Strategies to Facilitate Photovoltaic Applications in Road Structures for Energy Harvesting

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Abstract: Photovoltaic (PV) facilities are sustainable and promising approaches for energy harvesting, but their applications usually require adequate spaces. Road structures account for a considerable proportion of urban and suburban areas and may be feasible for incorporation with photovoltaic facilities, and thereby have attracted research interests. One solution for such applications is to take advantage of the spare ground in road facilities without traffic load, where the solar panels are mounted as their conventional applications. Such practices have been applied in medians and slopes of roads and open spaces in interchanges. Applications in accessory buildings and facilities including noise/wind barriers, parking lots, and lightings have also been reported. More efforts in existing researches have been paid to PV applications in load-bearing pavement structures, possibly because the pavement structures cover the major area of road structures. Current strategies are encapsulating PV cells by transparent coverings to different substrates to prefabricate modular PV panels in factories for onsite installation. Test road sections with such modular solar panels have been reported, where inferior cost-effectiveness and difficulties in maintenance have been evidenced, suggesting more challenges exist than expected. In order to enhance the power output of the integrated PV facilities, experiences from building-integrated PVs may be helpful, including a selection of proper PV technologies, an optimized inclination of PV panels, and mitigating the operational temperature of PV cells. Novel integrations of amorphous silicon PV cells and glass fiber reinforced polymer profiles are proposed in this research for multi-scenario applications, and their mechanical robustness was evaluated by bending experiments.

Keywords: photovoltaics; solar panel; energy harvesting; highway; urban street; experimental investigation

1. Introduction

Photovoltaic (PV) facilities are able to generate electricity from solar energies without emission of pollutions or greenhouse gases, providing a sustainable solution to energy acquisition [1]. They have attracted global interest, especially in the background, as countries having set targets of reduction in greenhouse-gas emission in response to the Paris Agreement since 2016 [2]. PV facilities usually cover large areas in order to receive adequate solar energy and thereby are usually limited to remote open areas, e.g., deserts [3,4]. In order to avoid long-distance transmission of electricity, efforts have been made to allocate the PV facilities in spare spaces of urban and suburban areas, especially the exteriors of buildings [5]. They have been mounted by frames on rooftops similarly to those on the ground [6]. In some cases, PV panels may also function as building elements apart from generating electricity, for example, they may be used to shade light [7,8], and transparent or semi-transparent PV cells may be used as windows [9,10] and skylights [11].

In some recent practices, PV cells are integrated into conventional building elements and function as facades [12,13] and roof tiles [14,15]. There are four main strategies for such
integration in existing applications and researches. First, a direct approach is to adhesively bond the entire commercial PV panels with building profiles [16,17]. Second, commercial PV panels may be installed by mechanical structures to facades of buildings [5]. Third, PV cells without face coverings are placed into transparent adhesives (e.g., Ethylene Vinyl Acetate, EVA) applied on building profiles, then a transparent covering (e.g., glass, composites materials [11] and concrete [18]) is applied on top of the cells for encapsulation [19]. Fourth, photovoltaic materials are directly deposited to surfaces of building elements (e.g., roof tiles) in the factory [14], and the prefabricated elements with PV skin can be installed conveniently on-site.

However, several challenges hindered more extensive applications of such building-integrated or building-applied photovoltaics [20,21]. For example, building designs are usually associated with aesthetic considerations while convention PV panels are flat and associated with limited colors [22]; second, different structures or functions of buildings may require customized products or installation arrangements, which may impair their affordability and cost effectiveness [23]. In addition, the available exterior area of a single building is usually limited especially considering the building orientation and shadings in the urban environment (e.g., adjacent buildings and landscapes) [24].

