s.
Photo source:RWS

Accordingly, the Dutch have worked to push boundaries in solar noise barrier research, especially regarding new noise barriers. Building a new barrier gives designers the most flexibility to design both noise abatement and electricity generation features optimally. The Rijkswaterstaat (RWS), which is the agency responsible for the design, construction, management, and maintenance of the road network, waterway network, and water systems in the Netherlands, is now working to implement the "LIFE Solar Highways" project, an effort that may pave the way for a more extensive deployment of PVNBs. To do so, RWS is partnering with the Energy research Centre of the Netherlands (ECN) and the Solar Energy Application Centre (SEAC) to demonstrate the technical feasibility of a prototype, fully integrated PVNB and to develop a workable financial business case. The team also aims to show the environmental and social benefits of using multifunctional constructive elements for building highway noise barriers. The project is funded by a European Commission LIFE+ grant[19] worth about €1.4 million in combination with RWS finances.

Identifying a site for the project, which involves the construction of a 400-meter long, 5-meter high, grid-connected bifacial PVNB barrier, has been a challenge. A combination of characteristics need to be present: planners are looking to find a road that generally had a north-south orientation in order

[19] LIFE is the European Union's financial instrument supporting environmental, nature conservation, and climate action projects. http://ec.europa.eu/environment/life/about/index.htm

to demonstrate that energy can be successfully harvested from the bifacial technology; there has to be a noise barrier need at the site; and it has to be in a municipality willing to host the barrier. A site is expected to be selected in summer 2017, and beginning in 2018, the barrier is expected to provide about 40 households with locally-generated renewable energy (Figure 10).

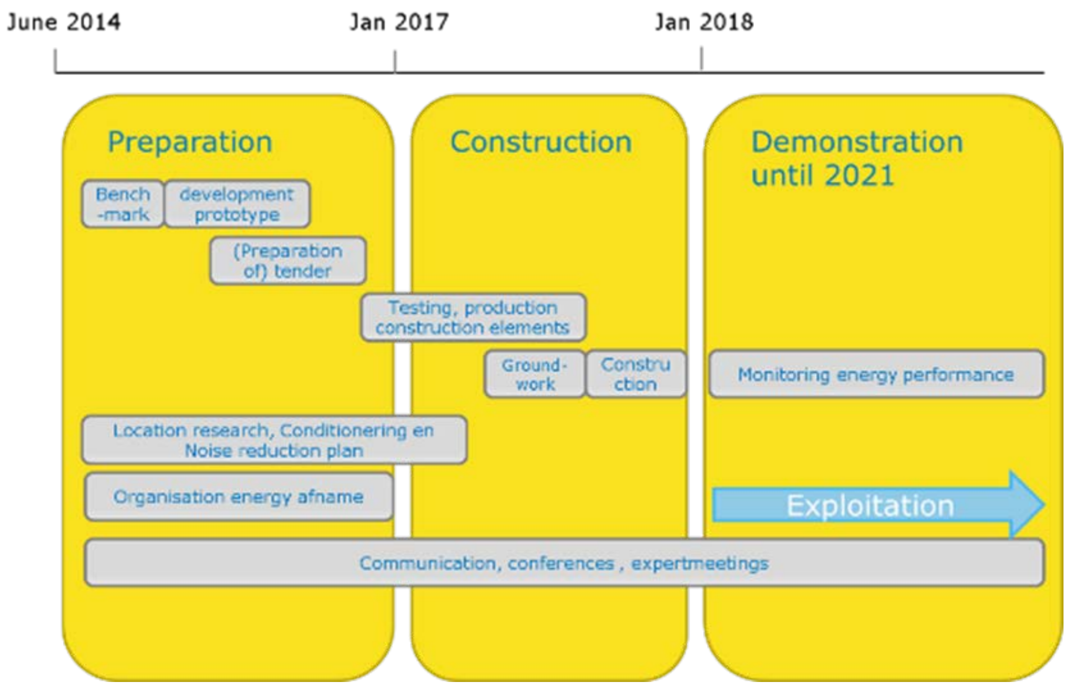


Figure 10. The fully-integrated PVNB is expected to begin operation in 2018. *Image source: RWS*

