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PHOTOVOLTAIC NOISE BARRIERS AS ENERGY GENERATING INFRASTRUCTURE: FUNCTIONAL OVERVIEW ABOUT FIVE SOLUTIONS

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ABSTRACT: Photovoltaic Noise Barriers (PVNB) serve as suitable example for Integrated Photovoltaics, as they make use of existing area of infrastructure to create a secondary function in form of energy generation. Since this secondary function must cohere with the requirements of the primary function of noise protection and additional fulfill mechanical requirements, PV integration into noise barriers is a field of development for special solutions depending on different use cases. Within the project "PVwins", we developed in collaboration with industry partners five different solutions to be build up for testing and monitoring at the end of the project. This paper provides a comprehensive overview of their use case, working principle, impact on acoustical properties, estimated power generation per meter length, and achievable energy yield per meter length. In addition to presenting measurements and simulations, we showcase prototypes. The solutions range from simple street-averted vertical integration of standard modules, to a construction method involving the mounting of standard modules on top of noise barriers. We also developed customized modules with an unique layout incorporating acoustic absorbers between PV strings. For optimal functionality in terms of acoustics and photovoltaics, small-width custom modules are mounted on triangular acoustic absorbers in the cassette solution. Lastly, we introduce an innovative R&D solution featuring a transparent microperforated absorber that offers sound absorption capabilities and enables the full area integration of bifacial modules.

Keywords: Integrated Photovoltaics, Road Infrastructure PV (RIPV), Photovoltaic Noise Barriers, Module Design

1 INTRODUCTION

To tackle the climate crisis and generate affordable energy, photovoltaic will become one major renewable energy source in terms of installed capacity [1]. Achieving this aim requires large areas of land. In countries with high population densities, integrating photovoltaic systems into areas with other primary functions can mitigate land-use conflicts with natural habitat, agriculture, and urbanization [2]. Among integrated PV applications, Photovoltaic Noise Barriers (PVNB) are a good example for Road Infrastructure PV (RIPV) [3]. The current German Federal Government announced plans to utilize the area next to highways stronger for renewable energies and make use of the wind and solar potential for new highway constructions if possible [4]. Also, rising interest from local municipalities, institutions such as BASt (Germany) [5], ASFINAG (Austria) [6], ASTRA (Switzerland) [7], or the European Union with the EU solar energy strategy [8] bring PVNB into the perspective as part of future infrastructure. Photovoltaic noise barriers have been demonstrated in European pilot projects since around 30 years [9] but did not become the state-of-the-art solution for new noise barrier infrastructure yet. On the one hand, organizational obstacles such as the tender design, planning approval process, insufficient political pathways and restrictive legal, as well as technical regulations prevented large scale implementation in Germany [10]. On the other hand, maintaining the main technical function of sound absorption together with all additional requirements still pose challenges to design solutions fulfilling these in an economically attractive way for different use cases.

Within the project "PVwins" [11] (public funded by BMWK) technical solutions for PVNB were explored and developed in cooperation between Fraunhofer ISE and the industry partners R. Kohlhauer GmbH, IGRA Power GmbH and Megasol Energie AG. On the advisory side helped the associated partners Bundesanstalt für Straßenwesen EGIS eG and the Eisenbahn Bundesamt EBA. From this collaborate work we showcase five technical solutions for PVNB.

2 TECHNICAL REQUIREMENTS

2.1 Primary function of noise reduction

As depicted in Figure 1, a noise barrier reduces the sound between the place of emission and the place of immission through reflection and absorption. What remains is a transmitted (not reflected or absorbed) and diffracted part of the emitted sound. Thereby the required noise reduction at the place of immission needs to be larger than 25 dB according to ZTV Lsw 22 [12].