In the research process optimizing the building-applied photovoltaics, attention has also been paid to the highway and urban street structures which cover a considerable area of urban and suburb districts and may have potentials for integration with PV facilities. Some strategies used for developing building-applied photovoltaics have also been applied to road structures. Compared to buildings, highways and urban streets are associated with less esthetic considerations; due to almost uniform cross-sections of road structures, the design for applicable PV facilities may be easier and a successful practice may be conveniently promoted to similar projects. Second, highways and urban streets are usually maintained by professional teams, which is favorable for sustaining long-term performance of PV facilities. In addition, the increasing number of electrical vehicles brings a demand for access to electricity in remote highways [25], where the PV facilities may be even more cost effective than constructing grid electricity facilities. An attractive application of PV facilities on the pavement is to realize wireless charging for electrical vehicles during driving with inductance coil [26–28].

However, it should be noted that the pavement structures may be subjected to traffic loads, while conventional PV cells (e.g., mono-crystalline and multi-crystalline silicon PV cells) are brittle and may break at even a small mechanical strain [29]. In existing researches, efforts have been paid to three main strategies as follows.

- To utilize the spare spaces without traffic load, e.g., medians and side slopes of highways, open space of interchanges [30], and side faces of noise barriers [31].
- To insulate the PV cells from mechanical loads through robust and transparent upper structures [32], e.g., glass, composites materials [11], transparent concrete [18] and high molecular polymers, such as polycarbonates, polymethyl methacrylate, and resin [33].
- To introduce PV cells with adequate resistance to mechanical loads [34].

Despite the extensive researches on the applications of PV facilities in highway and urban street structures, successful practices are still limited. This is possibly because the existing researches are independent and focus on certain detailed aspects without an overall consideration. PV facilities are not among conventional materials for pavement construction and such applications require interdisciplinary experiences in pavement engineering and photovoltaics. An extensive review may help to understand the difficulties to apply PV facilities in load-bearing scenarios and share experiences from different existing trials. Several reviews about utilizing road structures for energy harvesting have been available, but PV facilities are merely listed as a single brief section alongside piezoelectric, thermoelectric, wind, and other energy-harvesting facilities [28,35,36].

The main objective of this review is to present the approaches, in use or recently proposed, for applying PV facilities in road structures for energy harvesting. It starts
with the PV facilities applied in spare spaces without traffic loads, which are similar to the conventionally applicable scenarios of PV panels. After that, existing practices of PV facilities acting as structural components bearing traffic loads are extensively reviewed, with their constitution, electrical and mechanical performance, and current service status presented. Limitations of current studies and research opportunities are discussed. In addition, a novel integration of amorphous silicon (a-Si) PV cells and glass fiber reinforced polymer (GFRP) profiles are proposed and their mechanical performance is evaluated by four-point bending experiments.

2. Applications in Spare Spaces without Traffic Loads

2.1. Spare Ground

Mounting PV panels on the spare ground is a direct application in road structures, and the PV panels may be installed at the optimal orientation similar to their conventional applications in PV power plants [37]. Such spare ground includes medians of roads, slopes along expressways, open ground among interchanges, and disused highways [30]. The feasibility of such applications has been verified by a wide range of practices and research. For example, an economic analysis of using two open spaces among two interchanges in South Korea was conducted considering the land lease fee for the ground, and one of them was suggested to be economically feasible [30]. PV applications in the spare ground of roads have been widely implemented but the majority of them were not reported in academic literature since their technical innovations from conventional PV applications are limited. In order to provide an overview of such applications, two large-scale distributed PV systems on the spare ground of expressways in China are introduced.

In 2017, distributed PV systems were installed to three expressways (i.e., the Ji-Qing Expressway, the City Expressway, and the Airport Expressway) in Jinan, China. The project included PV applications on open spaces of several interchanges (see Figure 1a), 8 pairs of service areas, and 7 toll stations. For the Ji-Qing Expressway alone, the investment was CNY ¥180 million (about €24 million), and the estimated annual power output was 10 million kWh. Considering the industrial electricity price is CNY ¥1.0 per kWh, the cost payback time is thereby 8 years without considering the performance degradation of the PV cells, the maintenance cost, or feed-in-tariff policies [38,39].

