Simulation and Concept Evaluation of Extendable Lightweight Photovoltaic Modules for Vehicle Integration under Wind Loads

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ABSTRACT:

In this work, a design and concept evaluation of lightweight PV used for vehicle applications is shown, which uses honeycomb material as a supporting structure. Furthermore, the concept includes extendable modules to the side at the top of the vehicle which could higher the solar power output up to three-times when the vehicle is stationary. The mechanical properties of the honeycomb material depend on several design parameters and finding the right parameters can be time-consuming. Thereby, we present Shell-Solid-Shell approach with equivalent homogenized honeycomb core parameters to use it in a Finite-Element-Analysis (FEA) for structural mechanic simulation, which speeds up the design process and avoids time-consuming material tests. The Shell-Solid-Shell approach was evaluated with three-point bending test, which shows good coincidence with only 2 % difference in deflection at maximum force comparing it to meso-scale modelling of the honeycomb material. Although the approach underestimates stiffness, resulting in a 40% difference in the flexural modulus of elasticity compared to the experimental data, we consider the Shell-Solid-Shell approach suitable for determining the correct honeycomb parameters. We define specific load scenarios for vehicle integration according to DIN EN 13561 and simulate a full-size lightweight honeycomb PV module. The simulation of the bare honeycomb material shows a good correlation between the analytical and numerical solutions, with a difference in maximum deflection of 9.6 %. Including the PV layers results in a maximum deflection of 40.4 mm for the module under a load of 84 N/m². Furthermore, we reduced the maximum deflection by performing a parametric study that increases the thickness of the lightweight honeycomb PV module. Increasing the thickness from 10 mm to 30 mm for the lightweight module reduces the deflection by 90%, while the weight increases by only 36%. These results provide valuable insights for the future development and integration of lightweight honeycomb structures in vehicle and other applications.

Keywords: lightweight, honeycomb, VIPV

1 INTRODUCTION

The market share of integrated photovoltaics is expected to grow in the coming years [1]. In the field of integrated photovoltaics (PV), lightweight PV plays an increasing role because it is often the only way to integrate PV into a system, especially when weight capacity is limited, like in vehicle-integrated photovoltaics (VIPV) [2–6]. When integrating PV into vehicles, lightweight materials should be used to keep the weight low, as well as a low profile while maintaining the mechanical strength of the system to preserve the aerodynamics of the vehicle, as these are the two main factors that influence the energy consumption of a vehicle [7]. Because the possible space for PV on the vehicle is limited, one solution is to extend the solar area when the vehicle is at standstill. Extending the solar area when stationary can further increase the solar yield compared to fixed solar modules, thus increasing the solar range, and reducing the energy consumption of the vehicle. Solutions to extend the PV modules have already been presented for many concept vehicles [5, 7, 8]. Especially for camper or cargo vans, the integration of PV modules that can be extended to the sides is easily done because of the flat roof of most vans. For applications in camper vans, this also brings the advantage that the PV modules can act as an awning during your stay (see Figure Figure **1**). Nevertheless, there is a contradiction between maintaining the weight by simultaneously increasing the solar area and thus module power. Lightweight modules with honeycomb material as a supporting structure could be a solution for this. However, it must be noted that honeycomb solutions are not only restricted to VIPV but could also bring advantages in PV integration fields, depending on the requirements, as already shown by [7–9]. In the following paper we show design concept of extendable lightweight honeycomb PV modules and their evaluation of possible wind loads.

2 DESIGN CONCEPT AND BILL OF MATERIAL OF LIGHTWEIGHT HONEYCOMB PV MODULES FOR VEHICLE INTEGRATION

First, we want to introduce the concept of a lightweight honeycomb PV module for vehicle integration by explaining the general setup and presenting a possible module layout, as well as the BOM used for this concept.

2.1 DESIGN CONCEPT

The integration concept, which can be seen in Figure 1, considers a camper or cargo van with modules mounted on the top of the roof, which can be extended to the sides. This means integration inside the vehicle shape or by adding an additional structure mounted on top, depending on the available space in the vehicle. The PV modules are fixed with telescopic rails on both shorter sides and can be extended, manually or automatically with actuators, to the sides when the vehicle is stationary. Considering that the extendable modules are the same size as the fixed modules on top of the van, this could lead to a three-time higher solar power output when stationary and can be used for charging the vehicle's battery or powering peripheral equipment. In this concept, the honeycomb modules are considered as horizontal flat modules to follow the flat surface of the van and allow for easy module production. The module has a length of 2.0 m and a width of 1.2 m. However, it is also conceivable to curve the honeycomb module and adjust it to the shape of the vehicle, as done by [9]. This will lead to higher mechanical strength in the direction of thickness, but also increase module production effort. Figure 1 also shows, how we considered possible load case with direct wind load acting on the external modules for further mechanical simulations.

