

Review

Integrating Renewable Energy in Transportation: Challenges, Solutions, and Future Prospects on Photovoltaic Noise Barriers

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Abstract: The photovoltaic noise barrier (PVNB), a solar noise barrier, is an innovative integration of transportation and renewable energy. It is primarily installed alongside roads near acoustic environmental protection targets in proximity to traffic lanes. PVNBs serve the dual purpose of reducing noise pollution and harnessing solar energy. The electricity generated is used for traffic lights, surveillance, and even feeding into the power grid. This helps to reduce pollution and carbon emissions and improve energy efficiency. This paper provides a comprehensive review of the current research and practical applications of PVNBs, focusing on their unique features. It systematically addresses challenges and proposes solutions concerning optimal site selection, safety standards, noise attenuation effectiveness, power generation efficiency, durability, operational maintenance, and collaborative efforts across various departments. Additionally, this paper highlights the importance of conducting advanced research into glare mechanisms, improving site selection processes, optimizing design strategies, enhancing management and maintenance systems, and conducting comprehensive life-cycle cost–benefit analyses. This research aims to offer scientific insights for designing and deploying PVNBs, thereby fostering the progressive adoption and application of distributed photovoltaics in transportation infrastructures.

Keywords: photovoltaic noise barrier; characteristics; transportation; renewable energy



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1. Introduction

The photovoltaic noise barrier (PVNB) is an environmentally friendly facility that integrates solar photovoltaic power generation technology with traditional acoustic technology to reduce noise and provide electrical energy simultaneously [1]. Since 1989, when the world’s first solar noise barrier system was built in Switzerland, “Traffic + Photovoltaic” projects have been successively implemented in countries such as Germany, the United Kingdom, France, Italy, and China [2]. Transportation and new energy integration have rapidly developed with increasing climate change concerns. Distributed photovoltaics have a broader application scenario in the transportation sector, where “Traffic + Photovoltaic” products quickly emerged and rapidly became the research hotspot [3].

However, transportation scenarios are unique, making photovoltaic power generation systems face more significant challenges, such as increased wind pressure loads, vibration, flying stone impacts, shading, and vehicle exhaust, while also requiring corresponding demands for driving safety and roadbed stability. Therefore, new issues frequently arise when applying distributed photovoltaic power generation technology to traffic scenes, even though it has matured in other fields. Especially for noise barriers closer to vehicles, their photovoltaic applications face more practical challenges, such as site selection rationality,

safety, noise reduction effectiveness, power generation efficiency, durability, operational maintenance, and interdepartmental cooperation.

Currently, numerous studies and patents are related to PVNBs, and their practical applications have been reported repeatedly, but they are not systematic. Based on the performance, material, and shape of PVNBs, this paper systematically summarizes their development status and existing problems and puts forward solutions to critical problems combined with traffic scenarios. It is expected to provide a reference for the research and development of safe, reliable, efficient, and easy-to-maintain “Transportation + Photovoltaic” products, promote the integrated development of transportation and new energy, and positively contribute to the fight against global climate change.

2. Characteristics of PVNBs

2.1. Performance

A PVNB is a vital facility to reduce noise along propagation paths. Its primary function is noise reduction; its additional benefit is power generation [4]. Therefore, a qualified PVNB must meet corresponding standards regarding its fundamental, acoustic, electrical, and optical performance.

Regarding fundamental performance, the appearance, strength, wind pressure resistance, impact resistance, corrosion resistance, fire resistance, moisture resistance, aging resistance, and surface smoothness of the PVNB must meet the quality inspection and evaluation standards for noise barrier engineering. Additionally, particular environments should be considered when PVNBs are applied to different geographical locations, such as areas with strong ultraviolet radiation, intense winds, and heavy snowfall [5].

Regarding acoustic performance, the sound insulation value (R_w) of the non-transparent noise barrier material of the PVNB should comply with the corresponding standards, and the insertion loss of the noise barrier should align with the design noise reduction objectives to pass acoustic acceptance. For example, in China, the R_w should not be less than 26 dB, and the insertion loss value should be more than 10 dB (A) higher than the structural design of the noise barrier. At the same time, the R_w of transparent acoustic materials should not be less than 20 dB, and the noise reduction coefficient (NRC) of the sound-absorbing noise barrier should be greater than or equal to 0.6 (Chinese standard JT/T 646.4-2016 [6]).

In terms of electrical and optical performance, the essential performance, photoelectric conversion efficiency, and power attenuation of the photovoltaic components of the PVNB need to meet reliability and safety requirements. For example, the photoelectric conversion efficiency of monocrystalline and polycrystalline components should not be less than 20% and 18.4%, respectively, and the average annual attenuation over 25 years should not exceed 0.7% in China. Furthermore, these indicators are subject to dynamic changes with technological advancements.

With respect to the safety perspective, anti-glare requirements should be met at the specific traffic scene [7]. Additionally, due to the proximity of the PVNB to fast-moving vehicles, it is exposed to more substantial wind pressure loads from vehicles, more frequent vibrations, a higher probability of impact from flying stones, and a greater concentration of vehicle exhaust, which puts forward higher requirements for its mechanical load resistance and impact resistance and the specific positioning of its photovoltaic components [8,9]. For places with high landscape demand, compatibility with the surrounding landscape should also be considered [10].

Furthermore, the structure and performance of PVNBs under extreme climatic conditions such as cold, arid, humid, and high-altitude environments also need to meet special requirements [11].

