TECHNICAL ASPECTS FOR ROAD INTEGRATED PHOTOVOLTAICS TOWARDS A MORE SUSTAINABLE MOBILITY SECTOR

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ABSTRACT: Photovoltaic modules can be integrated into the mobility infrastructure, to realize a dual use of already sealed land. While the theoretical potential is very large, actual technical solutions are unlikely to be installed in every road, railway and bike path. In this work, we evaluate three different integration categories: Into the traffic area, *e.g.*, PV-Pavement, beside the traffic route, *e.g.*, PV-Noise barriers, and above the traffic area, *e.g.*, PV-Roofing. We discuss four quantitative technical aspects, the Specific Yield (kWh/kW$_p$), Specific Costs (€/kW$_p$), Non-PV Cost Share (%), and Integration Capacity (kW$_p$/rm) and two qualitative aspects, the availability of specific Site Requirements and the PV Module Complexity. For each aspect, we assign a rating to the three categories and discuss the advantages and disadvantages of the current technical solutions. We find that PV upgrade solutions for existing noise barriers have a high technical feasibility, while PV-Roofing has the highest practical potential. Solutions for PV-Pavements are currently mostly relevant for niche applications, but all approaches can contribute in different places to the generation of sustainable energy in already sealed areas.

Keywords: Road Integrated PV (RIPV), Module Integration, Dual-Use Infrastructure

1 INTRODUCTION

The mobility sector has enormous need to reduce the associated greenhouse gas emissions (s. [1] and updates). With the current shift towards e-mobility it is also important to supply enough sustainable energy [2]. With the addition of photovoltaics (PV), this energy can be harvested on the existing transportation infrastructure, without the need to seal additional areas.

We refer to this dual use of already sealed land in the present infrastructure or associated areas of the mobility sector traditionally as “Road Integrated Photovoltaics” (RIPV). More generally, we include other transport as railways, bike or foot paths in this category and address applications beyond the substitution of pavement.

The theoretical potential for such applications is enormous. In Germany for example, around 5 % of the land area are is dedicated to transport (18,000 km²), according to the Federal Statistical Office [3]. While certainly not all of it can be combined with PV, a significant amount of nominal PV capacity (GW$_p$) could be installed here. Previous estimations of the theoretical potential for RIPV in Germany have identified up to 660 GW$_p$ on motorways, national roads, regional roads, and railways [4], due to an available area of 3,300 km². To further the discussion, one should go from a theoretical assessment (*i.e.,* multiplying the available area by a common assumption of 200 W/m²) to a technical evaluation of applications and available technology and ultimately a practical-economical potential. This work describes several technical aspects, as they are found today, to take into consideration.

To utilize the sealed land in the mobility infrastructure, different approaches for RIPV have been developed by several groups. The most direct integration might be the replacement of pavement or railbed by adopted PV modules. Studies have been performed in the US [5], the Netherlands [6] and France [7] for example. Another approach is utilizing associated infrastructure, such as noise barriers. Here, the first studies have been started already in 1989 [8] and are continued until today [9]. To circumvent the mechanical load on the PV modules and utilizing the technology of carports and other related applications, lately roofings with PV modules have been suggested as dual-use installation on roadways or associated areas [10, 11].

For a more general discussion, we categorize these into integration into the traffic area, *e.g.*, PV-Pavement, integration beside the traffic route, *e.g.*, PV-Noise barriers (PVNB), and integration above the traffic area, *e.g.*, PV-Roofing (s. illustrations in Fig. 1).

