DEVELOPMENT OF SOLAR PAVEMENT IN JAPAN AND ITS CONTRIBUTION TO CARBON NEUTRALITY

T. KAJI & T. YOSHINAKA
General Technical Department, Technical Division, NIPPO CORPORATION
kaji_tetsuri@nippo-c.jp

ABSTRACT
In road paving, solar pavement is being developed worldwide against the backdrop of the Paris Agreement, which set a long-term goal of mitigating climate change by 2050 and beyond, SDGs, carbon neutrality and other initiatives. In addition to providing traveling space, pavement, which covers a certain size of surface area in cities and regions, has the potential to generate new values to create renewable energy. We are developing solar pavement with the aim of developing road paving technology that contributes to carbon neutrality, and are conducting demonstration testing, primarily, test paving, in places with vehicle traffic.
Pavement is warped and deformed by the load directly applied by people and vehicles. Therefore, it is necessary to use paving materials that allow for warping and deformation and do not break. The solar pavement we are developing uses materials that allow for warping and deformation to ensure that it withstands the load from people and vehicles and has the skid resistance necessary for traffic safety.
To evaluate the durability of the solar pavement, we performed indoor testing of pavement samples and test paving with vehicle traffic. In the indoor testing, we determined how the solar pavement module would break under a load representing a vehicle and by directing ultraviolet light at the module, we examined the relationship between the number of years of outdoor exposure to ultraviolet radiation and the amount of power generated. In the test paving with vehicle traffic, we installed the solar pavement on roads with traffic of regular vehicles and in bends where large trucks slow down. In both cases, we showed that the solar pavement module does not break and demonstrated that it can be easily installed, including the wiring below the module, and generates power.
Through the testing, we have made progress in developing solar pavement for practical application. This report describes our development activities, including an evaluation of the contribution of road paving to carbon neutrality.

1. DEVELOPMENT OF SOLAR MODULES FOR PAVEMENT APPLICATIONS

A pavement is directly subjected to loads from pedestrians and vehicles and is constantly subject to deformation and deflection. Therefore, solar cells installed on the pavement surface must be made of materials that allow for deformation and do not fail. Therefore, loads from pedestrians and vehicles are not considered in the design of solar cells that are widely used in rooftop solar and mega-solar systems. The authors started to develop a solar cell (a solar module for pavement applications; hereinafter the “module”) that can be used for pavement applications.
Figure 1 shows the construction of the module being developed by the authors. The module is constructed with layers of materials that allow for deflection, is durable to withstand pedestrian and vehicle traffic, and provides the skid resistance required for a pavement.

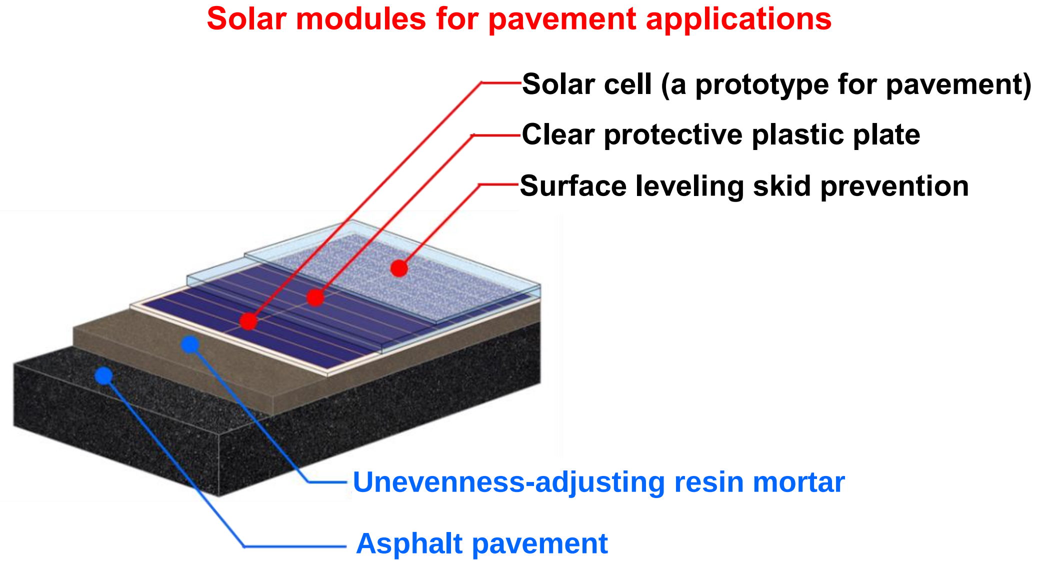


Figure 1 - Solar pavement under development (example).