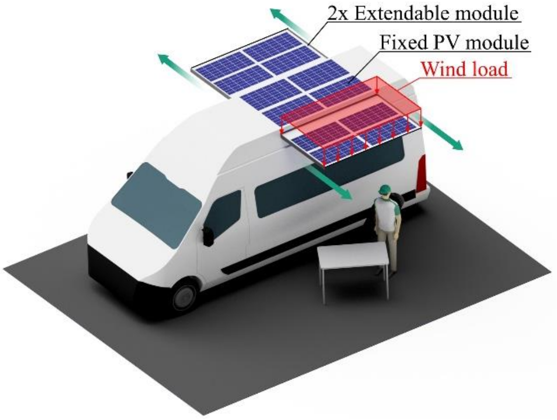


Figure 1: Vehicle integration concept for lightweight honeycomb PV module with a fixed module on top and extendable modules to the sides (green arrow) in stationary condition. It also shows a considered wind load scenario for further mechanical simulations.

The PV module layout used for the simulations is an extended butterfly setup with four bypass diodes as shown in Figure 2 and presented like [10]. The module layout considers half-cut monocrystalline silicon solar cells in wafer format of M3. The lightweight PV modules is divided into four segments with three strings and eleven cells per string. The segments are connected pairwise parallel and may achieve higher shading resilience and solar power output by adding an additional bypass diode.

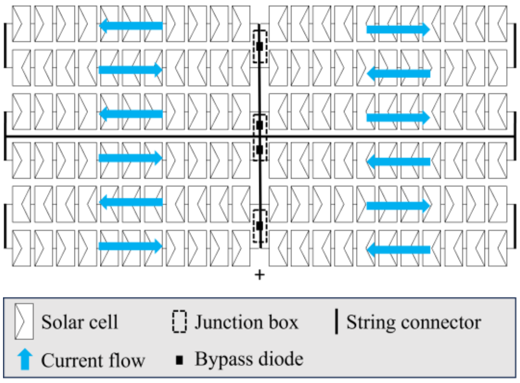


Figure 2: Possible cell layout for lightweight honeycomb VIPV module. The layout consists of four segments (3 Strings with 11 monocrystalline half-cut cells) including several bypass diodes for better shading resilience.

2.2 BILL OF MATERIAL LIGHTWEIGHT MODULE

The cross section of the assumed Bill of Materials (BOM) for the lightweight honeycomb PV module can be seen in Figure 3. The front material is based on a resistant polymer foil made from ethylene-tetrafluoroethylene (ETFE). ETFE has already shown good suitability as a front material in lightweight PV [6, 7, 10].

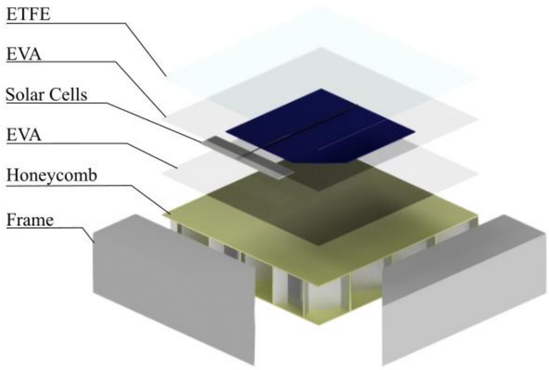


Figure 3: Cross section of considered BOM with U-shaped aluminum frame (ETFE-EVA-Cell-EVA-Honeycomb).

As encapsulant material, Ethylene-vinyl-acetate (EVA) was considered, and as supporting lightweight structure, hexagonal honeycomb material was used. The considered honeycomb material has an aluminum core with hexagonal unit cells and bidirectional GFRP face sheets. The whole module, with a total honeycomb thickness of 10 mm, is framed with a simple aluminum U-frame of 15 x 15 x 1.5 mm^3. The used material thicknesses, as well as values for Young's modulus E and Poisson's ratio ν, are presented in Table 1. For the following Finite Element Analysis (FEA) the materials considered as linearly elastic and isotropic, except for the orthotropic honeycomb core and anisotropic silicon solar cell.