2.2. Materials

From the perspective of noise reduction mechanisms, PVNBs are similar to traditional noise barriers, mainly divided into sound-absorbing and sound-insulating composite types, sound-insulating types, and specific frequency interference types. The sound-

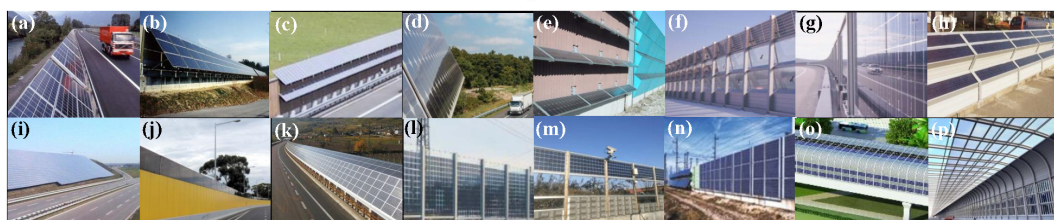
absorbing barrier typically adopts a “panel + sound-absorbing filler material + back panel” structure, often with cavities, and the panel includes single-layer perforated panels, double-layer micro-perforated panels, etc. [12]. In addition, the hole types include pinholes, micropores, louvers, etc. The sound-absorbing filler material, as the core material for the sound absorption function of the barrier, has matured technologically and has entered the stage of industrial development, with a wide range of options available [13]. The back panel primarily serves the sound insulation function [14]. There are also barrier structures that combine a panel and a sound-absorbing filler material, such as foam aluminum panels, aluminum fiber panels, perlite panels, cement–wood chip panels, micro-particle sound-absorbing panels, and clay panels [15–18].

In contrast, PVNBs require the addition of photovoltaic power generation structures based on traditional noise barriers [19]. One of its core components is the photovoltaic module, with monocrystalline and polycrystalline silicon being the most common [4]. Despite the rapid technological updates, iterations, and cost reductions in recent years, new materials such as cadmium telluride, copper indium gallium selenide, gallium arsenide, and perovskite have emerged [20–23]. However, due to various constraints in deploying photovoltaic modules on noise barriers and the need for customized dimensions, the cost of matching photovoltaic modules with the basic structure of existing noise barriers is relatively high. Additionally, inverters, photovoltaic cables, and other balancing components are often required [24,25]. The typical structural composition and materials of PVNBs are illustrated in Figure 1.

Furthermore, as a new technology in noise control fields, metamaterials have also received significant attention in recent years [26]. Sound waves interact with these components, and, since the dimensions of the elements are smaller compared to the sound wavelength, the metamaterials assume specific physical properties, such as a negative elastic modulus, a negative mass density, or a negative refractive index [27]. Therefore, metamaterials can unconventionally manipulate the waves to obtain a deformation of the acoustic field and attenuations that traditional materials do not allow. The results suggest that the barriers obtained with metamaterials can be used to mitigate noise due to road traffic or other noise sources, especially low-frequency noise, which is difficult to control, so they can be a valid substitute for traditional barriers [28]. So, unique structures and shapes of metamaterial noise barriers can be designed based on the frequency band type of noise, site conditions, and surrounding landscape features. Moving on to PVNBs, it can be said that based on metamaterial noise barriers, it is highly anticipated to form a new type of PVNB by adding photovoltaic power generation facilities with high stability and efficiency.



Traditional noise barriers' appearance



Solar photovoltaic noise barriers' appearance

Figure 1. Structural components and materials of common PVNBs. Pictures (a–c,e–h) replotted from ref. [2], pictures (d,i,j) replotted from ref. [29], and pictures (k) replotted from ref. [30].

2.3. Shape

PVNBs can theoretically present all the geometric shapes of traditional noise barriers, commonly including upright, arc-shaped, top-enhanced, semi-enclosed, and fully enclosed types (Figure 2) [31–34]. The top-enhanced structure type can theoretically include angled, inverted L-shaped, T-shaped, Y-shaped, curved top, dome-shaped, curved dome, deer horn-shaped, waterwheel-shaped, deformed T-shaped, mushroom-shaped, dumbbell-shaped, etc. (Figure 3) [35,36]. Considering the particular performance requirements of PVNBs, the upright type is more common, mainly placing the photovoltaic modules vertically on the entire barrier or in the upper part of the barrier, occasionally placing the photovoltaic modules on the top [37]. Traditional noise barriers generally have a typical equivalent height of 3–6 m, with a noise reduction effect (insertion loss) in the sound shadow area ranging from 5 to 12 dB. Studies have shown that for every 1 m increase in the height of the barrier, there is a 2 dB (A) increase in insertion loss [38]. However, when the height exceeds 4 m, in addition to obstructing the line of sight, the self-weight of the noise barrier increases, wind resistance decreases, and the foundation cost also rises, leading to a significant decrease in cost-effectiveness [39]. Considering this factor, it is common to increase the design of the top structure to avoid setting the noise barrier too high and reduce the phenomenon of sound interference at the top of the noise barrier. This design also has a certain effect on controlling low-frequency noise. Therefore, the overall height of existing PVNBs generally ranges from 3 to 4 m.

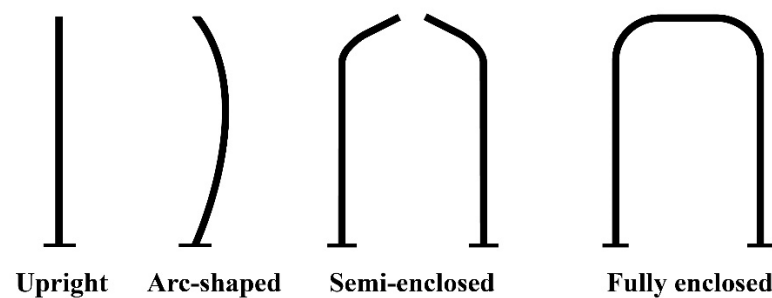


Figure 2. Main types of noise barriers.