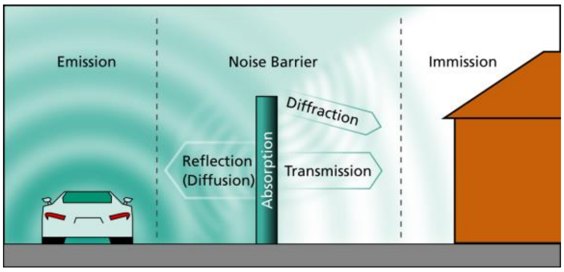

Figure 1: Sound reduction through a noise barrier © ISE

With a hard surface such as concrete or glass, sound can be reflected at the noise barrier. However, this is not feasible at all locations, as it increases the sound on the other side of the street, where potentially also noise protection is required. Therefore, as seen in Table 1, noise barriers often must be sound absorbing. Depending on the local situation, absorption requirements are defined in levels of requirements groups which vary from <4 dB (not absorbing = reflecting), 4 to 7 dB (absorbing) and > 8 dB (highly absorbing) [12]. Since PV modules act with their glass surface highly reflective and are considered as secondary function of a noise barrier, solutions to incorporate PV need to vary depending on the local requirements. For example, distinguishing between street facing- and averted installations is important in terms of noise functions.

Table I: Absorption groups according to ZTV Lsw 22 [12]

Group	Noise Absorption DLa	Explanation
A1	< 4 dB	Not absorbing
A2	4 to 7 dB	Absorbing
A3	8 to 11 dB	Highly absorbing
A4	> 11 dB	

2.2 Additional mechanical requirements

Apart from the noise-related requirements, there are numerous other norms that need to be fulfilled. Since photovoltaic integration is not yet a standard practice, it is not mentioned in the existing norms, and therefore must adhere to regulations which are already in place for long time without being adjusted for the needs of photovoltaics.

One of the main challenges for photovoltaic integration are stone- and snow impact resistance [12]. As safety by design measure, we avoid deploying photovoltaic modules lower than 1.5 m to 2 m above ground. This also is an issue for the susceptibility of vandalism such as graffiti and prevents shading from ground vegetation.

Other concerns of disturbing optical sun reflection on the glass surface of PV modules need to be analyzed site specific and can be solved with anti-reflective glass surfaces. On street averted sides PV integration is more relaxed regarding those acoustic and mechanical requirements. Besides that, different solutions are required for new installations in contrast to retrofit installations of PV modules on existing noise barriers.

For the variety of use cases, solutions for different szenarios are required, of which our five solutions are a demonstration of possibilities. The start of such a design process is an evaluation of the local sound absorption requirements, the orientation of the street and possible designs that fulfill mechanical, aesthetical, and economical requirements.

3 FUNCTIONAL OVERVIEW ABOUT FIVE PHOTOVOLTAIC NOISE BARRIER SOLUTIONS

We present five technical solutions for PVNB in different settings of usage and with different requirements. Furthermore, preliminary estimations regarding acoustical behavior and energy yield are shown, based on tests and simulations. For all five noise barrier concepts it is assumed, that the noise barrier is 4.5 m high, and the bottom 1.5 m above ground are kept clear from PV integration.

3.1 Rear side integrated solution

As an attractive option for noise barriers located on the south side of the street, we propose a road-averted integration of low-cost standard photovoltaic modules. In this particular use case, simplified requirements for optical anti-reflection and stone or snow impact resistance can be advantageous, as custom modules with thicker glass may not be necessary. Also, noise protection is achieved through full-surface absorbers facing the road. The rear side integrated solution is made from two conventional modules, which are integrated into a special designed noise absorber housing, filled with stone wool on the rear of the modules. Three of these elements are then stacked onto one another.