In 2018, an upgraded program for expressways was conducted in Hubei Province of China, where PV panels were installed to 16 pairs of service areas, 34 toll stations, and 36 medians adjacent to tunnels (see Figure 1a). The total investment was CNY ¥80 million (about €10.7 million), and the estimated annual power output was 10 million kWh. Considering the industrial electricity price is CNY ¥1.0 per kWh, the cost payback time is thereby 8 years without considering the performance degradation of the PV cells, the maintenance cost, or feed-in-tariff policies [38,39].

Figure 1. Solar array mounted on spare spaces of (a) a median of an expressway in Hubei, China and (b) an interchange of Ji-Qing Expressway in Jinan, China (117.00° E, 36.56° N).

In 2017, distributed PV systems were installed to three expressways (i.e., the Ji-Qing Expressway, the City Expressway, and the Airport Expressway) in Jinan, China. The project included PV applications on open spaces of several interchanges (see Figure 1b), 8 pairs of service areas, and 7 toll stations. For the Ji-Qing Expressway alone, the investment was CNY ¥180 million (about €24 million), and the estimated annual power output was 36.5 million kWh, leading to an estimated payback time of 5 years. All PV panels used in this project were 265 Wp poly-crystalline Si PV panels, and the system was connected to the grid.

It may be noticed that in the two projects, PV panels were usually installed only adjacent to energy-consumption facilities although spare space may exist along the whole
length of the expressways. This is possibly because PV facilities in such locations are more cost effective due to the on-site consumption of electricity. A photo for the PV panels mounted at a median of an expressway in the aforementioned project in Hubei is provided as Figure 1a, and a capture of the satellite image from Baidu Map for the PV panels installed in an interchange of the Ji-Qing Expressway in Jinan is provided as Figure 1b. The PV systems in tolls and service areas are usually installed on rooftops, which may be reasonably categorized into building-applied photovoltaics instead of road-applied ones. Slopes were not considered in the former two projects possibly because the slope orientation is constrained by road alignment, and the optimal orientation may not be available for the PV panels. An evaluation approach to estimate the power output of PV panels installed on highway slopes has been put forward based on digital elevation model (DEM) and road alignment information, and it was used to examine the potentials of ten highways in South Korea [40].

2.2. Other Accessory Facilities and Buildings

Other accessory road facilities without major mechanical loads have also been investigated, as demonstrated in Figure 2a. PV facilities have been extensively applied in shadings of parking lots (see Figure 1a) due to the increasing number of electric vehicles [41], and they are used in conjunction with the charging piles. The largest solar parking project was reported to be the North Park Project located in Dhahran, Saudi Arabia, at the headquarters of the oil company Saudi Aramco [42], which covers 200,000 m² and has 4450 parking spaces, and the CIS (copper indium diselenide) PV panels with a total power of 10 MW are used as shadings.

Lights powered by PV facilities have been used for lighting [43], traffic lights, and traffic studs [31] (see Figure 2b,d,e) and they are usually used on occasions without convenient access to grid electricity and are integrated with battery energy storage systems to manage energy consumption.

![Figure 2. Applicable scenarios in road facilities: (a) parking lots, (b) lighting, (c) noise/wind barrier, (d) traffic lights and (e) traffic studs.](image)

Installation of PV facilities on noise/wind barriers has a long history, and the first application in Europe was reported to be the one in the municipality of Domat/Ems, Switzerland in 1989 [31]. Shown in Figure 2c is a noise barrier without PV panels. It should be mentioned that, although noise/wind barriers are not subjected to vehicle loads, the barriers may deform at the effects of wind, and the mechanical strain of the barriers may
be transferred to the integrated PV panels [44] therefore, the strain effects on the PV panels should be investigated before their applications. Some barriers may also extend to the top of roads and cover the whole top and side faces of roads, providing more space for PV application, for example, 4400 PV panels were installed on the rooftop of the Blackfriars Railway Bridge in London. Several existing researches have also investigated the feasibility to install a top roof for a whole length of a highway to allow installation of PV panels, but the cost effectiveness was not evaluated [45].