2 APPROACH

In this work, we look into the three categories with five different applications and compare them in six categories. To evaluate the examples in these categories, we use published data from literature, expert opinions from public or private sources, and internal project results from our

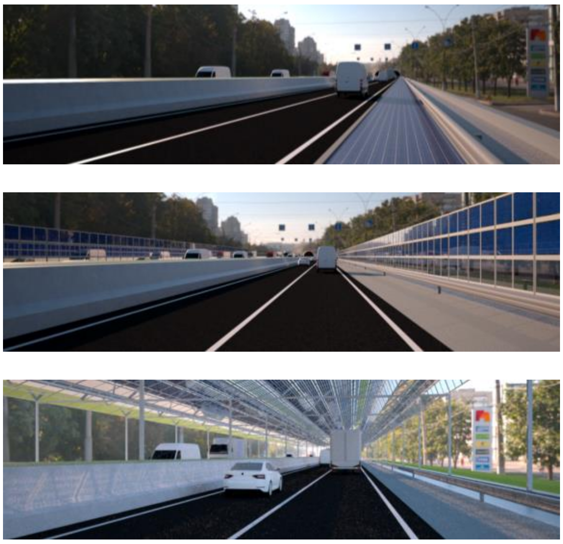

Figure 1: Illustrations of the three RIPV categories: integration into the traffic area (top), integration beside the traffic route (middle) and integration above the traffic area (bottom). Copyright: Fraunhofer ISE.

ongoing research. Where current data is not conclusive, we discuss it in the text.

To compare the different examples, we rank their described advantages and disadvantages in each category on a one (largest disadvantage) to five (highest advantage) scale. The results of this rating are displayed in Fig. 2.

In the following, we first describe the five examples and then discuss them under each of the six categories.

3 INTEGRATION EXAMPLES FOR RIPV

3.1 PV-Pavement

For the integration into the traffic area, we chose the common and widely discussed example of PV-Pavement, where specialized PV modules with highly durable front sheet are used as the road surface (*cf.* [12]).

Fundamentally, PV-Pavement needs to cope with harsh conditions from vehicle loads (including braking action from heavy trucks), corrosion from winter service and soiling, temperature cycling (without rear ventilation) and high safety requirements (both electrical and mechanical). On the other hand, the installations are relatively simple, and the theoretical potential is quite high.

Several specialized products have been developed and are being tested (*e.g.*, [5–7, 13, 14]). Most of them use thicker front sheets to address the increased requirements, which unfortunately reduces the solar yield. In addition, shading from traffic has to be taken into account.

As previous studies have shown, the currently available products are not yet ready for a broad deployment on all traffic areas. Therefore, we refer to the current state of the art and consider applications that seem suitable and the associated solar yield. These are for example, the integration into motorway shoulders or other less frequently used areas such as bike or foot paths.

3.2 PV-Noise barrier (PVNB)

For the integration beside the traffic route, we chose PV-Noise barriers (PVNB). As mentioned above, developments for PVNB have started more than thirty years ago already [8]. Today however, several parameters have significantly changed. For example, the efficiency and costs of a PV module has improved a lot, which makes the application more feasible than before.

An easy integration is the mounting of PV modules on the ridge of existing barriers, referred to as "PVNB (Upgrade)". Here, the noise barrier remains with its previous functionality and the generated energy can repay the costs of installation etc. An illustration is shown in Fig. 3. Several products have been recently submitted to an innovation tender in Austria [15]. Of course, the statics of the noise barrier have to be taken into account.

Figure 3: Illustration of an upgraded noise barrier, referred to as "PVNB (Upgrade)". The modules are installed on the ridge of existing barriers.
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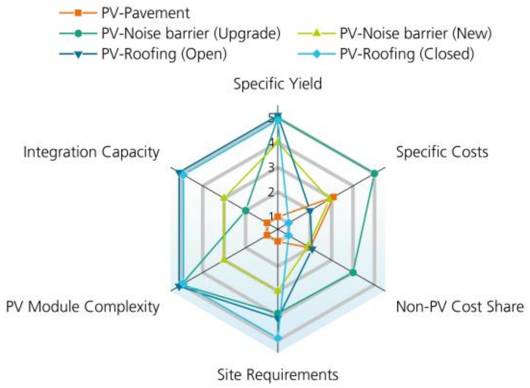

Figure 2: Combined rating of RIPV applications, derived in this work. The examples and ratings are explained in the text.