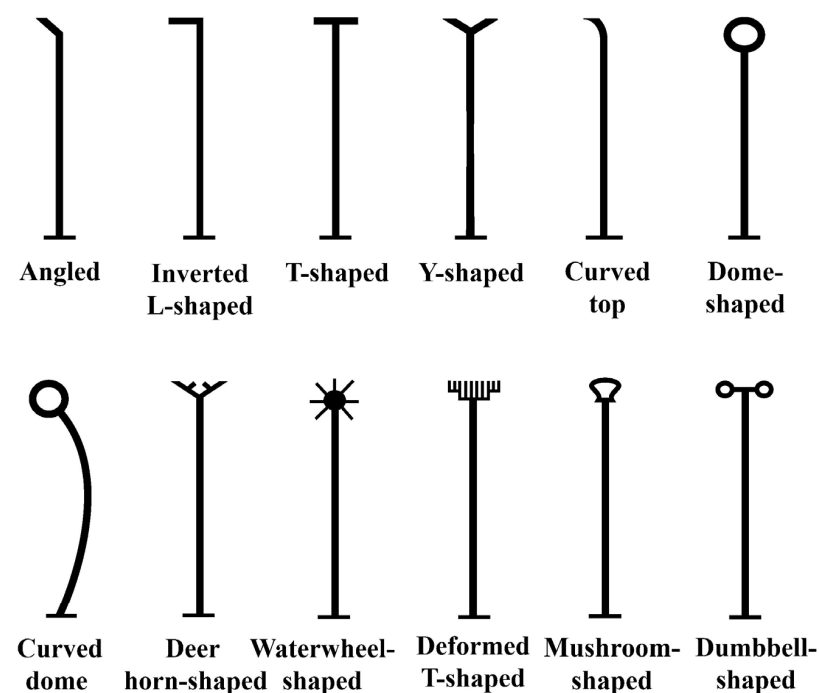


Figure 3. Typical shapes of top-reinforced noise barriers.

3. Research and Application Status

3.1. Research Status

Early research on PVNBs primarily focused on power generation potential and feasibility assessment [3,40]. Among them, European and American countries have studied power generation potential assessment earlier and gradually extended it from highways, railways, and other fields to various other fields. It has also extended from the power generation potential assessment of a single EU member state to the overall assessment of multiple EU member states [41]. Data indicate that noise barriers' peak power generation capacity along highways in six European countries, namely Germany, Italy, France, the United Kingdom, the Netherlands, and Switzerland, is 580 MWp (approximately 200 Wp per meter) [29,42]. Wadhawan et al. [3] analyzed the power generation potential of PVNB systems in the United States. The results revealed that, as of 2017, the existing PVNBs in the United States were sufficient to provide electricity to over 50,000 households, saving more than USD 66 million in electricity costs annually. Recent research has mainly focused on material selection for power generation structures, noise reduction structural design, and improving power generation performance [43]. In addition to traditional crystalline silicon photovoltaic modules, power generation glass, thin-film photovoltaics, semi-transparent photovoltaics, and luminescent solar concentrators (LSCs) have been applied in PVNBs [2,4,44,45]. Although the accumulation of dirt is relatively slow when installing photovoltaic modules on vertical screens, the annual power generation is reduced by 25–50% compared with the optimal inclination installation [46]. Therefore, some scholars have mitigated this impact by adopting designs such as T-shaped, sloping tops, shingles, cassettes, or zigzag, but these designs may cause self-shading of the photovoltaic modules, affecting power generation efficiency [29,47]. To address the self-shading issue, Kanellis et al. [45] attempted to integrate specially designed LSCs into the noise barrier and conducted tests and analyses of their power generation performance, influencing factors, and long-term performance. The results indicated that, although LSCs can significantly enhance the aesthetics, durability, and transparency of PVNBs and reduce costs, their output power is still not as high as that of traditional photovoltaic modules. It is worth noting that there are currently few literature reports on the safety performance of PVNBs, such as glare and collision prevention. In summary, further focused research is needed to balance noise reduction and maximize power generation in PVNBs' structural design, enhancing their safety performance while ensuring noise reduction and power generation functionality [43,48].

3.2. Patent Status

Zhang et al. [48] collected patent data related to PVNBs from the PatSnap Global Patent Database between 2012 and 2021 using the potentiometric method. Their analysis revealed that crucial technologies in this field primarily include the design of the top and outer structures of the noise barrier, the design of the sound absorption structure, and the application of double-sided photovoltaic modules. The related patents are mainly focused on various technical directions such as retrofitting photovoltaic power generation devices on noise barriers, adjusting the tilt angle of photovoltaic modules, the application of double-sided photovoltaic module devices, noise barrier structures conducive to heat dissipation, structures facilitating installation and replacement, damage prevention, sound feedback delay suppression devices, and devices to prevent driver visual fatigue. Overall, a patent layout and a certain technological foundation exist in the key technical areas related to PVNBs. Future inventions and innovations must further optimize structural design to balance noise reduction and power generation, glare prevention, and collision prevention. Furthermore, the number of PVNB patents has increased rapidly in recent years; the overall quality is not satisfactory, and there are relatively few high-value patents, which poses significant challenges in converting patents into productivity. Most patents blindly pursue innovation, which belongs to the inventors' creative ideas behind closed doors. The PVNBs structures described in the patents are complex and costly, have limited power generation

efficiency, and are difficult to maintain, resulting in low commercial value. Therefore, in translating patents into practical applications, it is necessary to comprehensively consider their noise reduction effectiveness, power generation performance, and economic feasibility. Next, we will combine practical application cases from both domestic and international contexts to discuss the progress in the field of PVNBs.