3. Applications in Pavement Infrastructures Bearing Traffic Loads

3.1. Associated PV Technologies

Although applications of PV facilities in scenarios without traffic loads have been developed, the applications to the pavement are still challenging since conventional PV cells may break at the effects of traffic loads. Existing researches have shown that crystalline silicon (c-Si) PV cells may break at 0.2 to 0.3% tensile strain [29,46], and the degradation in their electrical performance may happen at an earlier stage. In major associated applications and researches, c-Si PV cells are usually used, possibly due to the high conversion efficiency and easy availability from the market as presented in Table 1, where data for amorphous silicon (a-Si), CIGS (Copper Indium Gallium Diselenide), and CdTe (Cadmium Telluride) PV technologies is also provided. As presented in Table 1, c-Si PV cells are associated with the highest efficiency, and the PV modules and commercial panels made of c-Si PV cells also have higher efficiency than other technologies. The c-Si PV technology accounts for over 95% PV market and the mass production further makes their price competitive.

| PV Technologies                  | c-Si  | a-Si  | CIGS      | CdTe     |
|----------------------------------|-------|-------|-----------|----------|
| Cell efficiency [47]             | 26.7 ± 0.5 | 10.2 ± 0.3 | 23.35 ± 0.5 | 21.0 ± 0.4 |
| Module efficiency [47]           | 24.4 ± 0.5 | 12.3 ± 0.3 | 19.2 ± 0.5 | 19.0 ± 0.9 |
| Temperature coefficient [48]     | -0.37 to -0.52 | -0.10 to -0.30 | -0.33 to -0.50 | -0.18 to -0.36 |
| Efficiency of commercial panel [49]| 14.9 to 19.0 | 9.5   | 12.7 to 16.0 | 8.5 to 14.0 |
| Market share [50]                | 95.70 | 0.05  | 1.13       | 3.12      |

The temperature coefficient is used to quantify the output reduction with elevated temperature, and the temperature coefficient of -0.37 to -0.52% for c-Si PV technology means the power output will decrease by 0.37 to 0.52% when the temperature surpasses 25 °C (i.e., the temperature in standard tests) by 1 °C. Therefore, the performance degradation at the effects of elevated temperature is more obvious compared to other PV technologies, while a-Si PV cells are favorable in this regard. During the operation of the PV cells, some of the solar energy absorbed by the PV cells will be converted into heat, while ventilation is almost prevented when they are encapsulated into pavement structures; therefore, the elevated temperature would be witnessed in PV cells during operation, leading to reduced power output than the rated efficiency.

3.2. Existing Applications

Several existing applications of PV facilities in pavement structures are listed in Table 2. The walkway in Ashburn was made by Onyx and installed on the Virginia Science and Technology Campus, George Washington University. The landscaped walkway was reported to be “the first installation of a walkable solar-paneled sidewalk in the world” [31], and it consisted of 27 PV panels with a slip-resistant surface. The PV panels are semi-transparent based on the a-Si PV technology, allowing 450 LED, powered by the solar panels, to backlight the walkway. It should be mentioned that the semi-transparent PV panels have also been installed on top of buildings as skylights.

The bicycle lane in Krommenie, Holland (see Table 2) was constructed by the installation of 57 prefabricated modular solar road elements, and each element was constructed by encapsulating poly-crystalline Si PV cells using a 1-cm thick glass layer to a concrete slab...
(2.5 m × 3.5 m) [51]. The modular elements were inconvenient for installation due to the density of concrete and the large dimension. Delamination between the glass coverings and the PV cells was witnessed during the service of the lane [52]. Data for power-output observation and a prediction model are available from literature [53], and the actual power output for 2015 was 78 kWh/m², lower than the predicted 93 kWh/m²; it was suggested that using mono-crystalline Si PV cells to replace the poly-crystalline cells would increase the output by 50% and a project site with more abundant solar radiation should be selected.