2. INDOOR TESTING

2.1 Evaluation of bearing capacity

To evaluate the bearing capacity of simulated roads, we conducted a loading test according to the conditions specified in Japan's method of immersed wheel tracking test [1]. Table 1 shows the test conditions and Photo 1 shows the test setup.
The test was conducted using a sample immersed in water at 60°C, which is the highest road surface temperature in summer in Japan, and at the highest summer rainfall. The test duration was set to 18 hours, which is three times the ordinary duration specified in the Method of Immersed Wheel Tracking Test. To evaluate the feasibility of the module, a load was applied to the sample while light was directed on it to generate power.
After the test, the module continued to generate power without short-circuiting of the solar cells, showing that, in terms of durability, the layered structure of the module remains intact without breaking away.

Table 1 - Test conditions
(Method of Immersed Wheel Tracking Test)

Temperature	60℃
Sample condition	Water immersion
Load	49kN
Test duration	18 hours

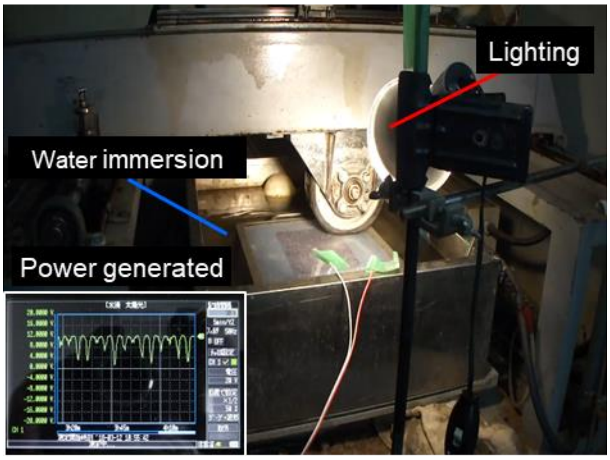


Photo 1 - Test setup
(Method of Immersed Wheel Tracking Test)

In the next step, we tested the wiring structure under the module. A test sample with a space representing the wiring was placed under the module and subjected to cyclic compressive loading equivalent to wheel loading from large vehicles. Table 2 shows the test conditions. Photo 2 shows the loading setup.
To evaluate the bearing capacity under accelerated test conditions, the condition of the test load was set to a value twice the contact pressure used in the Method of Immersed Wheel Tracking Test of Japan [2].
The test results are shown in Figure 2. The figure shows that the module does not break when subjected to more than 550,000 cycles of loading. In Japan, the impact of traffic loading on an asphalt pavement is said to be proportional to the fourth power of the wheel load [3]. Based on this, the number of loading cycles in the test is equivalent to 7,000,000 cycles of wheel loading from large vehicles. This indicates that the module can accommodate a traffic volume equivalent to traffic category N_6 (equivalent to national roads and government-ordinance-designated city roads).

Table 2 - Test conditions
(cyclic compressive loading test)

Test temperature	20℃
Control method	Load control
Loading jig	Diameter 40 mm
Setting load	1.26MPa
Loading speed	120mm/min

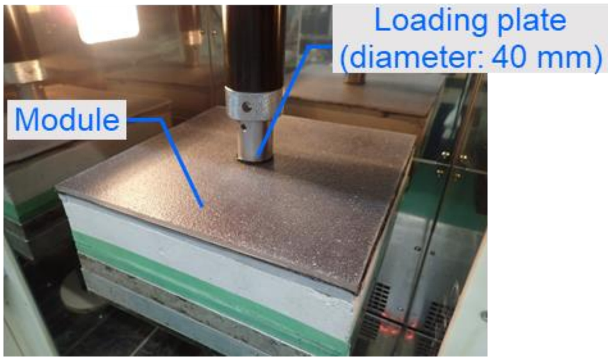


Photo 2 - Test setup
(cyclic compressive loading test)