Currently, the Solar Highways team is studying options for selling the electricity and capitalizing on possible tax benefits in order to ensure the project's cost-effectiveness. The team is also working on a procurement to hire a contractor to build the barrier. It is expected that the product will be mostly similar to what is normally delivered for a noise barrier in terms of construction design and dimensions with some unique components, such as cabling and the bifacial panels themselves. The Solar Highways team is confident that the project will be successful based on results from monitoring a similar, but smaller, demonstration project site for more than a year and subsequent modeling. In particular, the barrier's noise abatement qualities are not expected to be compromised since RWS has an obligation to meet noise barrier standards described under the law. The demonstration project will be designed to meet those noise requirements. The team is also working with the fire department with jurisdiction in the project's area in order to devise a standard framework for how similar PVNBs might be deployed across the Netherlands in ways that avoid or minimize public concerns, such as reflections, glare, and crash-worthiness.[20]

Other project characteristics include:

- Attempting to minimize self-shading from the bifacial technology's support structure.

[20] In the Netherlands, the fire department

- Minimizing future maintenance costs. With the PV panels being expected to last 20–25 years, cleaning, repair, or replacement needs are paramount. RWS is working to implement a solution that does not require excessive maintenance or that interferes with traffic. The Solar Highways team plans to closely monitor the noise barrier and relate its energy generation to weather conditions to better understand how much maintenance is economical.
- Continuing a strong public outreach campaign. The team has put much effort into communications with the public, including creating an informational booklet that was shared with area residents. By providing information and encouraging public involvement throughout the development process, the Solar Highways team is working to ensure the project is successful to show that taxpayer funds are being wisely used.

3.4 Australia

The Roads Corporation of Victoria (VicRoads) is the road and traffic authority in the state of Victoria, Australia. VicRoads has recognized that any renewable energy generating facility that VicRoads constructs is likely to be integrated into some form of road infrastructure,[21] including its noise barriers.

In summer 2007, VicRoads began selling to the local energy grid renewable electricity generated from PV panels integrated into the top of a noise barrier at a new highway interchange near the Melbourne's Tullamarine Airport (Figure 11). The innovative noise barrier was part of a larger, $AU

Figure 11. PV panels above precast concrete noise barrier in Melbourne, Australia. *Source: VicRoads*

[21] See "Appendix 3: Photovoltaic Noise Barrier Design Considerations" of VicRoads's *Renewable Energy Roadmap* (August 2013).

150M interchange redevelopment project intended to provide safer travel and improved traffic flow. The project, at the Tullamarine-Calder interchange, required the construction of new sections of the east-west oriented main highway and new bridges and ramps, ultimately separating local roads from the freeway.

When VicRoads's environmental analysis for the project indicated that a noise barrier was necessary, the agency decided to partner with a German engineering group, a local solar developer, and other consultants to demonstrate a new noise barrier technology.[22]

Using a $AU 140,000 grant from Sustainability Victoria, a state government body with statutory authority for delivering programs on integrated waste management and resource efficiency, VicRoads facilitated the deployment of the 500-meter long PV system that now provides an integral part of the precast concrete barrier's noise screening. The barrier's PV portion consists of 210 opaque amorphous silicon solar panels,[23] each weighing approximately 106 kilograms, installed vertically at the top of the 4-meter tall noise barrier. Due to the thickness of the panels' heat-strengthened glass, the acoustic tape installed between the panels, and an additional meter in height to the barrier, the solar panels operate like conventional noise walls. Performance data from the Tullamarine-Calder PNVB has been an indicator to VicRoads that PV panels can be as good a material as any for a noise barrier, assuming the noise wall can be an acoustically-reflective surface (as opposed to being required to be absorptive); the mass of the panel's is sufficient; and the reduced solar efficiency of a vertical panel as compared to an angled panel is acceptable.[24]

Generally, the Tullamarine-Calder PVNB has not presented any safety or maintenance issues (Figure 12). The panels are located at a height that is out of the way of any potential crash (or theft). Furthermore, driver distraction has not been identified as a concern; given the PV panels' integrated, vertical design, glare is not an issue and many drivers may not be aware that solar panels are even present.[25] The vertical orientation has also minimized dirt collection, and the panels have effectively been self-cleaning. Nearly all other maintenance can be performed away from the highway since the wall and its five inverters are installed on and accessible from the non-highway side of the wall.

[22] VicRoads uses the Calculation of Road Traffic Noise (CoRTN) algorithm to determine necessary noise barrier height. The CoRTN algorithm is the British equivalent of the Federal Highway Administration's Traffic Noise Model (TNM).

