IDEA

Innovations Deserving Exploratory Analysis Programs

NCHRP IDEA Program

Field Test and Evaluation of a Solar Snow Fence

Final Report for
NCHRP IDEA Project 234

Prepared by:
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EXECUTIVE SUMMARY

State highway agencies (“Agencies”) use structural snow fences to prevent blowing and drifting snow from encroaching onto roadways and causing public safety concerns. Agencies must budget for capital expenditures (CAPEX) and operating expenses to purchase, install, and maintain these seasonal-use structures.

By fully integrating photovoltaics (“PV”) into the design, structural snow fences can continue to perform their originally intended purpose while simultaneously providing the benefit of harnessing power from the sun. This added functionality can provide benefits to Agency energy management programs, achieve organizational sustainability goals, and help monetize right-of-way use.

The purpose of this project was to construct, test and evaluate the functionality, effectiveness, and reliability of a prototype solar snow fence in real-world conditions. The solar snow fence is a purposefully-designed, dual-use photovoltaic structure capable of generating electricity year-round in addition to protecting roadways from blowing and drifting snow.

Designed to operate autonomously, the solar snow fence tracks the sun in the day sky. When blowing and drifting snow conditions are detected by on-site sensors, the solar snow fence will cease solar tracking operations and move into to a 15° from vertical position to act as a snow fence. Solar tracking operations resume once blowing and drifting snow conditions have ceased.

A 25 linear-foot (7.6 m) section of solar snow fence was installed next to a 12 foot high (3.6 m) wooden structural snow fence at a test site along Interstate-80 in Wyoming. During the 15 month field test and evaluation, real-world data validated the system’s dual-use functionality and design.

Over the course of the testing period, the solar snow fence was able to trap and store blowing and drifting snow as effectively as the co-located wooden snow fence. In addition, the 25 linear-foot (7.6 m) section of solar snow fence generated 7½ to 15 kilowatt-hours of electricity per day over the course of the test period. The system operated autonomously, and responded to changing weather conditions. The system did not require maintenance or repairs despite being exposed to multiple winter storms, near hurricane force wind speeds, and temperatures as low as -23.8 °F (-31 °C).

The ability to generate electricity year-round and store blowing snow separates the solar snow fence from other snow fence designs. This dual-use functionality can be monetized to provide a broad range of benefits to include but not limited to: transforming Agency budgeting processes for winter road maintenance activities into revenue generating endeavors; expanding public-private partnership opportunities for infrastructure development; powering Agency infrastructure with renewable energy; and expanding benefits to landowners hosting snow fences on their property by providing renewable energy for their use.

CONCEPT AND INNOVATION

Blowing and drifting snow onto roadways poses a safety concern to motorists, with Agencies bearing the responsibility to keep roadways clear and passable. When compared to the more costly option of plowing and mechanically removing snow, Agencies use snow fences as a cost effective alternative to control blowing and drifting snow.

With an estimated installed price of $25 - $60 per linear foot (0.3 m) and annual operating expenses of $0.20 - $1.20 per linear foot (0.3 m) (*1*), Agencies must budget for both capital expenditures and operating expenses in order to purchase, install and maintain structural snow fencing – which provides only seasonal-use.

By fully integrating photovoltaics ("PV") into the design, snow fences can continue to perform their originally intended purpose while simultaneously providing the benefit of harnessing power from the sun. Transforming snow fences into dual-use structures creates year-round value and revenue-generating potential for these assets.

The development of the solar snow fence is intended to integrate winter road maintenance operations, energy management practices, and sustainability initiatives – allowing Agencies to save money and optimize resource allocation while keeping roadways clear and safe for drivers in the winter.

The solar snow fence is a purposefully-designed, fully integrated, dual-use photovoltaic structure – performing two separate but unique functions. By incorporating the structural design of a "Wyoming" snow fence with the functionality of a single-axis solar tracker, the solar snow fence is capable of harnessing solar energy year-round in addition to simultaneously providing the benefit of protecting roadways from blowing and drifting snow (*see figure 1*).