An alternative is the replacement of the noise barrier elements inside the wall (as illustrated in Fig. 1, middle). From our experience and due to the involved efforts, we expect that this is more likely to be considered for new walls, which is why we refer to it as "PVNB (New)" in this work.

Another integration level is the addition of PV modules on the street-averted side. As technical requirements are similar to those of standard PV installations, mostly regulatory questions remain. As these are very dependent on local legislation, we do not discuss these here in further detail. However, the high theoretical and technical potential for this application, especially for south facing walls, should not be forgotten.

3.3 PV-Roofing

For the integration above the traffic area, we consider PV-Roofing on motorways, as is currently investigated [10, 16]. While certainly having to fulfill the highest safety standards due to the overhead installation, it also has the highest theoretical potential, considering the vast road network.

In the near term, one should expect that PV-Roofing will be mostly done for shorter tracks close to consumers. This could be roadhouses or nearby residents, but also road infrastructure such as tunnels. A major challenge is the balance between safety standards and costs. While the supporting structure should be as simple as possible, it also has to withstand extreme events, such as collision of a truck.

Another issue with the roofing of a road is the noise propagation. As sound cannot escape here, the noise level in direct vicinity to the installation is increased. We therefore consider an open and closed installation, where the latter would be complemented by a common noise barrier at both sides, to contain and absorb road noise.

PV-Roofing is also a promising candidate for integrated PV in other areas, such as car ports, parking spaces, bike and foot paths or other urban areas. Some states in Germany have already started to extend the PV obligation from new buildings to public parking lots [17]. These new market segments might lead to synergistic advancements of necessary components.

4 RATING OF RIPV EXAMPLES

4.1 Specific Yield

The specific yield refers to the amount of generated power over one year (kWh), compared to the nominal installed capacity (kW$_p$).

This is obviously very dependent on the site of the installation and the orientation of the PV modules. Also, the expected performance ratio (effective vs. nominal efficiency) and systematic effects such as shading or soiling from the traffic areas need to be taken into account.

We calculated several different systems and locations using PV*SOL and compared the relative results, to derive some general rule of thumb for an expectable specific yield.

The ideal installation conditions for central Europe are commonly known to be slightly tilted towards the south, to get the most direct insolation. With this one can harvest around 1000 kWh/kW$_p$ per year (still depending on the exact location). With current PV module technology for roof top installations with 200 W/m², this amounts to 200 kWh/m².

However, horizontal installations can regularly harvest 85% - 95% of energy in the same places, as the sun passes over them during the day.

PV-Pavement, PVNB (Upgrade) and the PV-Roofings are all installed horizontally or only at slight tilt for self-cleaning effects. Only for PVNB (New) are the modules installed in the vertical wall. Therefore, also the yield is dependent on its cardinal direction, ranging from 50 % - 70 % compared to the ideal installation. However, if the vertical installation is bifacial, even with a bifaciality factor of only 0.7, the yield can be up to 100% for an ideal East-West orientation, with the additional benefit of a shifted generation profile (peaks in the morning and afternoon).

When evaluating PV-Pavement, it should also be considered that it does not have the desired back ventilation, will be systematically shaded by traffic, and more severely soiled over the year. While some bike paths have performed with less than 5 % of their expected yield in some studies [18], others have been able to provide a yield of around 73 kWh/m² [19], which was later increased to 93 kWh/m². Compared to a mounted installation this is less than 47 %.

On the one hand, one can certainly assume further improvements as the technology matures and more companies are engaging in this. On the other hand, the fundamental limitations of shading and soiling cannot be eliminated. We estimate that today an optimized installation might be able to reach around 50% compared to a mounted installation.

Concluding our analysis, we give an expected specific yield range (± 30 %) for the five considered examples in Table I.

We assign the highest rating to the three horizontal installations, PVNB (Upgrade), PV-Roofing (Open) and PV-Roofing (Closed). To account for the high variation with cardinal direction described for PVNB (New), we deduct one point. We assign the lowest rating (highest disadvantage) to PV-Pavement, which has a systematically lower expected yield, even assuming further improvements of demonstrated technology.