[23] Amorphous silicon is the non-crystalline form of silicon. It can be deposited on a wide range of flexible and curved substrates.

[24] The rated efficiency of the Tullamarine-Calder PNVB is 5.2 percent. It was argued during PV selection that performance losses due to an adverse angle of incidence (vertical orientation) would affect low-efficiency panels to a lesser degree than they would higher-efficiency panels.

[25] A second PVNB on the M80 motorway that has solar panels installed at 60 degrees from horizontal and which has resulted in some driver complaints about glare, as well as some maintenance challenges, is being decommissioned.

Figure 12. Routine maintenance on the PV panels can be performed on the non-highway side of the noise barrier. The backside of the PV panels is light in color and was designed to partially reflect the sky in an effort to make the wall less visually intrusive to abutters. *Source: Going Solar Projects–The Green Building, Review of System Performance, September 2009.*

VicRoads does not have plans for additional PVNBs, as it has come to the conclusion that they are not financially viable in the current Australian context. This is due in part to a low feed-in tariff for solar power in Australia. (VicRoads could not directly use the power generated because it did not have a daytime demand for electricity near the site). VicRoads has also found it to be more cost-effective to locate solar panels on the roofs of buildings since those projects involve less customization than do PVNBs. The agency is now exploring whether ground-mounted solar farm installations located on excess properties are more feasible.

4. POTENTIAL PVNB PROJECTS IN THE UNITED STATES

This section draws upon information gathered from interviews and correspondence with transportation professionals in the United States. The project team identified experts through existing professional networks.

4.1 Highway Noise Governance

The Federal-Aid Highway Act of 1970 includes mandates for FHWA to develop standards for the consideration of the effects of highway noise from projects. FHWA implemented those standards through noise regulations, which are codified in 23 Code of Federal Regulations (CFR) 772, describe procedures for abating highway traffic and construction noise on projects where a State Department of Transportation (SDOT) receives Federal funding. SDOTs must use FHWA's Traffic Noise Model (TNM) in their traffic noise prediction analysis for all projects subject to 23 CFR 772.[26] The FHWA TNM is a state-of-the-art, three-dimensional model that calculates traffic noise levels and noise level reductions based on user input of roadways, barriers, terrain features such as hills, valleys, woods, and lakes; structures, and traffic data. Otherwise, SDOTs have flexibility in determining the feasibility and reasonableness of noise abatement on roadways to balance the benefits of abatement measures with the social, economic, and environmental costs as described in FHWA approved policies.

The regulations define three types of highway noise projects:

- Type I projects involve the construction of new highways or improvements to existing highways. They typically involve the construction of noise barriers as part of projects that significantly change the horizontal or vertical alignment of an existing highway, increase the number of through traffic lanes of an existing highway, or relocate interchange ramps.

- Type II projects, also called retrofit projects for noise abatement, are standalone Federal or Federal-aid highway projects that involve construction of noise barriers on existing highways. Type II projects are voluntary noise abatement projects and constructed as state funding allows. They account for approximately 14 percent all noise barriers constructed in the United States.[27]

- Type III projects are Federal or Federal-aid highway projects that do not meet the classifications of Type I or Type II projects. Type III means the proposed activity does not require a noise analysis.

[26] Per 23 CFR 772.7(a), the regulation applies to all Federal or Federal-aid Highway Projects authorized under title 23 U.S.C. and therefore any highway project or multimodal project that:
(1) Requires FHWA approval regardless of funding sources or (2) Is funded with Federal-aid highway funds.
[27] See www.fhwa.dot.gov/environment/noise/noise_barriers/inventory/ for more information on noise barriers constructed in the U.S. as of December 31, 2013.

In each case, states must consider noise abatement measures where noise impacts are determined to occur as per FHWA's Noise Abatement Criteria, which are absolute noise levels for varying land uses (See Table 1 at 23 CFR Part 772). The noise regulations do not expressly prohibit the deployment of PVNBs, either as part of the retrofitting of existing noise barriers with PV modules or through the integration of PV modules with new barriers. While the regulation does not allow funding from third parties to make a barrier feasible or reasonable, the regulation does allow contributions from third parties for appurtenances, such as PVNBs.