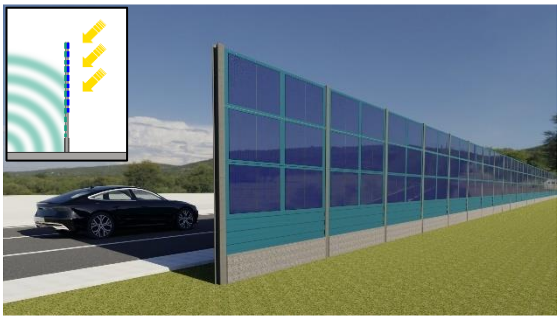

Figure 2: Rendering of rear side integrated solution © ISE

3.2 Top-mount solution

A very flexible solution for existing noise barriers and new ones was developed by our project partner R. Kohlhauer GmbH with the approach of top-mounted PV modules [13]. This solution ensures that the noise absorption capabilities remain unchanged compared to conventional noise barriers. Depending on the specific requirements of the location, PV modules can be mounted with flexible orientations, including inclinations towards the south, east-west, or horizontally. Horizontal integration is particularly beneficial for noise barriers with curved trajectories, as it helps prevent current mismatch.

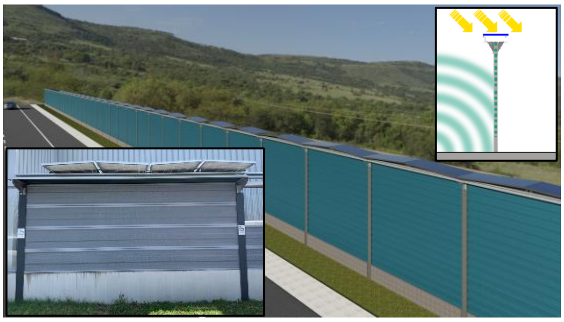

Figure 3: Top-mount solution: Rendering, principle illustration (© ISE) and photo of demonstrator at company R. Kohlhauer GmbH

To understand the noise diffraction behavior with variation of the module inclination from -35° to 35°, we simulated the single value of diffraction. The results in Figure 4 show, that the module decreases the noise behind the noise barrier particularly at higher inclination and are therefore beneficial for sound protection.

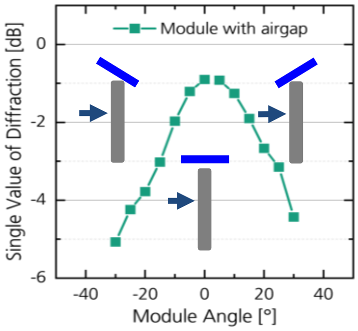

Figure 4: Diffraction variation in relation to module tilt angle

3.3 Combination solution

The combination solution offers a balance between the area dedicated to sound absorption and the area allocated for photovoltaic generation with the use-case of noise barriers with northern position towards the street. Both functional areas are placed vertically towards the street in an alternating parallel configuration. Therefore, we developed a custom module in oversize of 3.9 m length, with two individual substrings, seen in Figure 5 below. The substring between the absorbers is bifacial, the other one is monofacial on the rear of the absorbers, facing to the north.

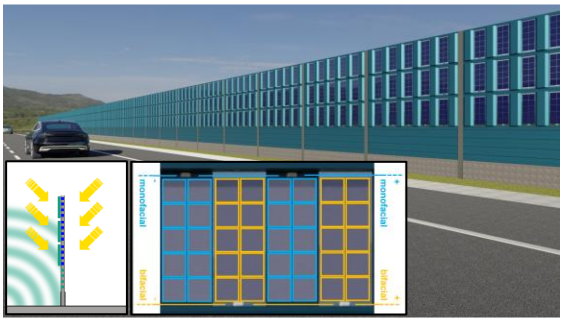

Figure 5: Rendering of combination solution with a sketch of the substring interconnections (view from rear) © ISE

To investigate the impact of parallel area combinations on acoustic performance, we conducted hall chamber measurements on various configurations with different ratios of PV area to absorber area. After evaluation, we selected a ratio that features alternating absorber stripes corresponding to approximately 40% PV area, shown in Figure 6.

