HISTORICAL DEVELOPMENT OF SOLAR ROAD PANELS IN PAVEMENT STRUCTURES

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Abstract

This paper deals with the history of the application of solar panels in pavement structures, i.e., the history of solar roads. Solar panels are becoming an increasingly popular way of generating energy because they use the inexhaustible sunlight to produce electricity. The primary goal of this research is to present the history of solar roads, their historical justification, general benefits and economic viability of constructing solar roads, as well as replacing modern asphalt roads with new, multifunctional solar roads.

The paper provides basic information about the historical development of solar roads and their implementation worldwide, their benefits and disadvantages, and an overview of their economic feasibility.

The construction of solar roads represents a significant civilizational step forward in several aspects: the production of electricity while simultaneously protecting the environment, improving and increasing traffic safety, enhancing communication between cities and countries, etc.

Keywords: solar energy, electricity, pavement, traffic, solar road, environment.

Introduction

The application of solar panels in pavement structures represents an innovative approach to environmental preservation, solar energy production, traffic safety enhancement, and the overall economic development of an area. Solar roads, as the final product and direct application of solar panels embedded in pavement surfaces, are the roads of the future.

a) b)

Figure 1. a) Coal-fired power plant; b) Illustrative representation of renewable energy sources

Solar energy is the renewable energy derived from the Sun's radiation, which reaches the Earth in the form of light and heat. The intensity of solar radiation in space fluctuates by about ±1.7% due to changes in the distance between the Earth and the Sun across different seasons. The average value of the solar constant is E_0=1.376 W/m^2. On Earth's surface, this value is reduced due to atmospheric effects and phenomena such as reflection, absorption, and scattering. The average intensity of solar radiation on a sunny day on Earth is about 1,000 W/m^2. Annually, the Sun

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delivers 220,000 trillion kWh of energy to the Earth, which is more than 2,500 times the energy needs of all humanity, or 25 times the energy that can be obtained from all fossil fuel reserves.
The Earth constantly receives 174 PW (petawatts), or 174,000,000,000 MW (megawatts), of incoming solar radiation (insolation) annually at the upper layers of the atmosphere. Approximately 30% is reflected back into space, while the remaining 120 PW is absorbed by clouds, oceans, and land surfaces. This amount of energy in one hour is greater than what all of humanity consumes in an entire year.

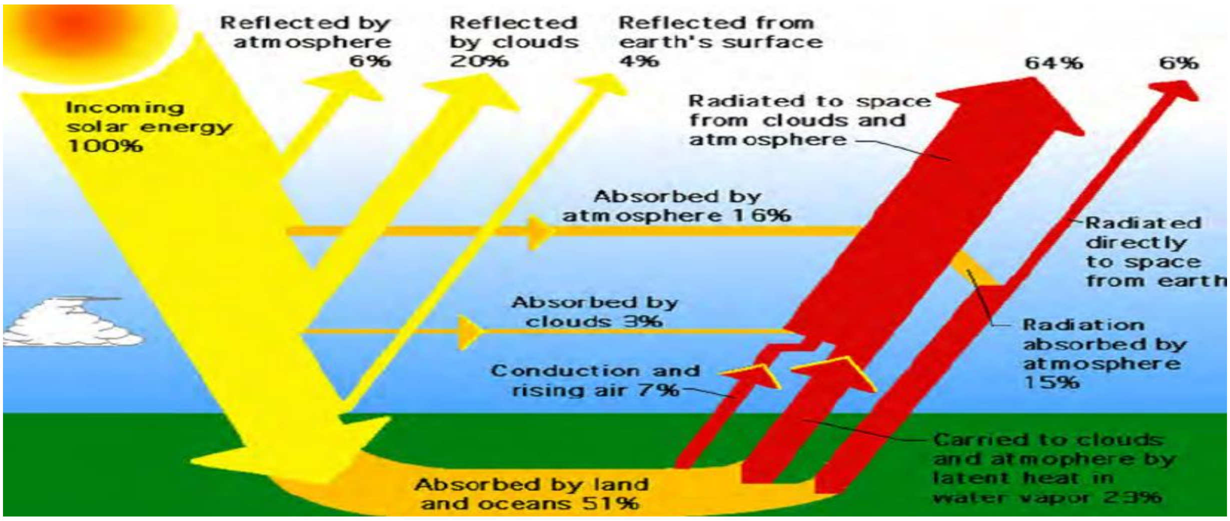

Figure 2. Solar radiation balance on Earth[13]