3.3. Application Overview

In 1989, TNC Consulting AG (a telecom consulting company) collaborated with the Swiss Federal Highway Administration to construct the world's first PVNB system in Switzerland. The project, spanning less than 1 km, is still operational and generates a net annual profit of approximately 108,000 kWh after deducting the power required for its monitoring system and inverters [49]. Around seven years later, three uniquely structured PVNBs were constructed on highways in Switzerland and Germany [50], featuring box-type, roof-type, and Z-shaped designs [2]. In 1992, Germany completed its first PVNB. Subsequently, due to the implementation of the German Renewable Energy Sources Act, various PVNBs were successively built across Germany, surpassing 18 locations by 2017 [29]. In 2007, the first PVNB with a capacity of 30 KW was built in Seoul, South Korea, by adopting integrated design and modular installation. In 2000, Switzerland completed the first thin-film PVNB [2]. In 2008, China's first PVNB was installed on the North Extension of Rail Transit Line 3 in Shanghai, China [51]. In 2012, the world's first large-scale application of PVNB was installed on the A22 highway in Brenner, Italy [30]. In 2015, the Massachusetts Department of Transportation, in collaboration with KO-Solar and its partners, completed a pilot PVNB project on Interstate 95 in Lexington, Massachusetts [52]. Additionally, countries such as Australia have also implemented PVNBs [52]. With the acceleration of urban elevated ring road construction and noise control processes, China has initiated pilot demonstrations on fully enclosed noise barriers [53]. As of 2023, at least 100 PVNBs have been installed in at least 14 countries, including Switzerland, Denmark, Austria, Germany, the Netherlands, France, Australia, the United Kingdom, Italy, South Korea, Croatia, Slovenia, and Sweden. Some have modified traditional noise barrier tops or panels to incorporate photovoltaic components, while others have pursued integrated designs for PVNBs [3]. In recent years, many cases have appeared where the photovoltaic components are vertically arranged on a vertical screen and the photovoltaic modules are mainly crystalline silicon materials. Double-sided photovoltaic modules are mostly used for photovoltaic panels to avoid the problem of low solar energy utilization efficiency of vertical screens [54]. Additionally, there are instances of placing photovoltaic components on the tops of noise barriers, often using thin-film cells that are flexible and lightweight and have good low-light performance and high-temperature adaptability [55]. Furthermore, some PVNBs are equipped with LSCs [29]. The typical applications of PVNBs are detailed in Table 1.

Table 1. Typical PVNB projects.

Year	Location	PVNB's Appearance in Figure 1	Scale	Characteristics	Reference
1989	A13 freeway, Switzerland	(a)	The installed capacity is 100 kW, with an annual power generation of 100 MWh and a total length of 800 m.	The world's first PVNB, featuring polycrystalline silicon photovoltaic modules tilted at a 45° angle toward the east and mounted on the upper structure of a 2 m high noise barrier. It has a total photovoltaic module area of 970 square meters and is still operational today.	[2,29]

Table 1. Cont.

Year	Location	PVNB's Appearance in Figure 1	Scale	Characteristics	Reference
1995	Giebenach A2 freeway, Switzerland	(b)	The installed capacity is 100 kWp, with an average power generation of 850 kWh/kWp.	The characteristic of this PVNB is that the photovoltaic modules are installed in two layers at an angle at the top and middle of the traditional noise barrier.	[2]
1996	Alpha A1 highway, Switzerland	(c)	The installed capacity is 75 kWp.	Equipped with 24 microinverters, the lower row of photovoltaic modules is shaded during the summer months.	[2]
1998	Highways near Amsterdam, Netherlands	(d)	It is 1.6 km long, generating 176,000 kWh of electricity per year.	It was the longest and largest PVNB in the Netherlands at the time.	[29]
1998	A96 highway in Munich, Germany	(e)	The installed capacity is 8.77 kWp, with an average generation of 751 kWh/kWp.	The photovoltaic modules are laid out in cassettes and equipped with a single inverter, integrating acoustic insulation and sound absorption. The module operating temperature is 40.9 °C.	[2]
1998	A96 highway in Munich, Germany	(e)	The installed capacity is 9.13 kWp, with an average power generation of 814 kWh/kWp.	The photovoltaic modules are arranged in a tile format and equipped with a single inverter, integrating sound insulation and absorption. The module operating temperature is 43.9 °C.	[2]
1998	A96 highway in Munich, Germany	(f)	The installed capacity is 10.08 kWp, with an average generation of 794 kWh/kWp.	The photovoltaic modules are arranged in a zigzag pattern and equipped with a single inverter, serving as a sound-insulating barrier. The operating temperature of the modules is 27 °C.	[2]
1997	Aubruugg, Switzerland	(g)	The installed capacity is 8.27 kWp, with an average power generation of 681 kWh/kWp.	It is the world's first bifacial power generation PVNB with ASE bifacial prototypes, serving as an acoustic isolation-type noise barrier. The module operating temperature is 26.5 °C. In the first two years of operation, its power generation efficiency was only 60% of what was expected.	[2,56]
1999	Wallisellen, Switzerland	(h)	The installation capacity of 9.65 kWp results in an average power generation of 497 kWh/kWp.	The photovoltaic modules are arranged in a zigzag fashion and equipped with 45 microinverters, serving as a composite sound-absorbing and sound-insulating noise barrier. The module operating temperature is 43.9 °C. It is near a railway line, but electromagnetic interference is not a problem.	[2]
2000	Wallisellen, Switzerland	-	With an installation capacity of 8.2 kWp, the average power generation is 446 kWh/kWp.	The photovoltaic modules are arranged in a vertical box layout and equipped with a single inverter, serving as a composite sound-absorbing and sound-insulating noise barrier. The module operating temperature is 34.8 °C. It was the first thin-film PVNB.	[2]

Table 1. Cont.