Figure 6: Test module with 40% PV area ratio

This choice was made among others because lower PV ratios were found to be economically unattractive. The absorption coefficient of this configuration was measured and is shown in Figure 7. A single value of absorption of 4.8 dB was calculated. It is important to note that the hall chamber measurements could not capture low frequencies, resulting in a lower single value of absorption as these frequencies were considered as zero. Additionally, it is not straightforward to compare measurements conducted in a hall environment with in-situ measurements, such as the Adrienne method, which is the new measurement standard in DIN EN 1793-5 and ZTV-Lsw 22. Therefore, in-situ measurements still need to be performed for validation. However, we project that this solution is suitable for absorption group A2, which requires an absorption of >4 dB.

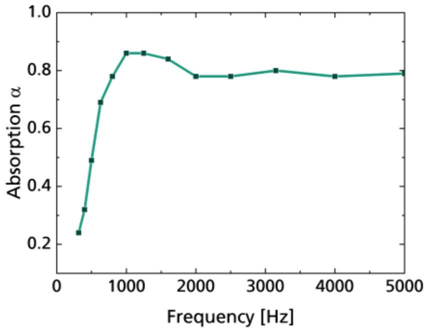

Figure 7: Absorption measurement 40% PV

3.3 Cassette solution

The cassette solution is an effective way to align the functions of noise protection and energy generation in a way that optimizes their individual performance.

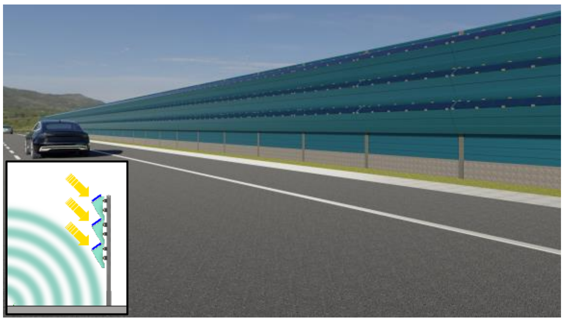

Figure 8: Rendering cassette solution © ISE

With the triangular cross-section, the absorbers are facing towards the road as origin of noise and the PV modules are mounted on the side facing towards the sun in an angle of 35°. Acoustically, the PV modules also improve noise protection by reflecting a part of the sound towards the sky. Since the basic concept is already commercially available [14], we focused on a solution that is not slided into the H-beams but can be mounted in front of existing noise barriers. Thereby it is a retrofit option for noise barriers which should be improved regarding their acoustic performance with additional PV integration.

Figure 9: Prototype of cassette solution with 1m length

We simulated the sound absorption using COMSOL and calculated single values of absorption between 9 and 10 dB. The simulated sound pressure is visualized for a frequency of 1000 Hz in Figure 10.

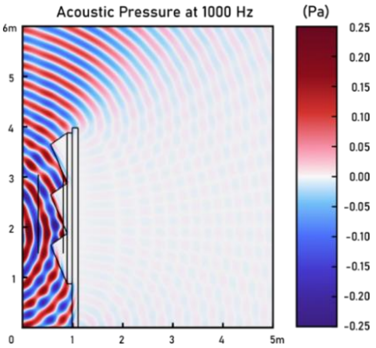

Figure 10: Test setup and absorption measurement

3.4 Microperforated absorber solution

A more innovative attempt is utilizing a sound absorption principle known from room acoustics in interior architecture known as microperforated absorber [15]. It consists of a transparent acrylic plate with micro-perforation of 40.000 holes per square meter, which is kept by distance holders with an airgap towards the sound reflective glass surface of the PV modules. The tested hole diameters ranged between 0.6 and 0.8 mm. Thereby, the functions sound absorption and energy generation are integrated in a serial way (see Figure 11) and are not parallelized as in the combination solution.