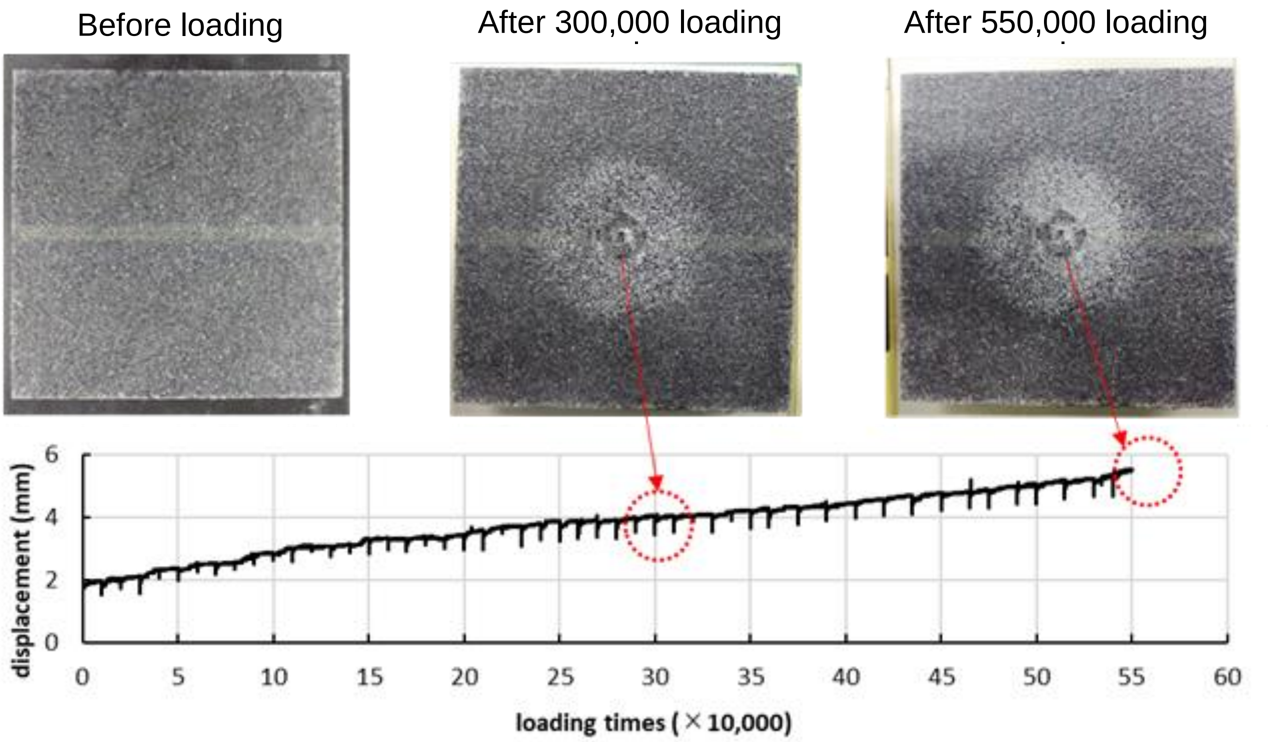


Figure 2 - Results of cyclic compressive loading equivalent to wheel loading from large vehicles.

2.2 Evaluation of weather resistance

The test for accelerated weathering of materials using an accelerated weathering tester was conducted to evaluate how much the power generated by the module decreases when it is exposed outside. Table 3 shows the test conditions. Figure 3 shows the results of a test to determine the power generation rate versus the number of years of outside exposure.
The test shows that, with a 100% generated voltage before the test, the power generation rate is 98.0% for 10 years of outside exposure and 94.2% for 20 years of outside exposure. The decrease in the power generation rate is 1.14% per year for power generation devices in widely used solar cell systems as shown in Reference [4] and 0.3% for the module. This shows that the decrease in the power generation rate due to outside exposure can be lower for the module than for widely used solar cells.