Year	Location	PVNB's Appearance in Figure 1	Scale	Characteristics	Reference
2007	Near Tullamarine Airport, Melbourne, Australia	(j)	The total length is 500 m.	A total of 210 pieces of 106 kg amorphous silicon solar panels are vertically installed on top of a 4 m high precast concrete structure. The decrease in power generation efficiency caused by the vertical installation is acceptable. There have been no security issues or thefts, and the installation is positioned high enough for drivers to notice without the effects of glare.	[29]
2007	Seoul, South Korea	-	The installed capacity is 100 kW.	By vertically installing photovoltaic modules, the noise barrier serves sound absorption, sound insulation, power generation, and landscape enhancement functions.	-
2008	North Extension of Rail Transit Line 3, Shanghai, China	-	Approximately 360 m in length, with a power output of 10 kW.	Amorphous silicon solar cell modules are used for grid-connected power generation. They are installed in a single row, with existing frames used on the top, bottom, left, and right edges. This system can generate over 6000 kWh per year, which is sufficient to meet the lighting needs along the route.	[51]
2012	A22 highway, Brennero, Italy	(k)	-	It is the world's first large-scale project combining photovoltaics with noise barriers.	[30]
2013	Munich, Germany	(l)	The installed capacity is 7.544 MW.	The photovoltaic modules are vertically installed on the noise barrier screen to provide sound insulation and power generation.	-
2017	Seoul, South Korea	(m)	The installation scale is 30 kW, generating 30,000 kWh of electricity annually.	The PVNB screen consists of three parts: the lower part is the sound-absorbing screen, the middle part is the transparent screen, and the upper part is the photovoltaic module vertical screen. This is the typical form of a PVNB.	-
2020	Tullnerfeld, Austria	(n)	Installed on the south-facing outer side of the noise barrier along the railway line, with a total installation capacity of 30 kWp.	The photovoltaic modules are installed at three different inclinations of 0°, 15°, and 30° on the noise barrier. This photovoltaic test system also includes an independent 10 kVA 16.7 Hz inverter.	-
2023	Hongmei South Road, Shanghai, China	(o)	With a total installed capacity of 1.5 MW, the total electricity generation will exceed 37.5 million kWh over the operational lifespan.	China's first elevated soundproof shed photovoltaic project, with lightweight flexible photovoltaic modules installed on the outer facade of the soundproof shed. It enables on-site power consumption and surplus power to be fed into the grid.	-
2023	Elevated Friendship Avenue, Wuhan, China	(p)	It is approximately 300 m in length.	Replacing the closed noise barrier facade and the top acrylic sound insulation board with double-sided photovoltaic power generation components.	-

4. Application Problems and Solutions

After conducting in-depth research, it was found that, although PVNBs have significant application potential, their adoption level, application number, and scale are far lower than expected compared to highway slope photovoltaics and service area photovoltaics carports, which are also in the traffic scenario but show a global trend of explosion. Therefore, an in-depth analysis of the underlying reasons, which may be based on comprehensive considerations of safety, economic feasibility, applicability, stability, and durability and involve technical and managerial aspects, is of great importance. These include the following key aspects.

4.1. Rationality of Site Selection

Reasonable site selection is critical to reducing the investment and maintenance costs and improving the power generation efficiency of PVNBs. From a technical perspective, solar radiation intensity and meteorological conditions significantly impact photovoltaic projects [57]. However, site selection should also comprehensively consider local electricity prices, grid connection, and power consumption [58–60]. Priority should be given to areas with higher electricity prices and adequate solar radiation intensity, and the barriers should be preferably installed on both sides of east–west-oriented roads, near grid connection points, or at power consumption sites [61]. Without considering benefits such as subsidies, if the electricity price in that area is too low to cover the LCOE (levelized cost of energy), then the construction of PVNBs is not economically feasible. The distance between PVNBs and the grid connection or consumption point directly affects the line loss. If it is longer than 2 km, a more cautious attitude should be taken towards the site selection. It is worth noting that what society needs is noise barriers that can generate electricity and bring benefits, rather than a “sunbathing” project. Therefore, the inability to connect or consume PVNBs in close proximity has become the main factor restricting their application.

4.2. Safety

4.2.1. Glare Impact

Although the mechanism of glare impact from PVNBs is not yet fully understood, the reflection of light from photovoltaic components may cause visual disturbance to drivers [52]. Research on PVNBs in Australia has shown that photovoltaic components installed at an inclination of approximately 60° to the horizontal plane have led to driver complaints about glare [29]. In practical terms, low-iron high-transmittance tempered glass or low-iron high-transmittance frosted glass can be used as panel materials; anti-reflective coatings can be added; the surface of monocrystalline silicon can be textured; and anti-reflective coatings can be applied to various reflective parts of photovoltaic components [62,63]. These methods can significantly increase the transmittance of glass cover plates and the absorption of light energy without significantly affecting their power generation performance [62,63]. This technology has already been used in a photovoltaic power generation project on the Taixin Expressway in Shanxi Province, China. Field measurements have demonstrated that the transmittance of the specially treated component panels reaches 94%, and the reflected light mainly exists in the form of diffuse reflection. Additionally, dark-colored components similar to regular tiles have been used in the project, effectively addressing the glare issue.

4.2.2. The Impact of Flying Debris and Vehicle Emissions

Considering these factors, installing photovoltaic components near the roadside or at low heights above the ground is not advisable. Reinforced polymer panels should be used on elevated roads, overpasses, and densely populated areas where transparent barriers are needed [64]. When glass is required as a sound insulation material, reinforced strengthened glass should be used [65]. Therefore, it is not difficult to infer that the PVNBs referred to in Pictures (g) and (l) in Figure 1, as they are placed on the side of the adjacent lane and start to be laid up close to the ground, will definitely encounter more risks of flying stones,

splashing impacts, and pollution from car exhaust or mud, and are also more prone to damage. The test data show that the PVNB referred to in Picture (g) has an expected power generation efficiency of only 60% in the first two years of operation, which may be related to this factor [2,56]. Due to this consideration, PVNBs installed in recent years have been trying to avoid this risk as much as possible.