Across most of the Earth's surface, the average insolation is between 150-300 W/m². During the process of converting solar energy into electricity, significant losses occur. The ratio between the produced electrical power to the power of the solar radiation hitting the solar cell is called the efficiency. For standard solar cells, this ratio varies from 12 to 18%. Solar radiation on Earth, without losses, is about 1,000 W/m². If this radiation falls on a monocrystalline cell with a size of 10x10 cm, it delivers 10 W of solar energy. With an efficiency of 18%, the cell generates 1.8 W of power, meaning that a solar converter with a power of 1.8 kW requires 1,000 such solar cells.
Due to the low power output of individual solar cells, in practice, multiple cells are connected together to form a photovoltaic module, and by connecting these modules, a solar panel is created.

History and Characteristics of Solar Road Panels

The first use of solar cells in pavement was carried out by the company Solar Roadways Incorporated, which produced the first prototype of solar road panels called SR1 (Solar Roadway 1) in 2010. This prototype featured LED lights but did not include solar cells and was not designed to withstand weather conditions and did not generate electricity.
Surface glass was used based on recommendations from the Penn State Materials Research Institute and the University of Dayton Research Institute in the United States.

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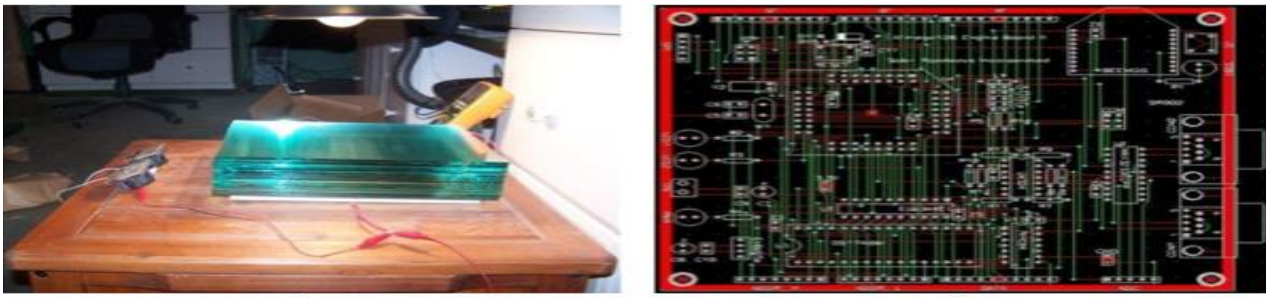
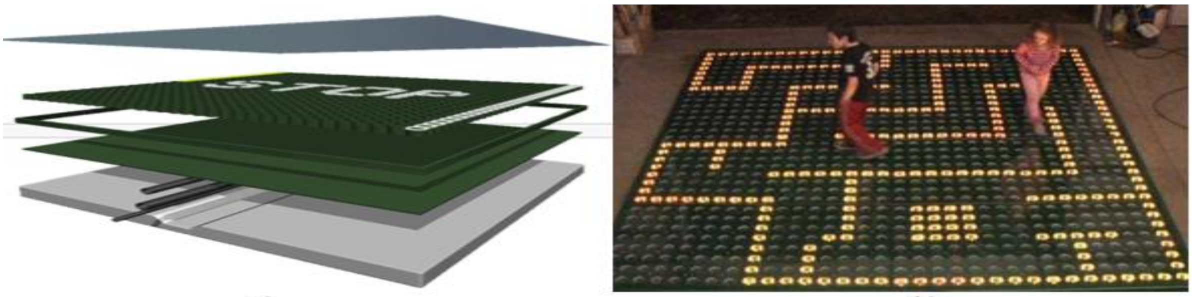


a) b)

Figure 3: a) Glass for SR1, b) Microprocessor board for SR1 [26]

The SR1 prototype also contains LED and a microprocessor board. SR1 is designed with an array of 32x32 LED cells. Each cell contains three white and three yellow LED to simulate road colors. [26]



a) b)

Figure 4. Solar road panel SR1: a) Theoretical model [7], b) Actual panel [21]

Figure 5. Installation of LED in the solar road panel SR1

In 2012, Solar Roadways Incorporated constructed and built an experimental parking concept called SR2 (Solar Roadway 2). The SR2 prototype is hexagonal in shape, with a smaller surface area and lighter weight than SR1, making it much easier to transport and install. The small hexagonal shape also allows the SR2 prototype to adapt more easily to curves. Heated glass was used for the surface layer of the solar panel. The SR2 prototype has pre-drilled mounting holes, reducing the usable surface area by 31%.