Table 3 - Test conditions (accelerated weathering test)

Tester name		Metal-halide lamp type (Weathering tester)
Control mode		Auto dimming
Light intensity		150mW/㎡
Operation mode		Lighting on/off
Water spray mode		Before/after lighting off
Test cycle	Lighting on	4.0 hours
	Lighting off	2.0 hours
	Water spray	60 seconds

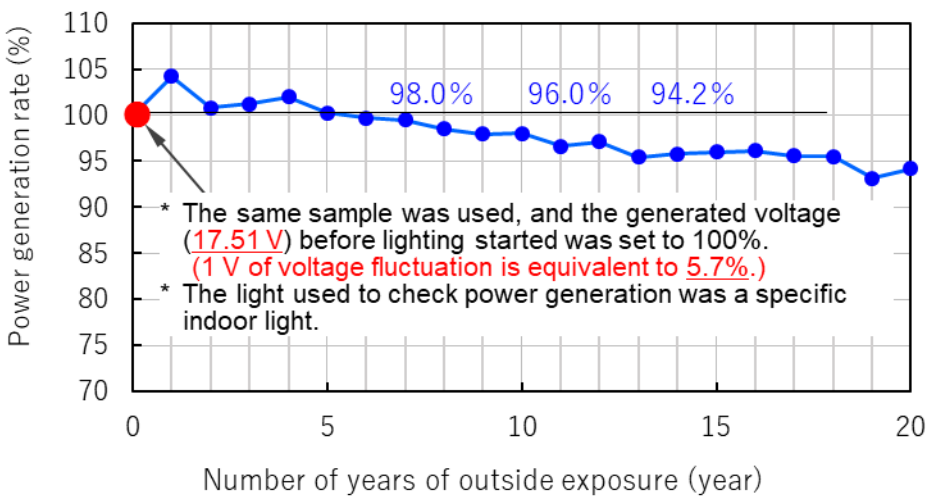


Figure 3 - Results of the accelerated weathering test.