Table 1: Material Properties for the different material types used in BOM of lightweight honeycomb PV module.

Material	Thick-ness t [mm]	Density ρ [kg/m^3]	Young's Modulus E [GPa]	Poisson ratio ν [-]
ETFE [11]	0.20	1750	0.82	0.42
EVA [12]	0.45	960	0.94	0.40
Silicon [12]	0.17	2329	aniso-tropic	aniso-tropic
GFRP [13]	0.30	1900	20.00	0.15
Honeycomb core [14]	9.40	77	ortho-tropic	ortho-tropic
Aluminum [12]	-	2700	70.00	0.33

2.3 Homogenization of Honeycomb core

To simulate the honeycomb structure in FEA we use Shell-Solid-Shell approach, which simulates the face sheet as shell elements and uses solid element for the core with homogenized material properties. For the Shell-Solid-Shell approach shown in this work, it is necessary to determine the equivalent elastic material properties for the hexagonal honeycomb core to simulate it as an orthotropic material. The approach of homogenization and the use of equivalent elastic properties is shown in [15, 16] and is based on the Bernoulli-Euler beam theory presented in [17]. The nine elastic material parameters, and thus the mechanical properties of the honeycomb material, depend on several design values, e.g. foil thickness, core cell unit size or material type of the used honeycomb core and can be calculated without the use of time-consuming mechanical experiments. Table 2 shows the calculated homogenized orthotropic material properties for our investigated honeycomb core. We considered a hexagonal aluminum core with a cellular size of 4.8 mm and a foil thickness of 0.05 mm for all simulations [4]. For the aluminum core, we used the same Young's modulus like for the frame shown in Table 1.The core thickness, which does not have an influence of the equivalent core parameters, was set to 9.6 mm at beginning and adjusted in further investigations e.g. parametric simulations.

Table 2: Calculated homogenized orthotropic linear elastic moduli, shear moduli and Poisson ratios for the considered honeycomb aluminum core.

E1 [GPa]	*E2* [GPa]	*E3* [GPa]	*G12* [GPa]	*G23* [GPa]	*G31* [GPa]	*v12* [-]	*v23* [-]	*v31* [-]
0.95	0.95	194.44	0.57	3.90	0.26	0.99	0.0	0.35

For stability reasons and to avoid singularities, it is recommended to set ν12=ν23=ν31=0 [13]. For the same reason, it is also recommended to set E1=E2=1 GPa [13]. After obtaining equivalent material properties for the honeycomb materials, it is possible to simulate the lightweight honeycomb PV module.

3 SIMULATING WIND LOADS ON HONEYCOMB LIGHTWEIGHT PV MODULE

After working out the necessary material properties, we simulate the lightweight honeycomb PV module by static structural mechanic simulation and using Shell-Solid-Shell approach. We begin with evaluation of the honeycomb structure simulations before simulating the entire PV module stack.

3.1 Evaluation of Shell-Solid-Shell Approach

For the evaluation of the presented Shell-Solid-Shell approach and the calculated equivalent material properties for the honeycomb core, a comparison between experimental data and direct simulation of the honeycomb unit cell, based on a three-point bending test, was performed. The goal of this evaluation is to investigate the suitability of the Shell-Solid-Shell approach in the elastic linear region for the considered honeycomb material. Figure 4 shows the experimental results of the three-point bending test for three bare honeycombs specimens with the prescribed properties and dimensions below. We used a Zwick universal testing machine with a test velocity of 20 mm/min and a support width of 100 mm to perform the three-point bending test. The length of the honeycomb specimen is 150 mm, and the width is 30 mm. At the beginning, the specimen follows an almost linear progression, which displays the typical behavior of honeycomb bending tests. The linear region ends upon reaching the maximum fracture stress. In this case, the face sheets fail, ending the bending test. All three specimens reached maximum deflection in a similar range. Specifically, Specimen 1 reached a maximum deflection of 1.23 mm at 0.65 kN, Specimen 2 reached 1.36 mm at 0.66 kN, and Specimen 3 reached 1.45 mm at 0.68 kN. The direct modeling of each unit cell of the honeycomb, known as the meso-scale model, and the use of equivalent homogenized material properties of the honeycomb core, also known as the macro-scale model, are both displayed in Figure 4. The simulation results show good agreement between the meso- and macro-scale models. At a maximum applied force of 0.7 kN, the macro-scale model shows a deflection of 2.03 mm, while the meso-scale model shows a deflection of 1.99 mm, a difference of 0.04 mm. This approximately 2 % difference suggests that the meso-scale model is a suitable approach for simulating large honeycomb structures and, consequently, large lightweight modules. However, it is important to note that this conclusion is valid only for the assumption of minimal deflection, and larger-scale load tests are necessary to confirm these results. Compared to the experimental results, the actual honeycomb sandwich material exhibits higher stiffness than the FEA results.