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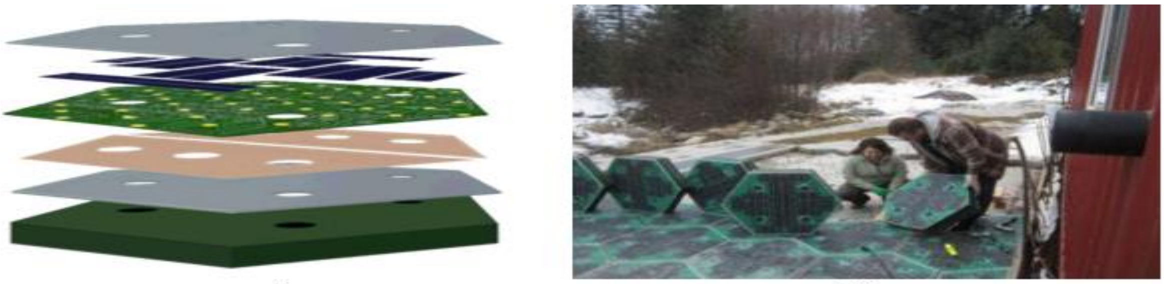


a) b)

Figure 6. Solar road panel SR2: a) Theoretical model, b) Actual SR2 [26]

To increase the usable surface area and productivity, research and production of Solar Roadway 3 were initiated. The SR3 solar road panel was developed in 2015, using edge connectors instead of mounting holes, which increases the usable surface area by 25% compared to SR2. The panel's power output was increased by over 22%.

a) b)

Figure 7. SR3 Prototype; (a) Schematic drawing; (b) Actual SR3 panels [61]

After testing SR3 at Jeff Jones Square in Sandpoint and at Marquette University in Milwaukee, USA, the obtained data was used to improve the design of the next generation of solar road panels. Therefore, in 2020, the development of a new prototype, SR4 (Solar Roadway 4), was initiated.
In SR4, compared to SR3, the power increased by approximately 14%, with the efficiency of the solar cells rising from 17.6% (SR3) to 22.5% (SR4). The cables used in SR3 panels had plastic sheathing, which cracked and allowed water to seep through. The SR4 prototype features cast rubber cables, which are much more flexible and therefore more resistant to any deformation and movement. [26]

a) b)

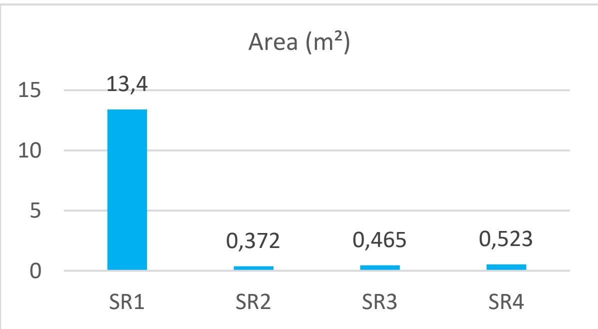
Figure 8. Solar road panel SR4 [26]

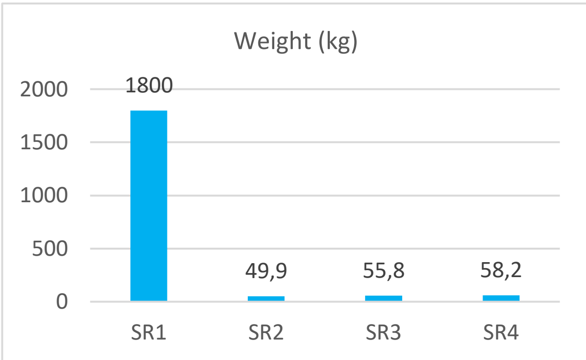
Table 1. Characteristics of solar road panels SR1, SR2, SR3, SR4 [26]

- Type of solar road	SR1	SR2	SR3	SR4
- Usable surface area	13,4 m^2	0,372 m^2	0,465 m^2	0,523 m^2
- Weight	1800 kg	49,9 kg	55,8 kg	58,2 kg
- Power	/	36 W	44 W	50 W
- Annual electricity production per 1 mile of 3.6m wide strip	/	414.984,00 kWh	601.426,00 kWh	676.424,00 kWh