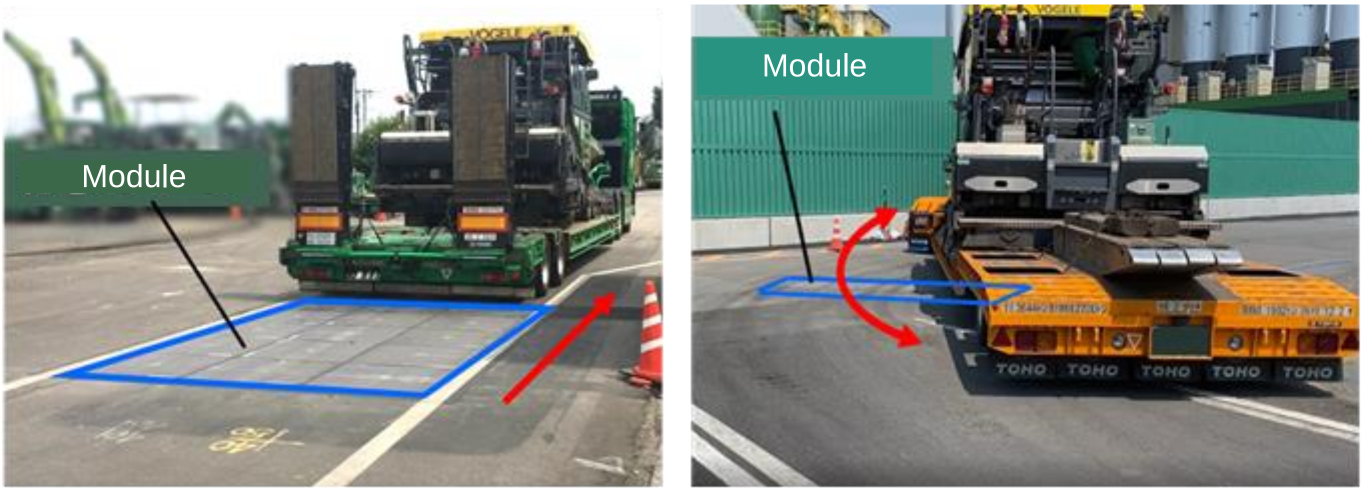
3. Evaluation by TEST PAVEMENT

3.1 Test pavement on the premises of our company

The authors laid a test solar pavement at a location with vehicle traffic on our premises in Saitama Prefecture [5] and have been conducting follow-up monitoring (Photo 3, pavement laid in November 2018). The durability and power generation characteristics of the module were evaluated as a pavement by running vehicles with a total weight of up to 6 tons. Some issues were identified with the adhesive strength between the components of the module. These issues were resolved by changing the type of adhesive used and modifying the fabrication process of the module.

In addition, we are evaluating the durability of the module on a road with large-vehicle traffic on the premises. A test pavement on a road with traffic of large trailers and pavement machines was laid on the premises of our motor pool in Saitama Prefecture (Photo 4). To evaluate the durability of the module under various external forces, which cannot be fully evaluated in laboratory testing, we selected sections where vehicles drive straight or turn left or right. Particularly at a curve (Photo 4 (b)), a large vehicle with double rear axles runs on the pavement while the tires slip laterally at low speed. Because of this, a vertical load and a large shear load are applied. We are continuing to evaluate the solar panel installed on the pavement under severe external loading conditions. We identified issues with the module, including the wiring structure under it, and made improvements to it. Thus, we are improving the level of technical completeness of the module.

Photo 3 - Laid test pavement.



(a) Straight section (b) Curved section

Photo 4 - Sections with large-vehicle traffic.

3.2 Test pavement outside the company

We laid a test pavement on the premises of a private company's factory in Aichi Prefecture in March 2021 and have been monitoring the pavement [6]. Photo 5 shows the pavement laid on a parking lot.
A wiring structure with an inspection hole inside the pavement is tested to evaluate the ease of installation and in-service durability of the structure. The power generated by the module is sent to the grid system connected to the adjacent factory. The power generation of the module is monitored and the power conditioner is checked to ensure that it works stably. As of January 2023, it has been 22 months since the module was put in service. No problem was found with the power generation or the module. The module has been shown to have the durability required for use on parking lots and can supply power stably.

Photo 5 - Pavement laid on the premises of a private company's factory [6].

4. Power generation characteristics

4.1 Power generation performance in an environment with both sunny and shaded areas

Unlike rooftops and mega-solar systems, the road is an environment where shaded areas tend to occur. Power generation devices are said to be susceptible to damage if solar cells are partially shaded [7]. Damage-resistant power generation devices have been chosen and circuits have been designed to prevent electrical damage. The test pavement location shown in Photo 6 is laid on the north side of the building that has both sunny and shaded areas. The test is being conducted under conditions where a partially shaded area occurs. It has been more than four years since the pavement was laid. Until today, the module has continued to generate power successfully with no damage to the power generation devices.

Photo 6 - With both sunny and shaded areas.

4.2 Relationship between received solar radiation and power generation

To properly determine the power generation characteristics in a road environment where shaded areas tend to occur, we developed a method of measuring the received solar radiation on the module [8]. Figure 4 illustrates how to measure the received solar radiation. In Figure 4, solar radiation in the sunny area and solar radiation in the shaded area were measured separately, and the received solar radiation was calculated from the solar radiation and the receiving area. Figure 5 shows the relationship between the received solar radiation on the module and the generated power. The figure shows that the generated power increases as the solar radiation increases and a trend in power generation at specific locations can be identified.