Table I: Expected specific yields (kWh/kW$_p$) with an uncertainty of ± 30 % for central Germany and derived rating (1-5).

	Specific Yield (kWh/kW$_p$)	Rating
PV-Pavement	450	●○○○○
PVNB (Upgrade)	900	●●●●●
PVNB (New)	800	●●●●○
PV-Roofing (Open)	900	●●●●●
PV-Roofing (Closed)	900	●●●●●

4.2 Specific Costs and Non-PV Cost Share

With the specific costs (€/kW$_p$) of the different application examples, we include all estimated costs for PV- and “non-PV”-components together and divide by the estimated nominal installable capacity.

However, these integrated applications fulfill a dual use and some require higher safety regulations in the mounting structure. To differentiate the costs of the adapted PV modules and the remaining costs, we also give the resulting “Non-PV Cost Share”, for each example.

We consulted several experts, *e.g.*, in the field of civil engineering, to discuss the costs of mounting structures and other “non-PV” components. We also consider the additional costs for adapted module materials and necessary engineering work, estimated from current research projects. Where possible, we also refer to price information given by suppliers of current (RIPV) products and compare these to our estimations. As most of these data is confidential, we can only discuss a qualitative comparison.

The upgrade option for PVNB can be realized at comparably low costs, as standard PV modules from mass manufacturing can be mounted on the barrier ridge. Still the price is likely more than double that of a standard rooftop installation, as the mounting structure must be more durable and reliable. Some intelligent engineering is necessary, to design a system that does not impede the structural integrity of the underlying noise barrier. From the present data, we estimate that the non-PV cost share will be around 55% in the end.

A fully integrated PVNB will likely be two to three times more expensive than the ridge top option, due to the higher material consumption and more complex PV modules. On the other hand, such a product also replaces part of the noise barrier, whose value could be deducted from the costs. From current commercial products [15] and our own designs, we derive a non-PV cost share of around 75%. Those PVNB however are mostly sound-insulating. For sound-absorbing barriers, more complex elements have to be built, which allow for less PV area. Therefore,

Table II: Estimated overall specific costs (€/kW$_p$), here relative, for different applications, and derived rating (1-5).

	Specific Costs (a.u.)	Rating
PV-Pavement	2 ×	●●●○○
PVNB (Upgrade)	1 ×	●●●●●
PVNB (New)	3 ×	●●●○○
PV-Roofing (Open)	4 ×	●●○○○
PV-Roofing (Closed)	5 ×	●○○○○

the non-PV cost share will be significantly higher for (highly) absorbent barriers, with a lower solar yield. Unfortunately, current legislation in Germany often promotes highly absorbent sound barriers.

The prices for PV-Pavement can be estimated somewhere in between both PVNB options, although the current prices vary significantly between suppliers [20]. Evaluating the different concepts, we estimate that a high non-PV cost share of around 70% is necessary for the save integration of adopted modules into the traffic area .

As part of the pavement is replaced, one could consider deducting a certain amount from the costs, similar to the discussion of noise barriers. However, it has to be demonstrated that PV-Pavement can achieve the same lifetime as standard paving, or additional replacement and maintenance costs must be added.

The PV-Roofing has the highest specific costs in our current estimation, as no standard mounting constructions are available and as we are considering motorway installation, with the highest safety level.

On the other hand, we assume that reliable glass-glass PV modules with an overhead certificate should be sufficient. Those are already available on the mass market at a slight premium compared to standard products. We therefore expect the non-PV cost share to be between 85% - 90%, as a steel and concrete installation is probably necessary on motorways [16]. For the closed installation, the specific costs and non-PV cost share is higher, due to the additional noise barriers. We estimate that compared to the PVNB (Upgrade), the specific costs will be three to four times as high. However, this can be significantly reduced for applications, where a less massive mounting structure is sufficient, *e.g.*, bike paths.