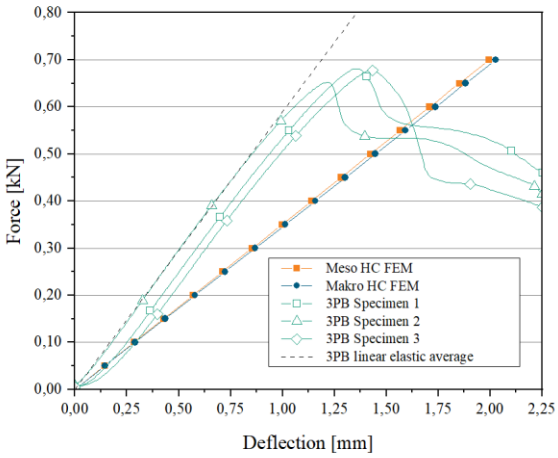


Figure 4: Force-Deflection curves of the three-point bending test data for three specimens made of the same honeycomb material and FEA data of the replicated three-point bending test of the honeycomb material simulated as meso- and macro-scale model.

Figure 4 also shows the average linear elastic region for the three investigated honeycomb specimen. It is possible to calculate the flexural elastic modulus E_f according to [16]. Resulting in flexural elastic modulus of 3.7 GPa for the three-honeycomb specimen in average linear elastic region. For the Shell-Solid-Shell approach the flexural modulus is 2.2 GPa. Resulting in a difference of 40 % and confirms the higher stiffness of the honeycomb specimen. The main discrepancy is due to the calculation of honeycomb parameters based on design parameters of honeycomb core and approximation of elastic material properties like for the face sheets of the honeycomb. This could be improved, by implementing the exact linear elastic properties provided by the supplier. Although the simulation underestimates stiffness, it still provides valuable insights into the mechanical behavior of honeycomb structures, when starting with the design of lightweight honeycomb PV modules. By using FEA with a Shell-Solid-Shell approach and equivalent material properties calculated from the honeycomb core parameters, the time to determine the correct parameters of the honeycomb materials used during the design process can be reduced. In further step we want to discuss possible load under direct wind load as scenario for prescribed concept of extendable lightweight PV module with honeycomb as supporting structure.

3.2 Assumed wind load scenario and boundary conditions

We considered a specific load case for the lightweight module, which is in worst case scenario, a static wind load acting perpendicular to the top surface area. The applied load was taken from the standard for external blinds and awnings – Performance requirements including safety DIN EN 13561 [18]. Awnings with jointed arms need to handle a maximum static wind pressure with a safety factor of 84 N/m^2, which we also considered in this research. According to the norms, this corresponds to wind class 2 with a maximum wind speed between 29-38 km/h and a Beaufort scale of 5. Higher wind speeds, and thus higher wind loads, need to be avoided by external safety features or by the operator itself. In the FEA we applied this wind load as a pressure load on top of the module surface (see Figure 1). The module is simply supported, with a pinned and a roller support along the short side of the module. Gravitational force was also considered. The simulations were done with the assumption of linear elastic material behavior at 293 K, and all layers are ideally connected by continuity. To keep the model simple and speed up the design process, the presence of ribbons and cross connectors was omitted.

3.3 Simulation of full-size lightweight honeycomb PV module

Before considering the whole layers of the module for the simulation, the deflection of the module without the PV layer and frame was compared, again for validation, to the analytical solution for bending of honeycomb samples as shown in [16]. The analytical solution and numerical simulation for the deflection over the module length for the bare honeycomb plate are shown in Figure 5.