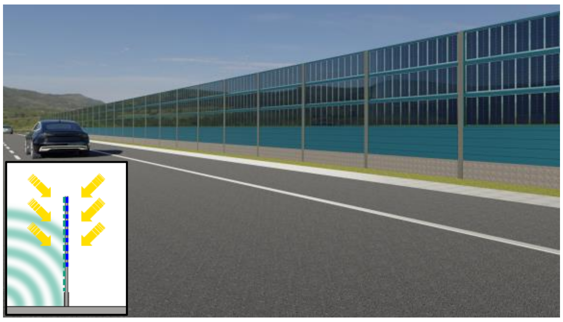

Figure 11: Rendering MPA solution © ISE

The sound absorption works according to the principle of a Helmholtz resonator. The sound waves propagate through the holes, get reflected at the glass surface of the PV module and a small resonating mass-spring-system evolves. The holes do not only let the sound pressure into this resonating system, but also cause friction to the moving air mass, which essentially dissipates a part of the sound energy into heat. The microperforated absorber (MPA) has four main parameters which influence the system behavior strongly and can be used to adjust the absorption with respect to frequency. As shown in Figure 12, these are the hole diameter, the distance between the holes, the thickness of the plate and the air gap distance.

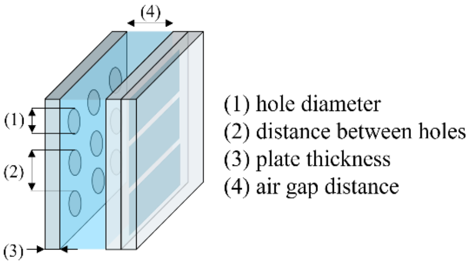

Figure 12: Parameters to adjust MPA system behavior

With these possibilities to vary the bandwidth of the absorption, the frequency of the absorption peak and the absorption maximum, we concentrate in this paper only on the effect of the air gap distance. In Figure 13 is shown, how the peak of the absorption is changing over the frequency range by variation of the airgap distance between 2 mm and 20 mm. The measurement is conducted in an impedance tube, in which a speaker is sweeping the frequency between 50 Hz and 5000 Hz and a microphone array measures the back reflected sound an calculates impedance and absorption values. It can be observed that increasing the air gap distance decreases the frequency of the absorption peak.

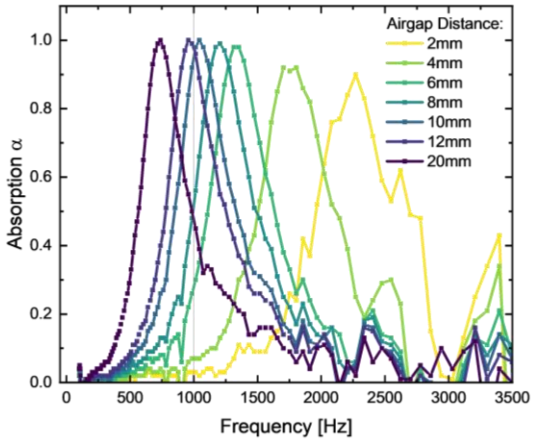

Figure 13: Absorption peaks for a MPA with parameters: (1) = 0.8mm, (2) = 5mm, (3) = 4mm, (4): Variation

Our experimental optimization objective was to achieve a high and broad absorption peak at 1000 Hz, as this frequency range has the most significant impact on the single value of absorption [16]. In the impedance tube experiments, the absorption peaks show small bandwidths, resulting in a single value of absorption of approximately 1.68 dB for the finally chosen plate parameters, still falling within the absorption group A1. However, through further research and development, we anticipate that by optimizing the microperforated absorber or combining it with absorbing frames, a higher absorption value of 4 dB will be achieved. The potential feasibility demonstrated Leistner et. al. [17] with an absorption value of 6 dB for a single layer MPA construction and even 9 dB with a second MPA layer.

Figure 14: Prototype of MPA solution with 1 m length

3.5 Comparison of reachable absorption groups

In Table 2, a short summary of the reachable absorption groups of the discussed five solution is given.