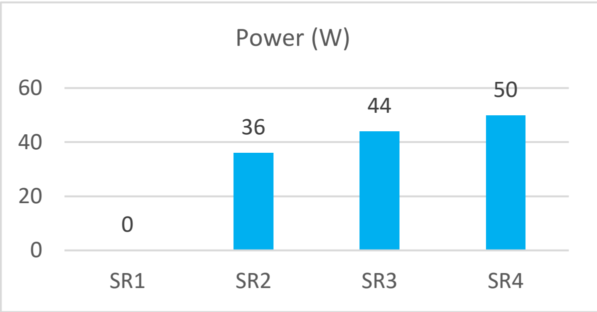
Table 2. Advantages and disadvantages of solar road panels SR1, SR2, SR3, SR4

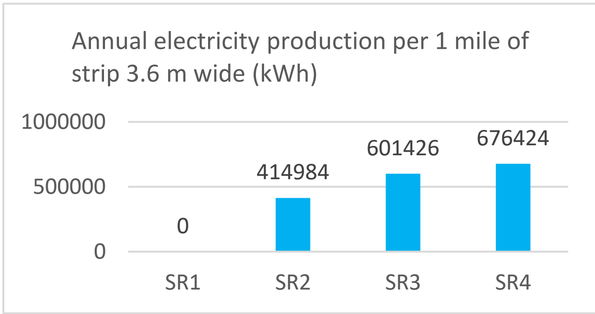
Solar panel	SR1	SR2	SR3	SR4
Advantages	- First implementation of solar panels in roadways, - Use of LED	- Smaller dimensions and lighter weight compared to SR1 - Easier installation in roadways and easier path tracing, especially in curves and on hilly terrain	- Removed mounting holes from SR2 - Larger usable surface area - Greater power - Higher energy production	- Larger usable surface area - Greater power - Higher energy production - Cast rubber cable installed, which is more flexible and resistant to deformation - Prevention of moisture infiltration
Disadvantages	- Large weight and dimensions - Difficult path tracing - No solar cells, thus does not produce electrical energy	- Mounting holes reduce the panel's usable surface area by 31%	- Use of cables with plastic non-elastic sheathing that suffer damage under stress - Corrosion due to moisture (a result of cable damage)	///





Graph 1. Representation of solar road panel area; Graph 2. Representation of solar road panel weights





Graph 3.Representation of solar road panel powers; Graph 4. Representation of the amount of electricity produced

The first implementation of solar road panels in practice was in 2012 in Idaho (USA) by Solar Roadways Incorporated. Parking lot in Sagle was paved with 108 SR2 panels, each measuring 3.6x11 meters, using the SR2 prototype solar road panels. The parking lot is still in operation and generates electricity for the needs of the Solar Roadways Incorporated facility.

a) b)

Figure 9. a) Construction of the solar parking lot, b) Condition after completion of work [26]

The first solar road, specifically a bike path, was opened in the Netherlands in Krommenie, near Amsterdam. The solar bike path, named SolaRoad, was opened in November 2014. The existing bike path is a total of 70 meters long and 2.5 meters wide, made of asphalt and paved with solar panel slabs measuring 2.5 x 3.5 meters. [27]
The roadway surface consists of modular panels made of rough, textured, tempered, and reinforced glass, which is treated with a non-stick coating to create adhesion between the bike tire and the surface. The path is constructed with a slight incline to reduce dirt accumulation and to improve solar exposure.

Figure 10. Solar bike path SolaRoad in the Netherlands

In the first six months, SolaRoad's electricity production exceeded expectations, generating more than 5000 kWh. However, the SolaRoad pilot project also revealed certain shortcomings that needed to be addressed:

- Due to its slight incline, the solar road panels become easily dirty, which contributes to a reduction in their maximum potential. Also, cyclists block sunlight while riding.
- High construction costs (with a price of $1,200 per m², electricity production of 70 kWh/m² annually, and a lifespan of 20 years),
- High connection costs to the grid, etc.

In November 2015, it was announced that the path had produced 9800 kWh of electricity over the course of a year. In october 2016, the path was extended to 83 meters in length. In February 2017, a crack appeared in the upper layer of one of the improved solar panels. By January 2020, there were significant damages on the path.The solar panels were removed in November 2020, marking the end of the SolaRoad project.
The world's first solar road for motor vehicles was built in Tourouvre au Perche, France, in 2016. The solar road, named Wattway, and was 1 kilometer long. It was intended to power the public lighting for the town of Tourouvre au Perche, which has around 3,400 residents. The Wattway solar road was designed and installed by the French company Colas in collaboration with the National Institute for Solar Energy. [1]