The countryside road in Tourouvre, France (see Table 2) was reported as the first large-scale solar road application [54]. It was constructed by adhesively bonding PV modules to road surfaces [55]. In the fabrication of each PV module, 28 mono-crystalline PV cells were encapsulated into a heavy-duty resistant material, and a glass layer was then bonded by transparent resin to the upper face, while a glue layer was applied to the bottom, enabling the module to be conveniently bonded to existing road surfaces. Each module has a dimension of 1257 × 690 mm², a thickness of 6 mm, and a weight of 5.5 kg [54]. Unexpected noise caused by passing vehicles and sharp degradation in power output of the PV modules in service has been reported [56]. The PV modules are commercially available and have also been applied to other sites on smaller scales, allowing only pedestrians and bicycles [55].

The walkway in Sandpoint, US (see Table 2), was constructed by the installation of multifunctional hexagon modular panels. Prototypes of the modular panels were made earlier, and optimizations are still being made. The present version of the modular panels weighs about 70 pounds (~32 kg), covering an area of about 0.4 m² with a thickness of 3.6 cm. Textured heated glass was used as the upper face. Batteries, LED lights, and microprocessor boards were integrated into the modular panels to realize more functions, e.g., dynamic traffic signs. They were designed and tested to sustain vehicle loads, but currently applied only as walkways. In the development of the modular panels, a series of test procedures were introduced as described in detail in literature [57]; it includes freeze/thaw cycling, moisture conditioning, heavy vehicle loading, shearing testing, and the British Pendulum test, providing a reference for developing similar panels.

The expressway in Jinan, China (see Table 2) was the only reported application of solar pavement in an expressway, and it was also constructed by the installation of solar panels. Each panel had a transparent concrete covering with a dimension of 1.50 × 1.06 m² [51]. Despite the numerical and laboratory experiments before the application, several panels were broken after only several days of open service. The expressway section was closed four times for maintenance in the following year, and the solar panels have been totally replaced by conventional asphalt pavement.

The road in the Hexi Service Area of the Yongtai Highway in Fuzhou, China (see Table 2) was open to the public in 2020, allowing passing and parking of vehicles. The square modular panel (about 0.5 × 0.5 m²) has a light weight and can be installed by a single person. Its surface was made of modified epoxy resin, and the four edges were reinforced with metal frames. A damping layer was applied beneath the panel to reduce vehicle vibration.

| Year | Location | Scenario       | Annual Output     | Investment       | LCOE       |
|------|----------|----------------|-------------------|------------------|------------|
| 2013 | Ashburn, US [31,52] | 10-m² walkway | 647 kWh (design) | -                | -          |
| 2014 | Krommenie, Holland [54] | 70-m bicycle lane | 11 MWh (actual) | €1.5 M (€10,714/m²) | €12.7/kWh |
| 2016 | Tourouvre, France [54] | 1000-m road | 150 MWh (actual) | €3 M (€1786/m²) | €3.1/kWh |
| 2016 | Sandpoint, US [57] | 14-m² walkway | 780 kWh (estimated) | ~€52,000 (€3714/m²) | €1.3/kWh |
| 2017 | Jinan, China [54] | 1080-m expressway | 1000 MWh (design) | ~€5.3 M (€1402/m²) | €0.5/kWh |
| 2020 | Fuzhou, China | 100-m² service area road | 36 MWh (design) | -                | -          |
4. Discussion

4.1. Capacity to Sustain Loads

The highway in Tourouvre and the expressway in Jinan (see Table 2) are the only two large-scale solar road applications, and they allow a relatively high speed of vehicles. The highway in Tourouvre was reported to have almost totally lost its capacity for electricity generation, while the expressway in Jinan has been destroyed. Although vehicle-load tests have been conducted before their implementations, severe damages were witnessed shortly after their opening to traffic. This is possibly because, in the vehicle-load tests, the load is applied by a static or smooth-running vehicle, while the impact loads caused by vehicle vibration and accidents were not considered. Based on this experience and in order to mitigate the vehicle vibration, in the application in Fuzhou (see Table 2), a damping layer was applied, and the base was specially designed with high-viscosity asphalt, but the road has been open to traffic for only a short time, and its current status has not been reported.