4.2.3. The Impact of Bird Strikes

PVNBs located near bird natural reserves or areas with frequent bird activity require additional bird strike prevention design to avoid real or transparent visual disturbances caused by the reflection of the barrier surface, which may lead to bird collisions and fatalities. Considering the differences in visual cells between most birds and humans and balancing visibility and driving comfort, ultraviolet (UV) ray coatings (polyurethane UV-curable coatings) can be applied to the panel glass or transparent screens of photovoltaic components, such as ceramic fritted glass, frosted glass, or painted glass [66]. This is because the UV wavelength range is generally 200 nm to 450 nm. After treatment, the panel glass or transparent screens will appear unchanged to humans' vision, but birds can see the UV light, thereby preventing collisions.

4.2.4. The Construction Techniques

When the height of the PVNB is less than or equal to 3 m, the steel columns should be made of integral steel. When the overall height exceeds 3 m, the steel columns can have a welded seam. If transparent materials are used for the noise barrier, an embedded connection structure should be used for fixing the frame rather than a rigid fixation with bolts or screws [67]. The sound-absorbing barrier should have drainage holes and a rainwater diversion board. The frame of the photovoltaic components should have a design that facilitates drainage. Structural steel bars or metal components should be used for electrical continuity and connected to the comprehensive grounding terminal [68].

4.3. Noise Reduction Effect

When all or part of the sound absorption screen in the traditional noise barrier is replaced with photovoltaic modules with a sound insulation function only, the overall noise reduction effect of the noise barrier will be reduced. Even though few reports actively mention this issue, it is indeed an indisputable fact. Additionally, sound reflection may lead to an increase in noise on the other side of the barrier. In this scenario, the design of the sound-absorbing barrier can be reinforced, for example, by using multidimensional structures, cassettes, or zigzag shapes. Alternatively, based on the principle of resonance sound absorption, micro-perforated panels can be added on the side close to the road, with a certain distance left between each photovoltaic component to form a sound absorption resonance cavity, thereby enhancing the sound absorption performance of the PVNB [14,69]. High-sound-absorption-coefficient materials such as foam aluminum can also be used, or the top of the noise barrier can be reinforced while avoiding obstruction of the photovoltaic components [70]. It is essential to consider the stability of the PVNB and the special requirements of the photovoltaic component material when the photovoltaic components are installed at the top of the noise barrier. Remedial measures, such as noise reduction through vegetation, can be taken to address the issue of increased reflection noise on the other side [71]. Furthermore, the noise reduction effect of the noise barrier is closely related to the frequency components of the noise. The noise reduction effect on high-frequency noise greater than 2000 Hz is better than that on intermediate-frequency noise around 800–1000 Hz. However, for low-frequency noise below 100 Hz, due to its long wavelength, it is easy to diffract from above the barrier, resulting in a poor noise reduction effect. In practical applications, targeted reinforcement of the top design can be combined with the specific noise characteristics of the road section to reduce low-frequency noise [72]. The theoretically feasible appearance design of the top-enhanced PVNB can be referred to in Figure 3, mentioned earlier.

4.4. Generation Efficiency

Although photovoltaic technology and its photoelectric conversion efficiency are increasingly improving, the output power of photovoltaic systems is easily affected by various factors and needs to be enhanced in practical engineering applications.

4.4.1. Solar Radiation Intensity

Solar radiation mainly includes direct, diffuse, and reflected radiation [73]. As the intensity of solar radiation increases, the output power of photovoltaic cells also increases [74]. The dynamic characteristics of solar radiation intensity affect the stability of photovoltaic systems. Generally, the higher the solar radiation intensity, the higher the power generation efficiency of PVNBs [75]. However, when the solar radiation intensity is too high, the temperature of the photovoltaic components also increases. The movement of electrons inside becomes more intense, thereby increasing the probability of electron recombination, leading to a decrease in power generation efficiency [76]. Traditional noise barriers generally operate at $-30\text{ }^{\circ}\text{C}$ to $50\text{ }^{\circ}\text{C}$. The operating temperature range of photovoltaic components is usually between $-40\text{ }^{\circ}\text{C}$ and $85\text{ }^{\circ}\text{C}$. However, research has shown that the optimal operating temperature of PVNBs is around $25\text{ }^{\circ}\text{C}$ and should not exceed $40\text{ }^{\circ}\text{C}$. Therefore, the solar radiation intensity and temperature of PVNBs can be controlled by regional macro-siting.

4.4.2. Wind Speed

Wind speed is one of the essential factors to consider in the construction of PVNBs, since it has a certain impact on the design, stability, and effectiveness of noise barriers. In general, the appropriate wind facilitates the removal of dust and pollutants from the surface of PVNBs, which can improve their power generation efficiency [77]. However, to ensure that PVNBs can withstand local perennial wind speeds and cope with extreme weather conditions, it is necessary to consider wind load effects in the design and improve the stability and wind resistance performance of PVNB structures, which inevitably increases the investment. In addition, the structure of PVNBs may be damaged when the wind speed is too high, e.g., exceeding a gale force of 8 [5].

4.4.3. Dust Contaminants

Research indicates that when the surface of PVNBs is covered with dust and pollutants, power generation efficiency decreases [78]. Furthermore, the impact of fine particulate pollutants is more significant than that of coarse particles [79]. Therefore, in theory, regular cleaning of PVNBs should be conducted. However, practical experience has shown that, in order to avoid cleaning costs exceeding the potential efficiency gains, it is advisable to utilize self-cleaning technologies for photovoltaic components whenever possible [29,80]. For instance, German photovoltaic panels typically do not require cleaning to prevent the cost of cleaning from outweighing the potential efficiency improvements.