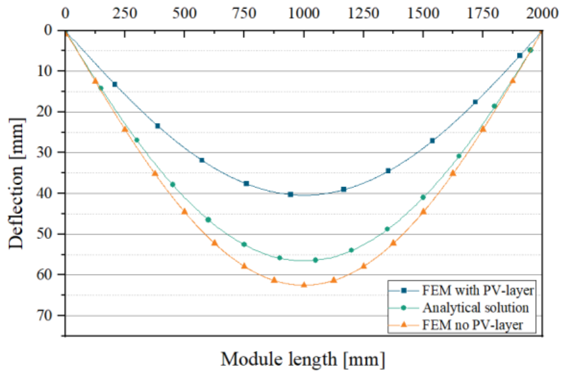
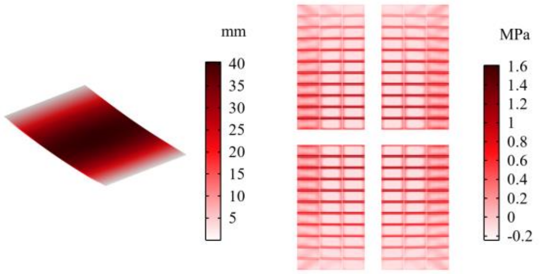


Figure 5: Deflection over module length for analytical calculation of bare honeycomb, FEA of bare honeycomb with shell-solid-shell approach without PV layer and FEA with shell-solid-shell approach with PV layer and aluminum frame.

The maximum deflection of the analytical solution is 56.5 mm and, as expected, occurs in the middle of the module. The maximum deflection simulated for the bare honeycomb plate is 62.5 mm. This results in a difference of 6 mm or 9.6 % deviation, which shows good agreement between the analytical solution and FEM solution for the bare honeycomb plate. It confirms the suitability of using the macro model during the design process. The maximum facing stress in the analytical solution can be calculated, like presented in [16] and is 14.0 MPa for this load case. The maximum facing stress found in the simulation for the bare honeycomb plate is 14.9 MPa. This also shows good agreement between the analytical solution and the FEA results and the use of this approach. In a further step, the PV layer as well as the frame were added to the honeycomb. As expected, this further decreased the maximum deflection of the whole module to 40.4 mm, which is a difference of 35.4 % compared to the simulation of the bare honeycomb module. The reduction in maximum deflection is primarily driven by the addition of the frame to the lightweight module. We also investigated the stresses at the cell level to determine whether failures in the cells could occur. Figure 6 (b) shows the first principal stress in the silicon cells, which is interpreted as tensile stress within the cells. The maximum first principal stress within the solar cells is very low and occurs at the cell edges, with a maximum value of approximately 1.6 MPa. This low stress occurs due to our specific boundary conditions, such as low face loads, simply supported plates, and the assumptions we made in modelling the lightweight honeycomb PV module. Because solar cells are known to be brittle, there is a higher risk from tensile-induced stress, which leads to a higher risk of cell fractures [12]. Nevertheless, the simulation shows that in this scenario the probability of cell fractures is almost zero. This also aligns with the experiences considering common deflections of standard PV modules [12]. But the comparison also shows, that the deflection of the lightweight honeycomb PV module is higher at given load [12].



(a) (b)

Figure 6: (a) Deflection of Lightweight honeycomb PV module with aluminum frame and PV layers at 84 N/m^2 **(b)** First principal stress of bottom side solar cells in lightweight honeycomb PV module.

Although it is assumed that there are probably no cells cracks within the module, the deflection can further be reduced by adjusting the honeycomb thickness. For this reason, we conducted a small parametric study by vary the honeycomb core thickness as next step.

3.4 Simulation of lightweight honeycomb PV modules with different thicknesses

A common lightweight concept is to improve the strength of sandwich components by increasing the area moment of inertia. This concept can also be applied to the lightweight honeycomb PV module design to easily reduce the deflection under the given load scenario by increasing the thickness of the honeycomb core with a simultaneous small increase in weight. For this reason, we present a small parametric study by adjusting the thickness of the honeycomb core and thus reducing its deflection under given wind loads which can be seen in Figure 7.