In addition, the performance tests for the panels are applied individually, and in several researches, each specimen is only subject to a single type of load (e.g., vehicle load, thermal load, or moisture conditioning), while in practice such loads and conditions are applied together, leading to different results comparing to the laboratory tests. Therefore, the application of PV facilities in scenarios with vehicle load is still challenging and requires improvement in both construction and test procedures of the panel specimens.

4.2. Investment

According to the estimation on the applications listed in Table 2, the investment is at least €1402/m², and the unit cost of the bicycle lane in Holland is exceptionally high, reaching €10,714/m². If the payback time was estimated considering the industrial electricity prices is CNY ¥1.0 per kWh as conducted in Section 2, the cost payback time is thereby about 40 years for the most cost-effective one listed in Table 2. It suggests the cost would never be paid back since the usual service life for PV panels is 25 years [58]. It should be mentioned that the payback time is 5–8 years for the large-scale appellations in spaces without traffic loads in Hubei and Jinan, demonstrated in Section 2. Therefore, from the aspects of cost effectiveness, load-bearing pavement is not a favorable scenario for PV applications.

Levelized cost of energy (LCOE) has also been used in existing researches to reflect the average cost of a power generation system [59,60]. It is defined as the ratio between the total life cycle cost and the total lifetime energy production, and it is presented as a net present value. LCOE for the PV pavements listed in Table 2 has also been provided, assuming that the systems would operate for 20 years with an annual output degradation of 1%, an annual maintenance cost of 5% of the initial investment, and a discount rate of 4%. The solar road in Holland is estimated to be associated with the highest LCOE of €12.7/kWh, and the road in Jinan has the lowest one of €0.5/kWh, which is yet competitive to grid electricity in most countries. Also, it should be noted that the estimation for the road in Jinan is based on the designed capacity, which is usually higher than their actual performance. For comparison, the LCOE for the two PV systems allocated in the spare space of roads as described in Section 2 is estimated as €0.10/kWh for the expressway in Hubei and €0.06/kWh for the one in Ji-Qing Expressway.

4.3. Compassion between PV Facilities in Spare Space and Pavement

In order to understand the differences between PV facilities in spare space and pavement, a summary is listed in Table 3, where their scale, space availability, applicable scenarios, technical maturity, and cost effectiveness are compared. In terms of technical maturity and cost effectiveness, practices in spare space are obviously more practical. However, the applications of PV facilities on the pavement are still attractive since the pavement structure is associated with large and continuous space, which provides opportunities for large-scale PV plants. In addition, the cross-section of the pavement structure is simple and
uniform, enabling successful cases to be promoted conveniently to other projects, which also reduces the challenges in installation and maintenance.

Apart from the aforementioned investigations, several other modular solar panels for pavement application are under laboratory investigations [34,52]. For example, a thin solar pavement module with a thickness of 20 mm and a dimension of 50 mm × 50 mm has been developed for walkable road and roof [52]; it was fabricated by encapsulating PV cells into tempered glass panels. Robustness and thermal responses of the panels at the effects of sunlight have been investigated by theoretical and experimental approaches. Several approaches have proposed to mitigate the elevated temperatures of the solar panels on pavement based on phase change materials [15,61] and soil regenerator [32]. A target of researches concerning solar pavement is to realize wireless charging for electric vehicles during driving using solar energy; theoretical verification and prototype experiments have been completed in several recent researches [26–28].

Table 3. Compassion between PV facilities in spare space and pavement.

| PVs on Pavement                                      | PVs in Spare Space                                      |
|------------------------------------------------------|--------------------------------------------------------|
| Scale                                                | Determined by demand and space, and large applications reached an output power of 10 MW. |
| Space availability                                   | Large and continuous space                               |
| Scenarios                                            | Small and distributed space                             |
| Technical maturity                                   | Pavement only                                           |
|                                                      | Spare ground: medians, slopes and interchanges; Other accessory facilities and buildings: shadings, lights and noise/wind barriers. |
|                                                      | The main technical route is prefabricated modular for onsite installation. |
| Technical maturity                                    | Mature and commercialized.                              |
|                                                      | Solar panels are mounted by frame as conventional applications or integrated into construction materials. |
| Cost effectiveness                                   | Low; LCOE: €0.5/kWh to €12.7/kWh; Cost may not be paid back. |
|                                                      | High; LCOE: €0.06/kWh to €0.10/kWh; Cost payback time: 5 to 8 years. |