Concluding this analysis, we give the relative expected specific costs and the non-PV cost share in Table II and Table III.

Table III: Estimated non-PV cost share (%) and derived rating (1-5).

	Non-PV Cost (%)	Rating
PV-Pavement	70	●●○○○
PVNB (Upgrade)	50	●●●●○
PVNB (New)	75	●●○○○
PV-Roofing (Open)	85	●●○○○
PV-Roofing (Closed)	90	●○○○○

We assign the highest ratings to PVNB (Upgrade), where we still see room for improvement in the non-PV cost share, but already a feasible specific cost range.

The considered PV-Roofing of motorways has a low rating mostly due to the high non-PV cost share, which needs to be reduced by new and improved mounting structures. The currently resulting specific costs are not attractive for a mass deployment and need to be improved.

For PV-Pavement and PVNB (New), we see high specific costs and assign a rating of three points. For the non-PV cost share, we deduct an additional rating point, to account for the fact that the dual use in these cases is only preserved by a high investment in the overall installation, making the RIPV application less attractive. As discussed, one could however argue that in both cases, part of the costs should not be attributed to the PV-installation, but to the replaced infrastructure.

4.3 Site requirements

For site requirements, we specifically acknowledge requirements of the considered applications compared to the theoretical potential, taking into account commonly available sites in the mobility infrastructure. Our rating is listed in Table IV.

Table IV: Rating for specific Site Requirements (1-5) for the considered applications, compared to the overall (theoretically) available mobility infrastructure.

Site Requirements	Rating
PV-Pavement	●○○○○
PVNB (Upgrade)	●●●●○
PVNB (New)	●●●○○
PV-Roofing (Open)	●●●●○
PV-Roofing (Closed)	●●●●●

Currently, most PV-Pavement solutions have demonstrated significant short comings in the realized yield and durability. This still leaves several applications in slow traffic areas, bike or foot paths, as companies are currently focusing. This is a significant reduction compared to the theoretical potential, and we therefore assign the lowest rating.

Similarly, the case of vertical integrated PV in noise barriers (PVNB (New)), currently has less practical applications, due to the aforementioned requirements of highly absorbent barriers. However, we think that the dual use of PVNB will be acknowledged more strongly in the future, and therefore assign the rating of three.

The closed PV-Roofing can be practically installed in almost any location, as it does not interfere with the infrastructure and residents. There might be cases, where the roofing might be unwanted by travelers (*e.g.*, panoramic views), but we do not consider these cases to be significant and assign the highest rating.

For the noise barrier upgrade and the open roofing, we deduct one point. The open PV-Roofing might cause an unwanted increase of noise in populated areas, which reduces its applicability compared to the theoretical potential. The ridge top PV mounting requires an existing noise barrier with sufficient structural reserves. Where noise barriers are already present, this should be given in many cases, but not all.

4.4 PV Module Complexity

With the category of PV Module Complexity, we acknowledge the applicability of existing PV module products, development potential and fundamental constraints identified for the applications. Our rating is listed in Table V.

For the PVNB (Upgrade) and both PV-Roofing applications, currently available PV modules can be used. The PV modules are also available from mass manufacturing and profit from the ongoing improvement of the industry. This is a strong advantage, and they all therefore receive our highest rating in this category.

For the vertical PVNB, different approaches exist. Most of those use adopted PV modules, which are however still close to standard fabrication. Also, certain synergies are assumed with the growing sector of Building

Table V: Rating for derived PV module Complexity (1-5) for the considered applications, with 1 indicating a low rating (high complexity) and 5 a high rating (low complexity).

PV Module Complexity	Rating
PV-Pavement	●○○○○
PVNB (Upgrade)	●●●●●
PVNB (New)	●●●○○
PV-Roofing (Open)	●●●●●
PV-Roofing (Closed)	●●●●●

Integrated PV (BIPV). We therefore give the rating of three points to this application. It should be noted that this does not apply to PV modules for highly absorbent solutions, which are likely more complex.