Figure 11. Wattway solar road in France

The Wattway solar road is covered with a special resin containing silicon, which protects the solar cells from heavy vehicles.
It was estimated that the Wattway solar road could power up to 5,000 households in Tourouvre au Perche. However, this was not the case. The region in Normandy, France, is known for its low sunlight, with only 44 days of strong sunlight per year. In the first few months, the amount of energy produced by the solar road reached only half of the expected. Expectations were 790 kWh per day, but producing was only 409 kWh per day. This was due to the low amount of sunlight, reduced light because of dirt on the road surface, and degradation of the glass surface. In 2018, only 215 kWh was produced daily, and in 2019, 200 kWh daily. The road surface soon degraded, the protective layer came off, and the vehicle speed was reduced to 70 km/h. As a result, further implementation of Wattway solar roads in France was abandoned. [11]
Just a few months after the first implementation of the Wattway solar road in France, the Ray C. Anderson Foundation, based in Atlanta, funded the construction of the first solar road in the USA, called The Ray. The Ray solar road, was installed over an area of 50 m² on Interstate 85 in Georgia.

Figure 12.a) The Ray solar road in Georgia [11]; b) Charging electric vehicles at the Ray [28]

The Ray solar road was designed and installed by Colas, the same company that installed the Wattway solar road in France, in collaboration with the National Institute for Solar Energy in the USA. Improvements were made to the spacing between the panels, which reduced the settling problems that occurred with Wattway in France.
It is estimated that one kilometer of the future The Ray road could power public lighting in a town with 5,000 residents. The Ray solar road will also have the option for charging electric vehicles. To reduce fuel consumption, The Ray has been equipped with a system for measuring tire pressure and tread wear, designed by the company WheelRight from England. Sensors measure tire pressure and tread wear as vehicles pass by and send notifications to the driver.

At the end of 2017, China opened the world's first solar highway, measuring 1 kilometer in length, in Jinan, the capital of Shandong Province, south of Beijing. The solar road spans 5,875 square meters and is capable of producing up to 1 GWh of electricity annually, which is enough to supply about 800 households. [11]

The energy generated by the solar highway is used to power street lighting, billboards, and surveillance cameras, as well as for melting snow from the roadway. In the first 14 weeks of operation, the solar highway in China produced 96 MWh of electricity.

Figure 13.Solar highway in China [30]

At the University of Western Ontario in the USA, experimental testing was conducted on solar road panel models designed from COMSOL Multiphysics, including:

- Testing of SR2 solar road panels for the effects of heavy vehicle loads, testing the roughness of the glass surface, and testing resistance to dynamic impacts.
- Testing of SR3 solar road panels for the effects of moisture, freeze-thaw cycles, heavy vehicle loads, and shear forces.

Solar road panels SR1 do not contain solar cells, and no experimental research has been conducted on them. Comprehensive load testing was performed in accordance with AASHTO standards.

Given that the maximum allowed deformation for road surfaces with solar panels is 0.5 cm, and for a standard maximum truck load of $1.82x10^3$ MPa, the test results showed that the maximum deflection would be 1.12 cm, which exceeds the permitted deformation and could damage the electronic layer. However, subsequent tests were conducted to assess the impact of loads from cars, bicycles, and motorcycles. These tests gave positive results. [10]

Tests on SR2 prototypes were conducted using various load combinations with 3D Finite Element Methods (FEM), and the results were satisfactory. The ability to withstand pulling, braking and vehicle control forces from vehicle wheels on the glass surface was tested using the so-called "British Pendulum Test." The results showed that the surface of the SR2 prototype had sufficient roughness or adhesion to allow safe driving at speeds up to 64.37 km/h for an average passenger vehicle. Under the same conditions, asphalt roads supported speeds up to 128.75 km/h. [3]

The first significant laboratory tests were conducted on SR3 solar road panels. It should be noted that the latest generation SR4 solar road panels were only recently designed, and significant laboratory testing has not yet been conducted for them.

To determine the effects of moisture and water on SR3 solar road panels and their mechanical and operational resistance, ASTM standards (Standard Test Method for Water Absorption of Plastics) were used. Prior to each test, the initial properties of the panels (initial electrical properties and weight) were measured.