4.2 Massachusetts DOT's Lexington Solar Retrofit Pilot Program

Since 2015, the Massachusetts Department of Transportation (MassDOT) has installed 5.5 MW of ground-mount[28] PV panels within its highway ROW as part of its "Solar PV Energy Program."[29] MassDOT has a goal of achieving 6 MW of aggregated capacity from ground-mount solar across the state. However, with limited space remaining for new ground-mount arrays on MassDOT properties, the agency has been interested in exploring other opportunities for accommodating renewable energy technologies, including noise barriers.

In 2015, a company approached MassDOT to discuss the concept of PVNBs. After two years of coordination and conceptual design work, MassDOT is now working to pilot a PVNB project along Interstate 95 in Lexington, MA (Figure 13). The project will be a retrofit of an existing noise barrier and will be financed through a public-private partnership. MassDOT plans to use the results of the pilot, including information about noise impacts, maintenance, cost, and community perception, to determine whether to make the pilot location permanent and whether to expand PVNB use elsewhere in the State.

MassDOT considered 25 potential sites for the PVNB pilot, ultimately selecting the Lexington site due to its orientation to the sun, the length of the noise barrier, topography and offset from the road, vegetation in the area, and access to a grid interconnection point. The noise barrier, which is on the north side of the highway, is 3,000 feet (~915 m) long, 20 (~6 m) feet tall, and is constructed of reinforced concrete. A critical aspect of the pilot program is to monitor noise levels to understand whether, if at all, the PVNB affects the noise levels that abutters perceive or that occur on the other side of the highway. The racks of solar panels will be installed on the highway side of the barrier, while the side of the barrier facing abutters would not change significantly.

[28] Ground-mount arrays are affixed to support structures that penetrate the ground.
[29] For more information on MassDOT's Solar PV Energy Program, see: www.massdot.state.ma.us/planning/Main/SustainableTransportation/RenewableEnergy.aspx

Figure 13. Visualization of proposed configuration of solar panel retrofit on existing noise barrier in Massachusetts. *Source: Massachusetts DOT*

The exact size of the PV module system has not yet been determined, but MassDOT anticipates that if the full length of the noise barrier is used, approximately 825,000 kWh will be generated annually. This would be the equivalent of supplying 120 homes per year with electricity. The project will add a small transformer within the ROW in order to connect to the electricity grid.

MassDOT would not incur any capital costs. Instead, MassDOT plans to release a request for proposals (RFP) for the project, and the selected developer will be responsible for the financing, installation, and maintenance of the solar panels, as well as any necessary upgrades to a nearby electricity substation. Although MassDOT is still working out the details of the partnership in the RFP, it is likely that the project would benefit MassDOT by allowing the agency to purchase the electricity at a guaranteed, long-term rate. The developer would likely receive credits under the Massachusetts solar renewable energy credit program or the new Solar Massachusetts Renewable Target (SMART) Program, a renewable energy tariff program.[30] The developer would also likely receive a Federal Solar Investment Tax Credit, which is currently a 30 percent tax credit claimed against the tax liability of residential, commercial, and utility investors in solar energy property.[31]

MassDOT solicited input on the project from abutters and other Lexington residents through letters to those living near the project site, a public meeting, and meetings with other stakeholders, such as Sustainable Lexington, a local advocacy group. Stakeholders raised several concerns before and during the public meeting, including potential changes to noise levels on both sides of the highway and noise impacts of the transformer and other equipment. MassDOT plans to address these

[30] For more information on the SMART program, see www.mass.gov/eea/energy-utilities-clean-tech/renewable-energy/rps-aps/development-of-the-next-solar-incentive.html.

[31] For more information on the Federal Solar Investment Tax Credit, see www.seia.org/policy/finance-tax/solar-investment-tax-credit.

concerns by conducting a final noise analysis prior to the solar panel installation; if the analysis finds that negative noise effects are created, the project will not move forward. At the conclusion of the public meeting, MassDOT held a referendum for abutters to vote on the pilot project (abutters not at the meeting were also able to request a ballot). In accordance with noise barrier standards,[32] a two thirds majority in support of the project was needed for it to move forward. Eleven votes were cast, all of which were in support of the pilot project.