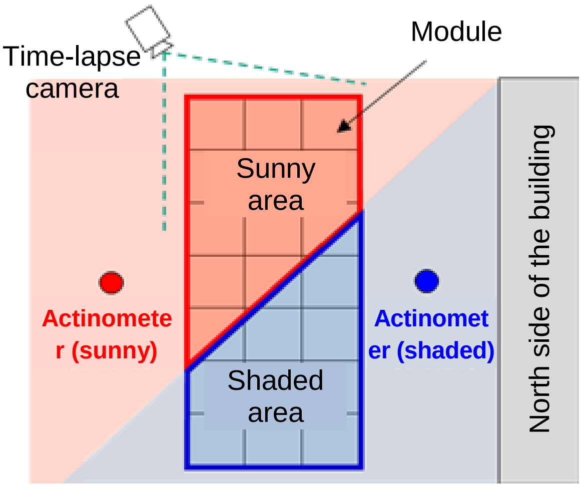


Figure 4 - Example of received solar radiation measurement.

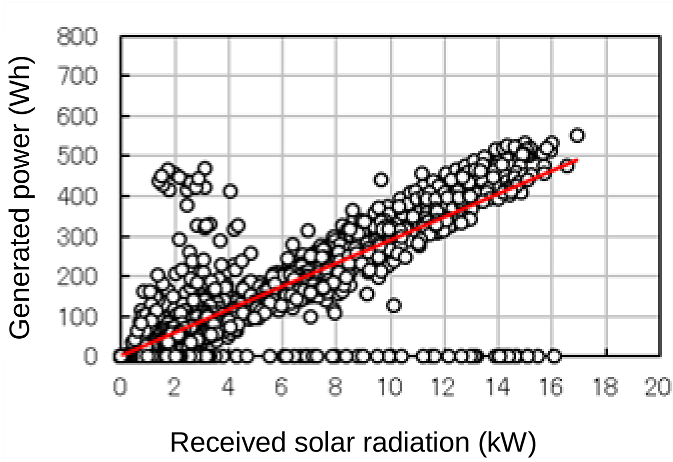


Figure 5 - Relationship between received solar radiation and generated power.

4.3 Effect of road surface levelling

In order to ensure safe traffic, the surface of the module is leveled using clear aggregate to provide the required skid resistance (Photo 7). Compared to widely used solar cells with a flat surface, the power generation performance of the module may degrade after leveling. Using a solar simulator, the relationship between the angle of the light source and the power output of the solar cells was investigated (Figure 6). The results show that, even when the sun's altitude (the angle of incidence on the module) is low, it is possible by choosing an appropriate material for surface leveling to make it easy to capture the sun's light and send it to the solar cells and thereby to ensure that the solar cells generate power.
Table 4 shows the power output with and without surface leveling, which we estimated from the relationship in Figure 6 between the incident angle (the sun's altitude) and the solar cell output power, based on the distribution of the sun's altitude on the first day of the month, which was calculated from the solar altitude data provided by the National Astronomical Observatory of Japan. The table shows that, in January to April and in October to December, when the sun's altitude is low, surface leveling increases daily power generation. The annual average power generation also increases. This shows that degradation of power generation performance can be prevented by choosing an appropriate method of surface leveling.

Photo 7 - Leveling the surface of the module.