The experiment had two objectives: the first was to measure the amount of water absorbed by the polymer material after immersion in water, and the second was to measure the changes, degradation of electrical and mechanical properties, changes in dimensions, and appearance of the polymer layer on the SR3 panels. [17]

a) b)

Figure 14.Moisture resistance testing of SR3 solar road panels: a) Immersion in water, b) Measuring
weight after immersion in water [17]

Table 3: Results of testing related to the increase in weight of SR3 solar road panels [17]

Increase relative to the initial weight measured before testing			
Solar panel No.	1	2	3
Results after 24 hours	No increase in weight was recorded	No increase in weight was recorded	No increase in weight was recorded
Results after 7 days	No increase in weight was recorded	No increase in weight was recorded	An increase in weight of 9.07g
Results after the first 14 days	No increase in weight was recorded	No increase in weight was recorded	An increase in weight of 9.07g
Results after the second 14 days	An increase in weight of 18,14g	An increase in weight of 18,14g	An increase in weight of 18,14g

All obtained results met the criteria of the ASTM standard. [17]
As for the results related to the testing of electrical resistance properties, after the initial 14-day test, one panel failed the electrical test. It was determined that the cause of the failure was a wire that had corroded before the experiment. [23]

Table 4. Results of testing the change in electrical resistance properties of SR3, [23]

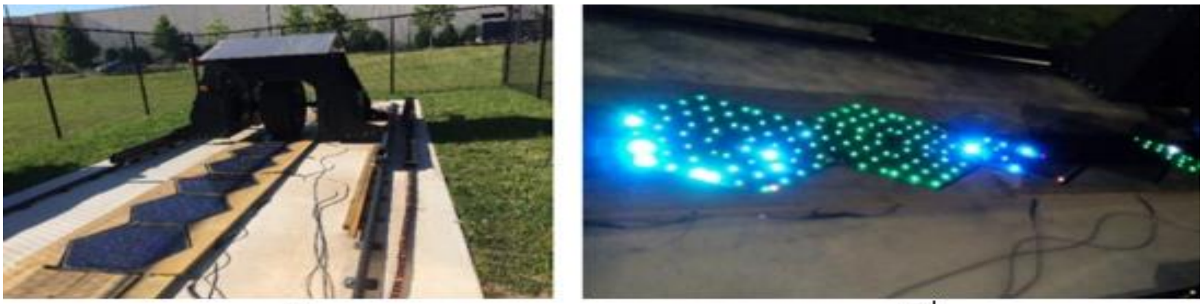
Solar panel No.	1	2	3
Results after 24 hours	Passed the electrical test	Passed the electrical test	Passed the electrical test
Results after 7 days	Passed the electrical test	Passed the electrical test	Passed the electrical test
Results after the first 14 days	Passed the electrical test	Passed the electrical test	Failed the electrical test
Results after the second 14 days	Passed the electrical test	Passed the electrical test	Failed the electrical test

Solar road panels SR3 that were tested met the current ASTM standard (Standard Test Method for Water Absorption of Plastics).
The freeze-thaw testing of the SR3 solar road panels was conducted based on the ASTM Active Standard C1645/C1645 M. A specialized ESPEC chamber was programmed to cycle the external temperature from -20°C to +50°C at 48-hour intervals. Two tanks, each with a capacity of 1000 liters, were prepared: one tank was filled with regular clean water, and the other tank was filled with water containing a 3% NaCl solution (to simulate salt). [58]
The entire test consisted of 10 freeze-thaw cycles, with 3 panels in each tank.

Table 5. Results of freeze-thaw resistance testing, [19]

Solar panel No.	1, 2, 3, 4, 5, 6
Increase in weight	There was no increase in weight in any of the 6 SR3 panels
Physical defects and damage	No physical defects or damage appeared in any of the 6 SR3 panels
Functionality of the LED	The LED were fully functional in all 6 SR3 panels

The dynamic load testing was performed by simulating the weight of a heavy motor vehicle according to a plan developed by AASHTO. This involved single-wheel loading with one million repetitions in two directions at low speeds (3-5 km/h) along the central line of the SR3 solar road panels. The SR3 panels were installed on a concrete pavement surface, with a layer of crushed aggregate and native clay soil underneath. [19]
The test was conducted at Marquette University campus in 2018.