4.4.4. Shadow Occlusion

When the surface of PVNBs is shaded, the photovoltaic conversion efficiency decreases [81]. When the illumination is uneven or the local strong light irradiation time is too long, it may cause a local high-temperature phenomenon in the blocked area of the photovoltaic panel (commonly known as the “spot effect”), affecting the lifespan and performance of the photovoltaic panel. Meanwhile, shadow occlusion may also lead to voltage instability and uneven current in photovoltaic systems, affecting the stability and safety of the system. Remote occlusion generally considers nearby mountains or other distant but large objects. Near shading and far shading include two aspects, i.e., the occlusion of the PV panel and the surrounding obstacles. Therefore, at the macro-site selection level, the position and orientation of PVNBs are crucial. At the micro-design level, self-shading issues should be considered [82]. It is worth mentioning that the remote occlusion analysis of PVNBs in cities with towering buildings is complex and also one of the difficulties.

4.4.5. Position and Angle of the Photovoltaic Module Layout

Typically, PVNBs are arranged along the road, aligned with the direction of the road. In theory, photovoltaic components can be synchronized with the trajectory of solar operation, no longer constrained by the direction of the road. However, this would significantly increase project investment and maintenance costs. In practical applications, considering the limitations of the installation area and traffic safety, it is more common to install photovoltaic components vertically, facilitating self-cleaning, albeit resulting in a decrease in annual power generation of 25% to 50% compared to the optimal orientation and tilt angle [46]. However, with stable support structures, double-sided PVNB technology can effectively alleviate the decrease in power generation efficiency caused by vertically installed photovoltaic components [83]. It is also possible to consider setting a certain tilt angle on the side away from the road to improve power generation efficiency. Furthermore, the working temperature of photovoltaic components directly affects power generation efficiency, making the ease of heat dissipation in the layout of photovoltaic components a vital consideration [84].

4.4.6. Electricity Loss

As a linear photovoltaic power station, excessive cable length during grid connection or the absorption process can lead to electricity loss, diminishing its practical value. Taking a single-crystal double-glass module with a size of $2000 \times 1000 \times 35$ mm as an example, the single chip power is 545 wp, the photoelectric conversion efficiency is 21.1%, and the maximum withstand voltage is 1500 V. If a 400 V grid connection is adopted, the distance from the inverter to the grid connection cabinet should not exceed 300 m. If a 10 kV grid connection is adopted, although the distance is no longer limited, a step-up transformer, a 10 kV incoming line, a PT cabinet, an outgoing line cabinet, a low-voltage outgoing line cabinet, a compensation cabinet, etc., need to be used, and the actual conditions may not meet the requirements. Therefore, cables should not be excessively long and be within an acceptable cost range. Superconducting materials should be used as much as possible to reduce electricity loss and improve power generation efficiency [85]. If grid-connected power generation is adopted, the rational layout of the grid connection point must be considered, ensuring that the voltage and current of the photovoltaic module's series-parallel connection system match the inverter while also ensuring that the cable length and line loss achieve the best cost-effectiveness ratio [86].

4.4.7. Device Options

The selection of photovoltaic modules, inverters, and cables directly affects the power generation efficiency and LCOE of PVNBs. In recent years, the records of various components' photoelectric conversion efficiency have been accelerated and refreshed, and the design of microinverters has been continuously optimized. The related technology updates and iterations are fast, but the cost is decreasing. Therefore, when selecting equipment, priority should be given to adopting new technology equipment while ensuring reliability, safety, and economy.

4.5. Durability

The durability requirements for PVNBs are higher than those for traditional noise barriers, incredibly demanding the ability to maintain good working conditions under extremely hot weather and intense ultraviolet radiation [87]. Different countries have varying standards for the service life of PVNBs. For instance, in China, the acoustic components of solar noise barriers are required to have a service life of no less than 15 years; the service life of the power generation structure should not be less than 25 years; and the service life of steel columns should not be less than 30 years. Other structural and foundation designs should comply with current national and industry standards. In terms of durability, the components of solar noise barriers are more prone to problems such as sound leakage, loosening of fasteners, and poor wiring, leading to power generation

issues [88]. Therefore, during the installation of PVNBs, it is essential to use weather-resistant sealants, cover plates, connectors, clamps, and anti-vibration fasteners.

4.6. Operation and Maintenance

The routine maintenance of PVNBs primarily involves visual inspections [89]. Positioned alongside roads with both sides exposed to the air, which is advantageous for construction and heat dissipation, maintenance presents particular challenges. Common issues include mud, dust covering, damage to components caused by flying stones, and wiring faults. When PVNBs are located far from urban areas, timely maintenance is complex. In urban areas, these barriers are typically situated on both sides of expressways, making repair work challenging due to heavy traffic and spatial constraints. Therefore, the power generation structure of PVNBs, especially components requiring frequent replacement, should preferably use standard modular products [90]. This approach facilitates commercial mass production and modular installation, reducing subsequent maintenance costs. Additionally, the electrical wiring and connections between modules should be safe, reliable, and straightforward [90].

4.7. Departmental Collaboration

PVNBs are both an environmental and power generation facility [1]. Due to the division of road construction, management, and maintenance among different departments, its construction and operation require coordination across multiple departments. The investment and returns involve various departments, such as municipal administration, highways, and electricity, making it difficult to distribute profits evenly. This challenge is particularly pronounced when the scale is small, as the long investment payback period makes it even harder to mobilize the enthusiasm of each department. To express this issue more clearly, we can take the PVNBs on Chinese highways as an example. They belong to transportation and environmental protection facilities, which are generally funded and constructed by highway investment units (there are many types) or can be independently invested in by photovoltaic investment units with permission. The ecological and environmental supervision department is responsible for approving the Environmental Impact Assessment documents, including the PVNB; the PVNB investment unit is responsible for conducting the environmental protection acceptance; and the transportation industry administrative department is responsible for the project completion acceptance. The highway maintenance department is responsible for daily maintenance. If PVNBs need to be connected to the power grid, they also need to obtain administrative permission from the power department. In short, it requires collaboration among multiple departments, and the management requirements of each department are not the same, which makes the development of PVNB management procedures more complicated than the technical difficulties mentioned above. Therefore, the nation and the industry must introduce relevant policies to address management bottlenecks actively.