5. Innovative Integrations for Multi-Scenario Applications

5.1. Conceptual Design

It may be noticed that the PV panels used in different scenarios are associated with different configurations and it may hinder wide applications. Based on existing experiences, this section thereby aims to develop an integration of PV cells and civil engineering materials feasible for applications in different scenarios of road structures and road facilities. According to the review on the current applications, the main strategy is to develop prefabricated modular PV panels with a substrate for convenient on-site installation. The “prefabrication and modular installation” strategy is effective to reduce the cost for construction and may also reduce the errors in wiring [62]. In order to reduce the total weight of the panels, the substrates made of civil engineering materials should have a high strength-to-weight ratio. Electric insulation is also an essential property for the substrate materials for safety considerations. Therefore, glass fiber reinforced polymer (GFRP) profiles are selected as the substrates due to their superior mechanical performance [63], cost effectiveness, resistance to aggressive environmental conditions [64], and electric insulation [65]. GFRP profiles have been used in multiple civil engineering scenarios, including retaining walls of road slopes [66], bridges [67], wind barriers [44], floor systems [68], and reinforcement for pavement [69]. In terms of the type of PV cells, a-Si PV cells were selected for the integration since existing applications suggested that the c-Si PV cells may not sustain long-term vehicle loads while flexible a-Si PV cells may operate normally even after deformation [17].

Strain effects on the a-Si PV cell samples have been investigated by our research team and the results have been available in literature [65,70,71]. Specimens of the a-Si PV cells
were first subjected to tensile experiments as shown in Figure 3a, which was conducted in accordance with ASTM D882 [72]. Artificial sunlight with an intensity of 1000 W/m² was applied [73], and the load was applied at 0.2 mm/min via a testing machine (Instron 4204). The open-circuit voltage (V_{OC}) of the PV cells was recorded continuously to indicate the operational status of the cells. Strains of the PV cells were obtained based on the spacing change of the bonded reflectors monitored by the laser extensometer (MTS LX500). According to the experimental results, no visible change in V_{OC} of cells was observed until a tensile strain of 1.4% [71], which was suggested to be the ultimate tensile strain for normal operation. It should be mentioned that c-Si PV cells may break at a tensile strain of only 0.2 to 0.3% [46].

The a-Si PV cells were then bonded by an epoxy adhesive layer to GFRP plates and then subjected to similar tensile tests as shown in Figure 3b, and the integration failed due to breakage of the GFRP plates at about 1% tensile strain [65], while the PV cells operated normally until the GFRP breakage. The a-Si PV cell samples have also been adhesively bonded with GFRP square hollow sections and subjected to compressive loads as shown in Figure 3c, where the specimens were not loaded up to failure and the maximum compressive strains applied was 0.8%. Results suggested that if a proper adhesive layer was applied, the a-Si PV cells may operate normally at even the maximum compressive strain applied [70].

![Figure 3](image_url)  
**Figure 3.** Experimental setup for (a) tensile test for a-Si PV cells, (b) tensile tests for integrations and (c) compressive tests for integrations.

### 5.2. Bending Experiment on Integration

The mechanical experiments on the a-Si PV cells and their integrations with GFRP profiles suggested that they may function normally for tensile strains within 1.4% and compressive strains within 0.8%. However, GFRP profiles are usually used as the sandwich form in order to provide robust support to structures. In addition, when such integrations are used as noise/wind barriers, walkable floors, and other facilities, bending loads may be transferred to the integrated PV cells, which may cause different effects from tensile and compressive loads. Therefore, an integration of GFRP sandwich and a-Si PV cells was fabricated as shown in Figure 4 and then subjected to four-point bending experiments as shown in Figure 5.