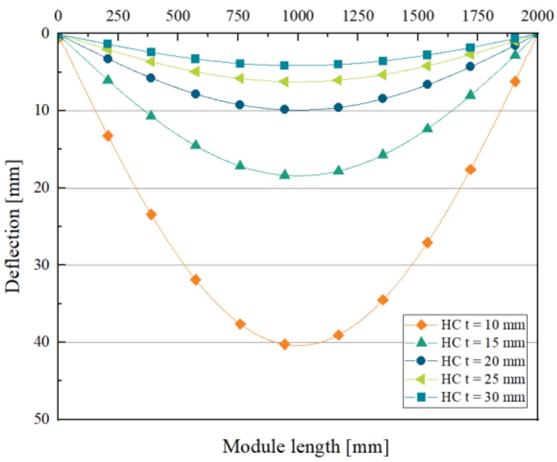


Figure 7: Results of FEA of deflection over module length for lightweight honeycomb PV module with thicknesses of 10 mm, 15 mm, 20 mm, and 30 mm.

We simulated different module thicknesses from 10 mm to 30 mm in 5 mm steps under the same previously shown boundary conditions by adjusting only the core thickness. In this parametric study, we did not change any other properties besides the core thickness. Due to the change in height of the honeycomb, the overall thickness of the module and thus the U-framed aluminum frame also changes, which affects the deflection. The dimensions of the frame change in the same 5 mm steps as for the module thickness. No change in the thickness of the aluminum frame (1.5 mm) was considered.. The curves show that, the maximum deflection can be reduced significantly. Increasing the honeycomb core from original 10 mm to 15 mm already reduces the maximum deflection from 40.4 mm to 18.4 mm, a difference of 54%. Considering the weight increase shown in Table 3 with the maximum deflection, increasing the module thickness to 15 mm results in an aerial weight increase of only 13.4%. Furthermore, we can decrease the deflection to 4.14 mm with a module thickness of 30 mm. Compared to the initial design core thickness of 10 mm, this reduces the deflection by 90% while increasing the weight by only 36%. The reduction is mainly due to the increased core thickness, but there is also an influence from the higher frame, which also lowers the deflection.

Table 3: Maximum Deflection and areal weight for different lightweight honeycomb PV module thicknesses at presented load case.

Module thickness [mm]	Areal Weight [kg/m^2]	Max. Deflection [mm]
10	3.60	40.40
15	4.16	18.42
20	4.73	9.90
25	5.12	6.23
30	5.69	4.14

With the possibility to analyze honeycomb core structures and the use of lightweight materials for PV using the shell-solid-shell approach and FEA, the optimum solution for a given application can be found very easily.

4 SUMARRY

In this work, we present the design and concept evaluation of lightweight PV modules for specific vehicle integration scenario, using honeycomb structures as supporting materials. The concept employs a lightweight PV module with a honeycomb structure as supporting structure. The BOM for the considered PV module is introduced, and important parameters of the honeycomb materials concerning their structural strength, as well as the considered module design, are described. The load case scenario was implemented based on DIN EN 13561 to investigate and simulate the mechanical influences of direct wind loads acting on the lightweight PV module using FEA. The concept of the Shell-Solid-Shell approach is introduced and used to simulate the honeycomb structure, finding the right parameters for the honeycomb materials, thereby speeding up and simplifying the design process. The Evaluation was done by replicating a three-point-bending test of the Shell-Solid-Shell approach shows only a difference of 2 % compared to the meso-scale modelling of the lightweight PV module. The difference in flexural modulus of elasticity between shell-solid-shell and experimental data is 40 % and is based on several assumptions in the material model but can be optimized. Nevertheless, we find Shell-Solid-Shell approach suitable for simulating lightweight honeycomb PV module structures for this application since the experimental results showed a stiffer setup. Simulation of large-scale honeycomb modules show good agreement with analytical solution. We calculated maximum deflection of lightweight honeycomb PV module of 40.4 mm at 84 kN/m^2 with only a thickness of 10 mm. A parametric study of different honeycomb thicknesses was conducted to demonstrate the use of the Shell-Solid-Shell approach in the design process to reduce deflection and mechanical influence on the PV module. We reduced the deflection of lightweight honeycomb PV module by 90 % by only increasing the weight by 36 % with adjusting the height to 30 mm. We have demonstrated a method to simulate the mechanical load of lightweight honeycomb PV modules.

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