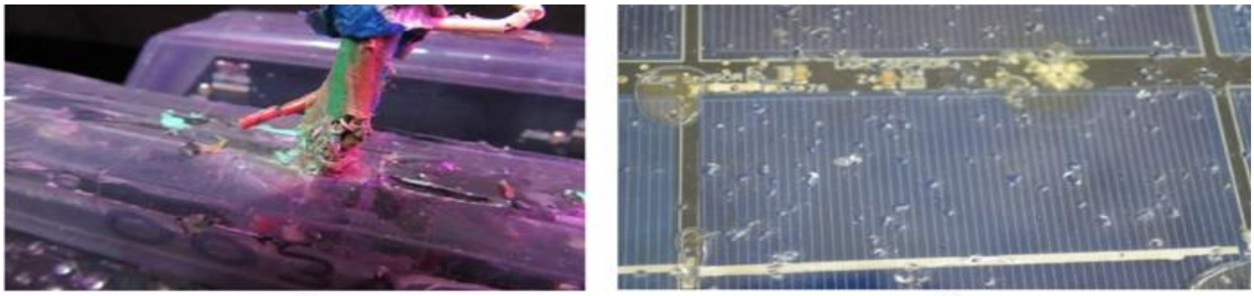


a) b)

Figure 15. a) Load simulator on SR3; b) Display of LED damage on SR3 after the experiment [19]

The test was designed for a load of 40 kN for single-axle loading from one wheel on 6 SR3 solar panels, but the actual wheel load was 42.22 kN. The wheel speed was 2.052 km/h, and potential irregularities caused by this load deviation were also analyzed using the equivalent single-axle load (ESO) concept in accordance with AASHTO regulations. Based on the fourth approximation for equivalent loads, the excess load could cause 1.241 times more damage and deformation than a 40 kN wheel load. When considered in the context of the AASHTO concrete pavement project, the static modulus of the pavement subgrade can be taken into account with a 50% reduction, as vehicle speeds on the road are much higher, making the damage factor 1.25 times greater. Taking both effects into account, each pass over the pavement in the heavy vehicle simulation (HVS) can be equated to approximately 1.551 x ESO. [19]

After completing the heavy vehicle load resistance testing procedure, it was concluded that no physical damage was observed on any of the SR3 solar road panels. The functionality of the LED gradually decreased, but this reduction was not due to the load; it was attributed to manufacturing defects in the solar road panels and the potential for moisture ingress due to continuous outdoor use.

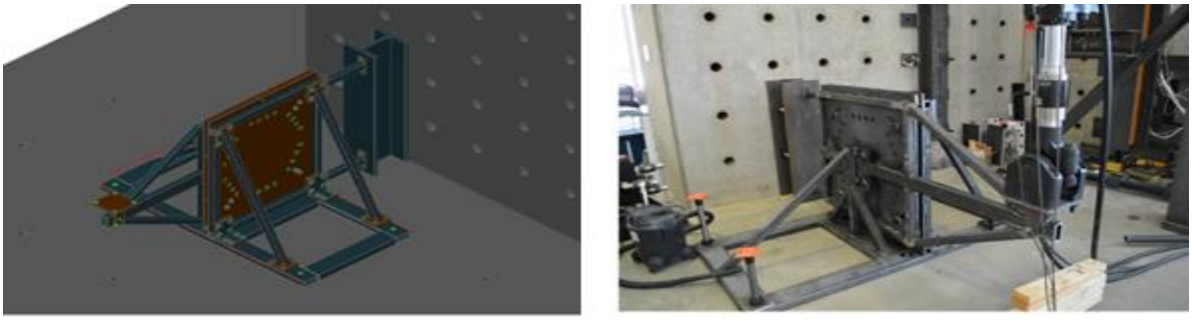


a) b)

Figure 16. a) Cable damage on the solar panel; b) Manufacturing defects [19]

The shear resistance testing under pressure of SR3 solar road panels was conducted according to ASTM D143-14 at the Engineering Materials and Structures Testing Laboratory (EMSTL) at Marquette University. Testing was performed individually for each material within the panel to assess the ability of each material layer to withstand the shear force applied by external pressure. Preliminary shear resistance testing results indicated that a force of approximately 5.8 x 10^3 kN would be required to cause a loss of shear resistance in the plane of a full-size SR3 solar road panel.

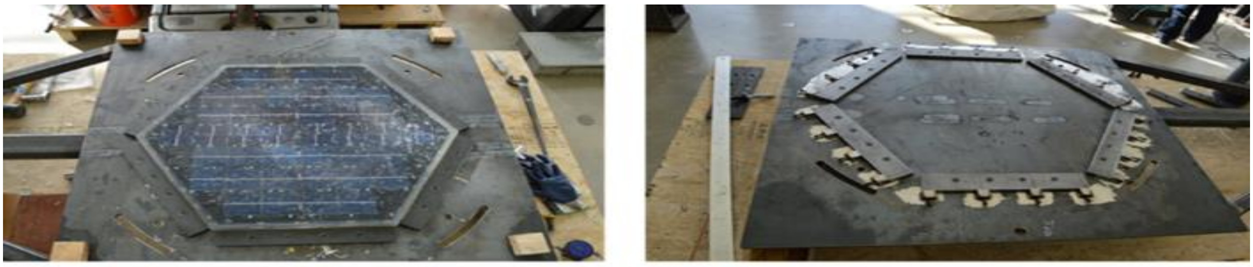
For rotational shear testing, the applicable standard ASTM D4255/D4255-15a was used, and a special rotational device was designed due to difficulties in securing the panel. [24]



a) b)