The RFP will likely be issued summer 2017, and the pilot is expected to last two years from the date the solar panels are operational. MassDOT is developing evaluation criteria for the pilot project that it will use to evaluate whether to keep the site in operation after the two-year demonstration period, as well as whether to expand PVNBs to other locations in the State. The evaluation criteria have not yet been finalized, but will likely include changes to the noise abatement characteristics of the noise barrier, required maintenance of the solar panels, impacts to the longevity of the noise barrier, total costs, and community feedback. If the pilot project is successful, MassDOT may consider options for retrofitting other noise barriers with PV modules, as well as piloting the PV integrated concept when a new noise barrier(s) is constructed.

4.3 The Ray: A Potential Testing Ground for Prototype Solar Noise Barriers

In 2014, the Georgia legislature named an 18-mile stretch of Interstate 85 (I-85) in west Georgia in honor of the late Ray C. Anderson, a leader in industrial sustainability. To align with its goals of enhancing the environmental stewardship and sustainability, the Ray C. Anderson Foundation (Foundation) labeled the I-85 section "The Ray" to be a living laboratory for emerging innovations related to sustainable transportation. The Foundation set a goal for The Ray to become a "net zero" highway that eliminates all deaths, waste, and carbon emissions. It has partnered with the Georgia DOT (GDOT) and other stakeholders to test innovations along and at a visitor center on the highway segment. Innovations demonstrated to date include solar-powered vehicle charging stations, a roll-over tire check safety station, bioswales to clean water runoff, a pollinator garden, and a novel solar-pavement technology.

Moving forward, The Ray may be a testing ground for a prototype PNVB. The Foundation is currently working with a consultant on a feasibility study that evaluates different types of PVNB technology, including noise barriers with mounted panels, thin film solar cells, concentrating PVs along the periphery of noise barriers, and a noise barrier that itself is a wall of solar cells. The Foundation plans to choose a technology that could be deployed in a PVNB demonstration project on The Ray based on the feasibility study's results.

A site has not yet been identified, but the Foundation is working with partners, including (GDOT) to explore opportunities. One option being considered is the construction of a new noise barrier at a location between The Ray and an adjacent high school. If a PVNB were constructed at the site, the team envisions the electricity being used nearby, for example to power lights at the school or one of

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[32] For more information, see the MassDOT Type I and Type II noise barrier guidebook at www.massdot.state.ma.us/Portals/8/docs/environmental/noisebarrier2012/NoiseProgramGuidebook_121412.pdf

its ball-field scoreboards. The team has pointed out, however, that first and foremost a PVNB demonstration along The Ray would need to be a noise barrier project. A wall would not be the optimal setting or configuration for a solar array. The Foundation plans to continue working with public and private stakeholders to assess noise abatement needs along The Ray and potentially find a suitable site and situation for the PVNB pilot.

5. CONCLUSIONS

In 1999, researchers quantified the technical potential of existing and planned highway noise barriers in Europe to produce renewable energy. [33] Data suggested peak capacity along roadways in 6 countries to be 580 MWp (~ 200 Wp per linear meter) and that a total of nearly 500 Gigawatt hours per year (GWh/yr) of renewable energy was possible. Extrapolating from these figures and FHWA's noise barrier inventory, the technical potential[34] for generating capacity along highway noise barriers in the U.S. is estimated to be on the order of at least 500 MWp and the renewable energy possibly delivered to be likely at least 400 GWh/yr. The latter is roughly equivalent to the annual electricity use of 37,000 homes (see Appendix C for calculations).

These are likely conservative approximations given that they only account for existing noise barriers constructed before December 31, 2013, and they only account for noise barriers made of select materials: berm only, concrete, concrete precast, concrete block, concrete cast-in-place, and combination berm/concrete. Over 45 percent (1,200 miles or 1,900 km) of noise barriers in the U.S. are made of other materials. This should not suggest, however, that noise barriers that are not berm or concrete cannot integrate PV modules. Additionally, the efficiencies of solar panel technologies have improved over time. State-specific estimates may vary considerably due to factors such as latitude and solar irradiance, noise barrier orientation and PV placement, and topography.

In general, large surface areas are necessary to generate electricity from PV modules.[35] Noise barriers offer surface area additional to land and rooftops to accommodate PVs and can provide better land utilization ratios for energy production than conventional solar PV farms.[36] Nevertheless, although PVNBs provide for the multiple use of road space, deciding whether to implement a PVNB in a highway setting is not based simply on renewable energy potential or performance. Rather, State DOTs will likely need to employ a holistic planning approach that balances broad view concepts, such as land use and sustainability goals, with site-specific details, such as safety, maintenance needs, and noise mitigation. While other sites, such as rooftops, may be more efficient than noise barriers from an energy generation perspective, transportation agencies should consider assessing their noise barriers for PV opportunities in conjunction with their other properties given the numerous potential benefits of PVNBs.