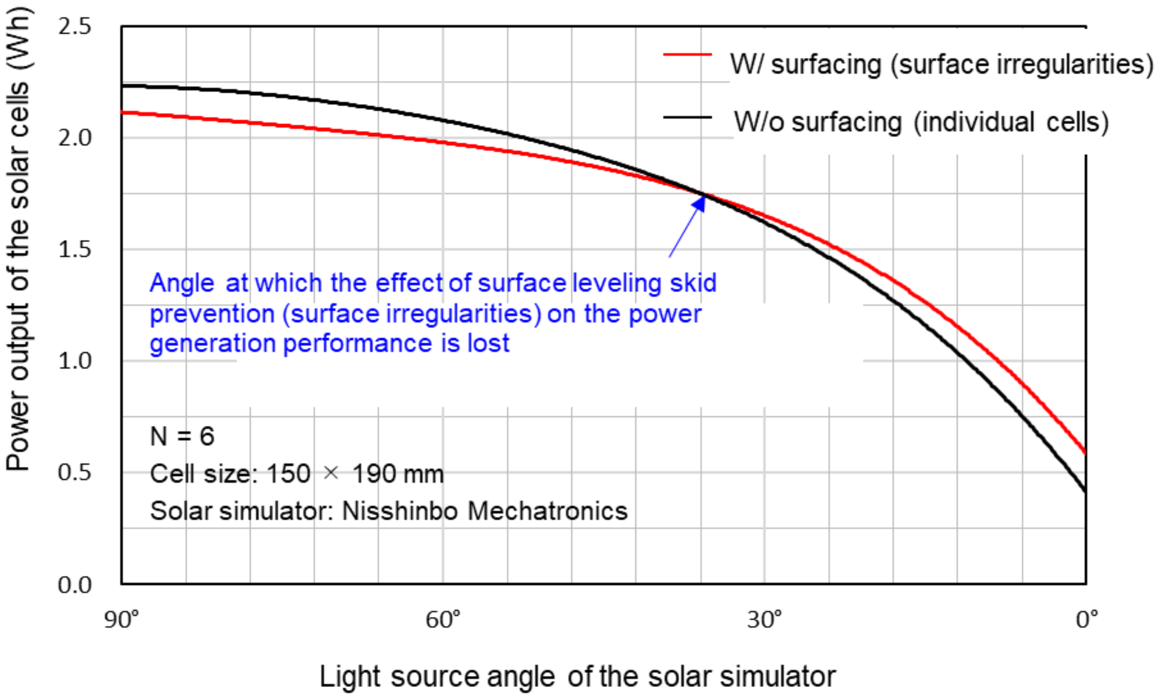


Figure 6 - Relationship between the angle of the light source and the power output.

Table 4 - Annual change in the sun's altitude and trend in the estimated power generation associated with surface leveling

Date of sampling		2018												Total
		1-Jan	1-Feb	1-Mar	1-Apr	1-May	1-Jun	1-Jul	1-Aug	1-Sep	1-Oct	#####	1-Dec	
Sun's altitude* and hours of daylight (hours: minutes)	Altitude 70~						2:15	2:15	1:15					4:08
	Altitude 60 ~ 69°					3:15	1:45	2:00	2:30	1:45				
	Altitude 50 ~ 59°				3:45	1:45	2:00	1:30	1:45	2:30	1:15			
	Altitude 40 ~ 49°			3:30	2:00	2:00	1:30	2:00	1:45	2:00	3:15			
	Altitude 30 ~ 39°	1:45	4:00	2:30	1:30	1:30	1:30	1:30	1:15	1:30	2:00	4:30	2:15	8:01
	Altitude 20 ~ 29°	3:30	2:30	2:00	2:00	1:30	1:45	1:30	1:45	1:45	1:45	2:30	3:30	
	Altitude 10 ~ 19°	2:30	2:00	1:30	1:30	2:00	1:45	2:00	1:45	1:45	2:00	1:45	2:00	
	Altitude 0 ~ 9°	2:00	2:00	2:00	1:45	1:45	2:00	1:45	1:45	1:45	1:30	2:00	2:00	
Comparison of solar cell* power output (Wh)	W/ surfacing (surface irregularities)	13.14	14.86	17.26	19.85	22.18	23.83	24.00	22.62	20.89	18.20	15.42	13.38	18.80
	W/o surfacing (individual cells)	12.38	14.19	16.85	19.78	22.32	23.98	24.19	22.78	20.89	17.94	14.75	12.66	18.56

5. Issues with the module as a road pavement

It is important in developing a power generation module to ensure that it has the bearing capacity and skid resistance required for a pavement, does not break when impacted by tire chains in winter, and is protected against electric shock because it is laid on the ground surface. Table 5 shows examples of the key properties required for a solar module for pavement applications, which were found through development of the module.

The materials, electrical wires, and cables used for the module have never been used for road pavement. Importantly, they need to go through cyclic laboratory testing and pavement testing. We showed, for example, that the type of damage is different for laboratory testing and for field testing, depending on the loading and pavement-laying conditions. Many of the fundamental issues with the solar pavement have been solved. The remaining issues are: improving the ease of laying the pavement, the durability of the wiring structure under the module, and the power generation efficiency; reducing the cost of the pavement, which is dependent of the scale of production; and increasing the reliability of the pavement.