Table 2: Comparison of reachable absorption groups

Nr.	Solution	Absorption Group
1	Rear-side integrated	A3
2	Top-mount	A3
3	Combination	A2
4	Cassette	A3
5	MPA	A1 → A2 (aim)

4 PHOTOVOLTAIC PERFORMANCE

To compare the energy generated by each solution we calculated installable rated power per meter, energy yield per installed kWp and energy yield per meter length shown in Figure 15. The yield estimations are an approximation calculated under the assumptions in Table 3 with the tool *PVGIS* [18] (https://re.jrc.ec.europa.eu/pvg_tools/en/).

Table 3: Assumptions for energy yield calculations

Location	48.004, 7.778 (Freiburg)
Shading of environment	none
Orientation	South
Module Efficiency	21 %
Performance Ratio PR	85 %
Bifaciality Factor BF	80 %

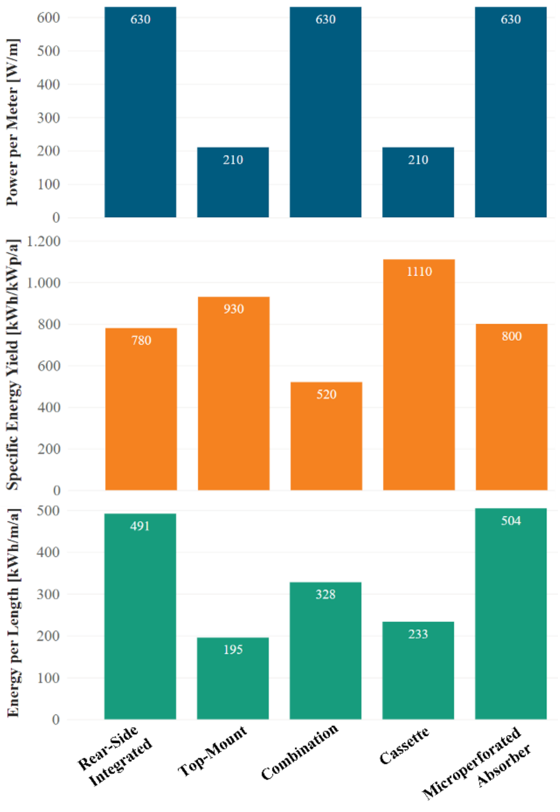

Figure 15: Calculated PV potential. Blue bars indicate the installable power per meter. Orange bars show the specific energy yield per installed kWp per year. The green bars depict the energy yield per meter per year.

The energy calculations of combination solution and MPA solution required extra assumptions. For the MPA solution additional optical absorption losses due the MPA plate were considered with a transparency factor τ_{MPA} of 80 % on the southward oriented front side. The yield of the rear side of the bifacial modules was calculated with a bifaciality factor BF of 80 % with respect to an otherwise monofacial yield on the northern vertical side of 222 kWh/kWp/a.

For the combination solution the energy yield of the two substrings was calculated with the geometrical area ratios of the strings to the whole module. For the bifacial substring, besides the bifaciality factor a shading factor SF of 90 % was also considered for self-shading due to the absorber slides.

Summing up the results in Figure 15, the MPA- and rear-side integrated solutions generate the highest energy yield per meter, since they accommodate PV modules over the whole available vertical area from 1.5 m above ground. However, also the top-mount and cassette solution could both together be integrated into a noise barrier with some modifications and could reach high yield and high noise absorption.

5 DEMONSTRATOR

A demonstrator with the discussed five PVNB solutions will be build up at the Fraunhofer ISE outdoor performance lab in Merdingen [19], as seen in the rendering in Figure 16. It will be placed with a H-pole distance of 4 m over a length of 16 m. The size of this demonstrator is the minimum required for conducting acoustical in-situ measurements [20] and understand how the PV integration solutions compare against a conventional aluminum absorber filled with stone wool for reference. Furthermore, energy monitoring will be conducted of each individual module using power optimizers.

Figure 16: Rendering of demonstrator © ISE

6 ACKNOWLEDGEMENTS

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