5.1 Lessons Learned Summary

The case studies of existing PVNBs in Europe and planned PVNBs in the United States provide several insights for transportation agencies interested in implementing PVNBs. The following table summarizes key lessons learned.

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[33] Goetzberger *et al.* (1999).

[34] "Technical potential" in this case assumes that all existing noise barriers made of the materials in the bulleted list will be upgraded with PV.

[35] The National Renewable Energy Laboratory has estimated approximately 181 m^2 of land area is required for PV per person to meet U.S. energy demands. http://dx.doi.org/10.1016/j.enpol.2008.05.035.

[36] Wadhawan and Pearce (2017).

PVNB technology	PV modules have been both deployed as retrofits to existing noise barriers and integrated into new noise barriers. Bifacial solar cells, which allow light to enter and be absorbed on both sides, are being used in Europe. These panels provide an advantage in that they can be used in any orientation. Other potential PVNB technologies include thin film solar cells, concentrating PV cells along the periphery of noise barriers, and luminescent solar concentrators.
Financial feasibility	The financial feasibility of PVNBs is highly dependent on the price of the PV panels, the price of electricity, and government incentives for renewable energy (such as net metering, feed-in tariffs, or tax credits) – all of which vary depending on the location and policy context. In the United States, organizations that implement PVNBs may be able to take advantage of statewide renewable energy credit programs, which are used to track progress towards meeting renewable portfolio standards, or net metering policies, which allow solar panel owners to sell excess energy back to the grid.[37] At the Federal level, the Solar Investment Tax Credit (ITC) provides a 30 percent tax credit claimed against the tax liability of residential, commercial, and utility investors in solar energy property (note that public entities such as State DOTs cannot directly take advantage of the ITC, since they have no tax liability). Many PVNB projects have been structured as public private partnerships where a developer takes on the construction and maintenance of the PVNB. This arrangement allows States to install solar panels with no upfront costs, allows the developer to take advantage of incentives that the State DOT may not be able to access, and provides the State with a long-term source of electricity, often at a fixed, guaranteed price.
Noise characteristics	Typically, the noise abatement characteristics of noise barriers have not significantly changed after being retrofit with PV modules, and new PVNBs can be designed to adhere to all relevant noise requirements. Since, PVNBs are primarily noise barriers with the added functionality of generating electricity it is important to measure noise levels before and after the installation of the PV to ensure that desired and required noise attenuation is achieved.
Safety	There is little to no evidence to date that PVNBs significantly affect driver safety. Driver distraction and glare can be minimized by locating the PV modules high on noise barriers and/or set back from the roadway, and by ensuring that the panels are at proper angles to minimize glare. PVNBs with a vertical design, such as the Australian PVNB, have not been shown to create glare. Additionally, solar panels are designed to absorb rather than reflect light. PVNBs are not expected to cause crashes if located behind a guard rail(s) or beyond the clear zone.
Maintenance	Several international examples have shown that existing PVNB technologies have minimal maintenance needs. In Germany, the PV panels are not typically cleaned, because the cost of doing so would outweigh any potential efficiency gains. In Australia, the vertical orientation of the PVNB minimizes accumulated dirt on the panels.

[37] For information about state solar incentives, see the Database of State Incentives for Renewables & Efficiency at www.dsireusa.org/

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APPENDIX A: POINTS OF CONTACT

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APPENDIX B: INTERVIEW GUIDE

Concept / Technology Identification

Could you tell us a little bit about the PVNB(s) your agency has implemented? How many? What does the project(s) entail?

a. What's the story? How did the idea come about? What were the motivations? Why?
b. How is the electricity generated used? Who owns the facility?
    i. Electricity stored, sold, used nearby or on-site?
    ii. DC or AC?
    iii. How are interconnections to the grid or other hardware handled?