Figure 17. a) Rotational shear device for SR3; b) Rotational shear testing of SR3 [17]

During the testing of the fastening mechanism, applied load was significantly higher than expected, causing the steel fasteners to deform. The testing was halted and then continued with reinforced fasteners.



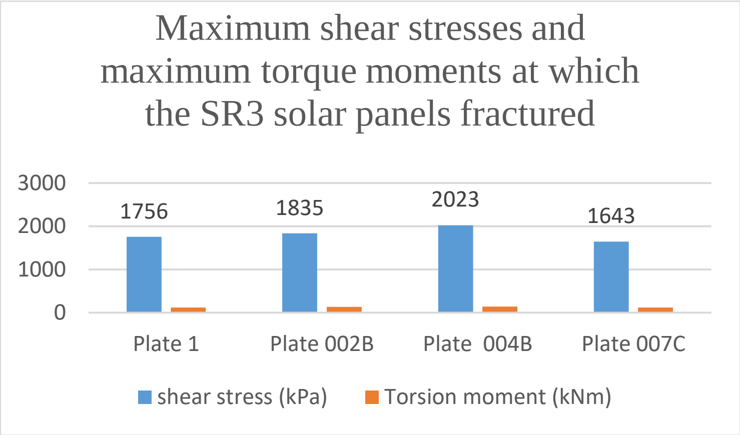
a) b)

Figure 18.a) Front view of the testing device with the fixed solar panel; b) Front view of the testing device with reinforced steel holders. [17]

The testing was continued and successfully completed on all four SR3 solar road panels in the following manner: For solar panels 002B, 007C, and 004B, the load was increased until physical damage occurred, i.e., the glass cracked, while for solar panel 1, which was the first to be tested, the load was increased until a malfunction in the electrical power supply of the solar cells occurred.

Table 6. Results of shear resistance testing, [17]

Solar panel	Maximum shear stress at which fracture occurred, kPa	Maximum torque at which fracture occurred, kNm
Panel 1	1756 (occurrence of a malfunction in the electrical power supply)	121,2
002B	1835 (recorded cracking of one of the glass panels)	131,3
004B	2023 (recorded delamination of the polymer material)	144,8
007C	1643 (recorded cracking of one of the glass panels)	117,6



Graph 5.Shear resistance testing results

It has been determined that the SR3 solar road panels are resistant to deformation under shear loading. All panels exhibited a failure of the electrical installations when the photovoltaic signal dropped to zero volts, which is a result of cell failure. In all cases, the mutual connection between the LED and the panel's output voltage was at a satisfactory level and remained functional before, after, and during each shear resistance test. The minimum shear stress at which the solar panel fractured was 1643 kPa. The results indicate that the solar road panels are resistant, durable, and functional under simulated shear stresses that correspond to real-world conditions.

Conclusion

A brief historical overview of solar roads, which shows that the use of solar roads, despite existing challenges, is highly beneficial and feasible, obliges us to dedicate ourselves fully to this topic. Solar roads combine, on one hand, the use of solar energy for electricity generation, which, aside from the initial investment, is almost free during operation, and on the other hand, meet all the requirements of asphalt or concrete roads for safe and efficient traffic flow. Research has shown that the lifespan, cost-effectiveness, and other benefits of solar roads exceed those of asphalt or concrete roads. The first criterion affecting the cost-effectiveness of solar roads is the amount of sunlight in the area where they are installed.

If we utilize existing asphalt and concrete roads to install solar roads, we save on earthworks, making the installation of solar roads even more cost-effective.

Existing solar roads should serve as examples where most of the essential functions of a solar road have been demonstrated: traffic flow, electricity generation for the road's own lighting, video surveillance, surface heating to melt accumulated snow and ice, etc.

Considering all this, and remembering that the lifespan of solar roads is longer than that of asphalt roads, along with the free electricity generated, we conclude that solar roads represent a significant innovation that, with proper installation and application, could fully replace asphalt roads with entirely new, eco-friendly roads.

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