The PV-Pavement solution uses a highly adopted PV module concept, including several different materials and additional process steps. We therefore assign this application the lowest rating, indicating the highest comparative complexity.

4.5 Integration Capacity

We estimate the available installation capacity per running meter of a road (W_p/rm), as an indication for the fraction of technical potential compared to the theoretical potential, which considers the available area as a whole.

As an example, we consider a two lane motorway including a shoulder (emergency lane) and noise barrier and compare what installation capacity could be realized with the different applications today. We again use these estimations to rank the examples. This rating is listed in Table VI.

Table VI: Estimated Integration Capacity per running meter (W_p/rm) and derived rating (1-5).

	Integration Capacity (W_p/rm)	Rating
PV-Pavement	240	●○○○○
PVNB (Upgrade)	340	●●○○○
PVNB (New)	370	●●●○○
PV-Roofing (Open)	3400	●●●●●
PV-Roofing (Closed)	3400	●●●●●

Current solutions for PV-Pavement have a lower specific capacity (W_p/m^2) than standard PV modules, to account for the additional requirements. Also, the existing solutions cannot be integrated in the whole roadbed. For our analysis, we assume a specific capacity of 150 W_p/m^2, derived from some product data sheets, and consider only the less used motorway shoulder with a width of about 1.6 m. This leads us to an Integration Capacity of 240 W_p/rm. This is the lowest value of our examples.

For the PVNB, we assume a standard PV module with 200 W_p/m^2, to be mounted on the ridge, and an adopted module with 185 W_p/m^2 for the vertical installation. We assume that for an optimistic mounting, we can fit one standard sized module (1.7 m × 1.0 m) per running meter, resulting in a maximum Integration Capacity of 340 W_p/rm. For the vertical installation, we assume a mean barrier height of 4 m, whereas the PV installation is only implemented above 2 m from the ground, due to soiling (dirt, snow, …) and potential stone impacts. With this, we arrive at 370 W_p/rm. One might consider that the height of noise barriers varies and that it is more likely that higher barriers are equipped with PV. We appoint a rating of two and three accordingly to these examples.

All other examples are dwarfed by the enormous potential of PV-Roofing. Considering a two lane street with emergency lane, a width of about 17 m can be assumed. Using standard PV modules with about 200 W_p/m^2, this results in 3400 W_p/rm. This is of course highly depending on the width of the street or rather the available area. In any way, PV-Roofing clearly has the highest Integration Capacity and is ranked highest for both application examples.

5 CONCLUSION

In this work, we have derived a qualitative comparison for three levels of RIPV integration. Considering the current state of the art, the installation of PV modules on the ridge of existing noise barriers as an Upgrade received the highest rating (mean: 4.2). While the solar capacity that can be installed with this approach is limited, it should already be a very attractive option for the mobility sector.

A very high solar capacity can be realized by PV-Roofing. However, the specific costs for such installations are dominated by the mounting structure if it is to be installed above a motorway. A couple of additional benefits could be considered to justify the high costs of the mounting structure, such as a lower degradation of the pavement, less winter service or environmental hazards for vehicles or noise insulation.

A very attractive option might be the extension of tunnel portals, where the PV installation can be used to adapt the lighting from bright daylight to the darkness of the tunnel with semi-transparent PV modules and the generated power can be directly used for lighting and ventilation, one of the major power consumptions in road infrastructure.

Another attractive option may be private entryways or road sections of distribution companies. Here, a roof may protect vehicles and personnel from rainfall and winter service may not be necessary anymore.

Solutions for PV-Pavement are less attractive (mean rating: 1.5), given the current limitations, also described in several studies. It is however possible that such installations remain to be seen in niche applications with controllable conditions such as bike paths or walkways with less requirements on the module pavement.

Another application with significant potential is vertical PV-installations to be used in PV-Noise barriers. While current legislation is limiting the applicability, costs can likely be further reduced when a sizeable market is opened. Currently, several countries are looking into this, e.g., Austria [21] and Switzerland [22].

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