5. Conclusions and Prospects

Due to their dual characteristics of power generation and noise reduction, PVNBs not only effectively reduce mid-to-low-frequency noise but also generate green electricity. Consequently, this reduces the consumption of standard coal and indirectly decreases the emissions of carbon dioxide, sulfur dioxide, and nitrogen oxides. Moreover, as no additional land is required, they hold the potential to become a new battleground for the integration of transportation and new energy development. This article provides a comprehensive overview of the characteristics of PVNBs, encompassing essential performance, acoustic properties, optical features, and electrical performance. It also examines the current research status and application landscape of PVNBs, along with a review of typical cases. Simultaneously, this article systematically scrutinizes the prevailing challenges of PVNBs in practical applications—including site selection rationality, safety, noise reduction efficacy, power generation efficiency, durability, operation and maintenance, and interdepartmental

collaboration—and offers solutions to these issues. The content of this article is relatively comprehensive, with the aspiration that it can furnish valuable guidance for researchers and practitioners involved in the study and implementation of PVNBs. It is imperative to acknowledge that, although there are no insurmountable technical impediments with PVNBs, attention to safety, economy, applicability, stability, and durability in research and practice remains crucial due to constraints in site conditions. In the future, we need to focus on the following areas:

(1) Enhance the research on glare mechanisms. Although glare issues can be alleviated through technical means or rational placement of its position and angle, in-depth research into the underlying impact mechanisms and experimental verification is still needed. It is possible to explore the relationship between the driver's pupil area and the light environment when driving on road sections with and without photovoltaic components installed on the noise barriers. This analysis can also involve studying the driver's gaze to investigate the reflective nature of PVNBs and the impact of the light environment on the driver's visual recognition, safety risk perception, and psychological and behavioral effects.

(2) Strengthen the site selection justification for PVNBs. A scientific site selection is a prerequisite, requiring thorough consideration of the overall site selection and environmental conditions. It includes a comprehensive assessment of road geography, solar resources, orientation, regional electricity prices, grid connection points, absorption capacity, surrounding obstructions, and other factors. The goal is to arrive at a scientifically reasonable site selection based on various constraints. Furthermore, a gradual approach is necessary to avoid practical mismatches and limitations in the face of complex influencing factors.

(3) Optimize the design scheme. The noise reduction and power generation effectiveness of solar noise barriers are directly related to the design scheme, which should be involved in the initial road design phase. As noise barriers, their acoustic performance must meet environmental protection requirements, necessitating an in-depth analysis of the barrier's form, height, noise spectrum characteristics, material, position, and function. Additionally, as photovoltaic facilities, the design should be conducive to considering the scale based on transformer capacity and selecting suitable inverters and photovoltaic components. For the photovoltaic components, high-performance modular double-sided photovoltaic modules can be utilized, or flexible photovoltaic modules with light weight, small thickness, high flexibility, and easy installation can be explored. These can be directly attached to light loads and curved surfaces to reduce the need for brackets or other mounting systems. Photovoltaic components should be designed according to the common standard dimensions of existing noise barriers or customized in shape, color, and pattern to suit various new and existing noise barrier scenarios. To ensure the reliability of the design scheme, the scheme demonstration phase should involve modeling optimization of the structural design parameters and dimensions based on environmental conditions.

(4) Improve the management and maintenance system. Due to the proximity of PVNBs to the roadway, the probability of contamination and the frequency of vibration affecting the photovoltaic components are significantly higher than for other traffic photovoltaic systems. Other equipment is also subject to varying degrees of aging and damage. Therefore, the need for cleaning, maintenance, or replacement is indispensable. The scope of road photovoltaic power generation technology is extensive, and the working environment is different from how it was before, rendering existing road management models and the technical expertise of maintenance personnel inadequate for the requirements. Hence, further in-depth research into the conduction of real-time tracking and monitoring and the establishment of an economically effective management system is needed.

(5) Improve the life-cycle cost-benefit assessment, including initial construction, operation, maintenance, and repair costs, as well as economic, social, and environmental benefits. Present cost-benefit studies of PVNBs focus on construction costs and direct electricity generation benefits, lacking a comprehensive assessment of operation, maintenance, repair, recycling, and social and environmental impacts. Furthermore, the development of PVNBs not only reduces carbon emissions in the energy production process but also contributes

to the advancement of related industries and the creation of employment opportunities. Additionally, the financial feasibility of PVNBs largely depends on factors such as photovoltaic component prices, electricity prices, and government incentives for renewable energy. However, these factors cannot be generalized.

Overall, according to the forecast for global PVNB growth trends (2023–2029), the capacity of the global noise barrier market is expected to grow at an annual rate of 4–5%. The construction market for PVNBs is also expected to expand, with a conservative estimate of at least 48 GW. As countries worldwide continue to intensify their focus on global climate change, the integration of transportation and new energy is likely to further develop. The application model of “Photovoltaics + Transportation” not only enhances the intelligence of transportation infrastructure and optimizes the energy structure of transportation but also promotes energy conservation and emission reduction in road transportation, harboring immense development potential and opportunities. PVNBs, under the premise of addressing power grid interconnection or absorption, will increasingly find more applications. Compared to traditional noise barriers, PVNBs, despite increasing initial construction costs, offer significant advantages in scenarios with substantial environmental protection objectives, high grid construction costs, or significant absorption demands, especially in the case of east–west-oriented highways or closed sections of urban roads, making them a priority setting for the deployment of PVNBs. In conclusion, the market potential for PVNBs is enormous, but further in-depth research and application in various aspects are needed in the future to lay the groundwork for the large-scale application of PVNBs, promote the deep integration of energy and transportation, and contribute to the realization of dual carbon goals.

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