Design / Siting

How did you know the selected location(s) was the right one? How would a transportation agency "know" it had a good location?

a. How was siting determined?
    i. Was a safety analysis conducted? Describe.
        1. Were there any limited access or traffic control issues?
        2. Were there any site-specific clear zone issues (crash)?
        3. Driver distraction an issue?
        4. Who is liable if an accident occurs (risk management)?
    ii. Was an environmental analysis necessary? Describe.
b. Same answers for new vs. retrofit?

How was the solar panel configuration/mounting determined?

a. How long?
b. How high?
c. New barrier or retrofit?
d. On surface of barrier or above barrier?

Cost / Financing

How were costs estimated?

a. Who did the estimates?
b. Was a benefit-cost analysis performed?
c. Was a life-cycle analysis done? If so, how soon do you expect to recoup the capital and operations/maintenance costs?
d. Did the initial cost estimates reflect reality? If not, what caused the change (lower power generation, higher maintenance costs, shorter lifespan, etc.)?

How was the project(s) funded? Are there any incentives to the private sector?

Installation / Construction

What special considerations had to be made for construction (e.g., season? Access to site? Was it like other construction projects?

Who was responsible for installation? How did the transportation agency oversee construction?

Operation / Maintenance

Noise perspective

a. How have the barrier's noise abatement characteristics changed?
b. Have noise complaints increased, decreased, or remained the same?

Electricity perspective

a. How much electricity does the project generate (monthly/annually)?
b. How much electricity is generated?
   i. Per linear mile / per installation?
   ii. What is the rated efficiency of the panels?
   iii. What is the efficiency reduction due to orientation?
c. Is panel cleaning necessary? How does it occur?

Other

a. Security: Has theft or vandalism been a problem?
b. Cost-Benefit: Has the project(s) been cost-effective? Has it been worth it? How do or will you know?
c. Unknowns: Have there been any unintended consequences of the project?

Stakeholders / Public Involvement

- Who are the stakeholders (internal and external) that have been involved?
- Did staff have the regulatory/technical/etc. expertise necessary? How would you describe the learning curve?
- What has public perception of the project(s) been like?
- What kind of outreach was performed, if any?

Best Practices / Lessons Learned

- What have you learned? What advice would you give other transportation agencies seeking to implement a similar project?
- Does your agency have plans for additional PVNBs?
- What are future research needs in this area your view?

Referrals

- Any contacts in other countries (as necessary)?

APPENDIX C: CALCULATIONS

Goetzberger et al. (1999) quantified the technical potential of existing and planned highway noise barriers in Europe to produce renewable energy:

TECHNICAL POTENTIAL

	Switzerland	Germany	Netherlands	Great Britain	Italy	France	
Reported:							
km of noise barrier	303.8	1525	475.9	204	50.7	352.7	
Generating capacity (MWp) along motorways	58.5	293.8	114.6	39.3	9.8	67.9	*Total 583.9*
GWh/yr	53.4	247.5	91.8	29.9	10.3	63.7	*Total 496.6*
Calculated:							
MWp/km of noise barrier	0.193	0.193	0.241	0.193	0.193	0.193	*Ave 0.201*
GWh/yr/km of noise barrier	0.176	0.162	0.193	0.147	0.203	0.181	*Ave 0.177*

Extrapolating from these figures and FHWA's noise barrier inventory, the technical potential for generating capacity along highway noise barriers in the U.S. is estimated to be on the order of at least 500 MWp and the renewable energy possibly delivered to be likely at least 400 GWh/yr:

Total Linear Length all U.S. Noise Barriers	2,737 miles (~4,380 km)
Total Linear Length of U.S. Noise Barriers that are concrete, berm, or concrete/berm	1,500 miles (~2,400 km)

*2,400 km * 0.201 MWp/km of noise barrier = 482 MWp*
*2,400 km * 0.177 GWh/yr/km of noise barrier = 424 GWh/yr*

424 GWh/yr is roughly equivalent to the annual electricity use of 37,000 homes in the U.S.:

10,812 kwh/yr/home in 2015, or 0.010812 GWh/yr/home (U.S. Energy Information Administration [EIA] www.eia.gov/tools/faqs/faq.php?id=97&t=3)

424 GWh/yr from PVNB

424 GWh/yr ÷ 0.010812 GWh/yr/home = 36,996 homes

According to the EIA, Hawaii had the lowest annual electricity consumption at 6,166 kWh per residential customer. If Hawaii's per home electricity use is used, the estimate increases to nearly 65,000 homes.