Table 5 - Examples of key properties required for a solar module for pavement applications

Required properties	Skid resistance	Impact resistance	Bearing capacity	Water resistance	Weather resistance	Shade tolerance
Requirements	Skid resistant when raining	No cracking, no breaking from impact load	Remaining functional to generate power with no breaking away and no breaking down when loaded	Remaining functional to generate power when raining	No warping, no breaking away, no discoloration	No damage to power generation devices when partially shaded
Examples of test methods	Skid resistance test (BPN)	Labeling test	Immersed wheel tracking test Cyclic loading test	Immersed wheel tracking test	Accelerated weathering test	Outdoor power generation demonstration test
Examples of criteria	Road: BNP > 60 Sidewalk: BMP > 40	No module cracking	No module cracking, no solar cell short-circuiting	No solar cell short-circuiting	No module warping	No solar cell failure
Widely used solar cell (tempered glass)	× ~ ○ W/o crack prevention W/ crack prevention	× Possibility of cracking	× ~ ○ W/o crack prevention W/ crack prevention	× ~ ○ W/o crack prevention W/ crack prevention	○ No warping	× Susceptible to failure
Our technology	○ Compliant with standards	○ No breaking	○ Durable to withstand large-vehicle traffic	○ No breaking	○ No warping	○ No failure

6. Possibility of development into the future

One movement towards transforming energy systems is a smart community initiative **[9]**. Developing energy management systems, such as a community energy management system (CEMS), is being considered, but utilizing road space is not included. From the perspective of decarbonization, a solar pavement can be potentially used as a road energy management system (provisionally named REMS). We expect that the solar pavement can make a significant contribution to carbon neutrality (Figure 7).

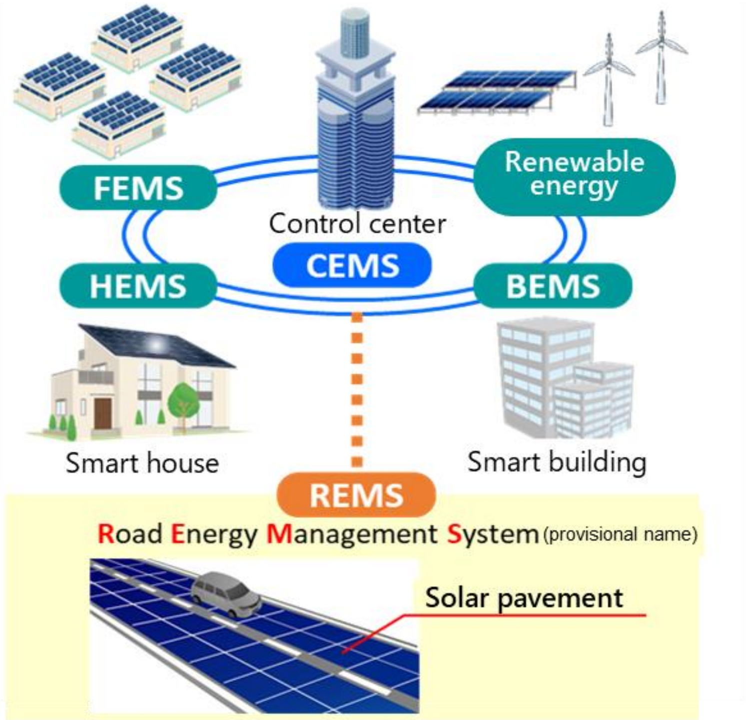


Figure 7 - Examples of carbon neutrality projects (image).

7. Closing remarks

After giving form to a solar pavement for practical applications, through a test pavement, we accepted visits from various sectors, including energy infrastructure companies, automotive manufacturers, and several research organizations. While being still in the research and development phase, the solar pavement has attracted attention, exceeding our expectations. We will try to meet expectations for its future and feel strongly responsible for completing the development of the module as soon as possible.

8. References

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