As shown in Figure 4a, the specimen was fabricated by two GFRP plates with a dimension of 550 mm (length) × 350 mm (width) × 6 mm (thickness) and three GFRP square tubes with a dimension of 550 mm (length) × 40 mm (width) × 40 mm (depth) × 4 mm (wall thickness) in between. The plates were bonded by an epoxy layer with a thickness of 1 mm. The a-Si PV cell with a dimension of 375 × 260 mm² was bonded to a surface of the GFRP sandwich, as shown in Figure 4b.
During the bending experiments, the specimen was supported at 50 mm from both ends, and artificial sunlight was provided to the PV cell by a halogen lamp. The mechanical load was then applied through four GFRP loading pads to avoid direct contact with the PV cells, as shown in Figure 5a. The load was applied at a speed of 0.5 mm/min until the failure of the specimen. The voltage of the PV cell was continuously monitored during loading to show the operational status.

5.3. Experimental Results

During the loading process, longitudinal cracks along the side walls of the GFRP tubes were initiated from about 35 kN as shown in Figure 5b, and the cracks propagated with the increase of the load. The maximum load was 46 kN for the specimen, corresponding to a deflection of 4.2 mm at the bottom of the mid span. At the maximum load, the cracks developed into a throughout crack from one end of the GFRP tube to another at the end of the experiments as shown in Figure 5b, meanwhile, the degradation in voltage was 4.1% for the PV cell, and when the specimens were unloaded, the voltage was recovered to over 99% of their original voltage values before mechanical loading.

This result suggests that a load of 35 kN may not cause visible damage to the GFRP sandwich. The 46-kN load caused temporary voltage reduction to the PV cell, which may be recovered when the load was removed. It should be mentioned that the typical load of one tire of a vehicle is about 4 to 5 kN. This integration, therefore, shows potentials to sustain vehicle loads.

Due to wide applications of GFRP profiles in road engineering, such integrations of PV cells and GFRP profiles are promising elements. For example, integration of PV cells and GFRP plates may be used as noise/wind barriers; integrations with GFRP sandwiches may be used as bridge decks and walkable roofs, while the a-Si PV cells may also be integrated into GFRP retaining walls in road slopes. The mechanical experimental tests on the PV cells...
and the prototype integrations may provide guidance for these applications, but further laboratory and outdoor investigations are necessary before practice. Further research will be focused on the responses of PV cells to cyclic loadings, the thermal performance of the integrations, and the selection of transparent coverings.

6. Conclusions

In this research, existing applications of PV facilities in road structures and facilities are reviewed. It starts with the PV facilities applied in spare spaces without traffic loads, where two systematic large-scale applications in China were introduced. Potentials of other facilities without vehicle loads were also presented in brief. Then, existing practices of PV facilities in pavement structures with vehicle loads were presented and discussed. In addition, a novel integration of amorphous silicon (a-Si) PV cells and glass fiber reinforced polymer (GFRP) profiles is proposed. Existing mechanical experiments on the a-Si PV cells and their integrations with GFRP profiles were introduced, and their mechanical performance was evaluated in this study by four-point bending experiments. The following conclusions may be drawn.

1. In the presented two large-scale PV applications in expressways, PV facilities were applied to open spaces of several interchanges, service areas, toll stations, and medians adjacent to tunnels. Slopes were not considered in the two projects possibly because the slope orientation is constrained by road alignment, and the power output may be reduced. The cost payback time was five and eight years, respectively, for the two projects.

2. The main approach to applying PV facilities to load-bearing pavement structures is prefabricated modular PV panels with a substrate for convenient on-site installation. Further investigations are required before making out successful panels to sustain long-term vehicle loads. In addition, the current applications were not cost effective.

3. The integrations of amorphous silicon (a-Si) PV cells and glass fiber reinforced polymer (GFRP) are suggested to have potentials for multi-scenario applications in roads. According to experimental results, the PV cells may function normally at a tensile strain of 1.4% and a compressive strain of 0.8%. When a load of 46 kN was applied to the integration of a GFRP sandwich and the a-Si PV cell, a 4.1% reduction in voltage of the cell was witnessed, but it may be fully recovered when unloaded, suggesting its potentials to sustain vehicle loads.

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