FIGURE 1: The solar snow fence (bottom, middle) utilizes the structural design of a Wyoming snow fence (top left) with the functionality of a single-axis solar tracker (top right).

Designed to operate autonomously, the solar snow fence tracks the sun in the day sky to maximize energy production. When blowing and drifting snow conditions are detected by on-site sensors, the solar snow fence ceases solar tracking operations and moves into to a near-vertical fixed position, facing the prevailing snow bearing wind direction. This is counter to conventional single-axis solar tracker operation -which stow in a near horizontal position during high wind events in order to minimize wind loading and damage to the structure. The solar snow fence does the opposite. During high wind events, the solar snow fence stows in a near vertical position which exposes the structure to maximum wind loads. The solar snow fence will remain in this position and act as a snow fence as long as blowing and drifting snow conditions are present. The use of bifacial solar panels allows the solar snow fence to maximize capturing solar energy from reflected sunlight, even when in snow fence position. Once blowing and drifting snow conditions have passed, the solar snow fence automatically transitions back to solar tracking operations.

IDEA PRODUCT

The solar snow fence is designed to trap and store blowing and drifting snow as effectively as existing structural snow fence designs, and produce year-round electricity equal to the output of modern crystalline solar panels.

Fence height, length, porosity, orientation, and site solar irradiance will dictate annual energy production; for reference, a 100 linear foot (30.5 m) solar snow fence, 12 feet (3.6 m) in height with 50% porosity located along Interstate 80 in Wyoming would have a rated output greater than 7.5 kilowatts and produce on average 40+ kilowatt-hours per day – enough to power an average US home. *(3)*

In the context of powering Intelligent Transportation System (ITS) equipment, a 280 linear foot (85.3 m) solar snow fence of similar height, porosity, and location could continuously power a 2-Line Dynamic Message Board (with a power consumption of approximately 4,700 watts); and a 150 linear foot (45.7 m) solar snow fence could continuously power a Variable Speed Limit Sign (VSLS) (with a power consumption of approximately 2,570 watts).

Besides its year-round utilization and ability to generate electricity, the solar snow fence incorporates flexibility, ease, and durability into its design principles.

Flexible Integration – The solar snow fence is designed to mimic existing structural snow fence dimensions and performance - allowing Agencies to utilize existing guidelines and processes to design and place snow fences. Fence heights, lengths, and porosity can be adjusted to meet site specific requirements. The solar snow fence can be utilized as a stand-alone, continuous snow fence or integrated seamlessly with existing wood or composite snow fences (*see figure 2*).

Ease of Installation – A 2-person team can install the solar snow fence without the need for heavy equipment or extensive ground preparation. The foundation system allows for quick installation and immediate use, with minimal ground disturbance. Integrated wiring in the structure's design reduces the need for extensive trenching or cable burying.

Flexible Use – An integrated programmable logic controller allows users to set solar tracking range-of-motion limits and snow fence position based on site needs and weather thresholds. Fence orientation is not limited to a north-south alignment, as the system is capable of self-adjusting its solar tracking operations based on any fence alignment. Integrated battery energy storage and power conversion equipment provide common electrical outputs (e.g. 60 hertz; single phase, split phase, or three phase alternating current; 120v, 208v, 240v, 277v, or 480v) allowing for ease in connecting and powering equipment. Systems can be designed for grid-connected, micro-grid, or off-grid operations.

Easy to Operate – Once installed, the solar snow fence is design to operate autonomously, without the need for continuous monitoring or adjustments. Maintenance requirements are minimal, with annual system inspections recommended.

Durable – With a 30+ year design life, the system components and structure are built to survive and operate in the harshest and most extreme weather conditions – including 120 mph (193 kph) wind gusts and temperatures as low as -30 °F (-34.4 °C).

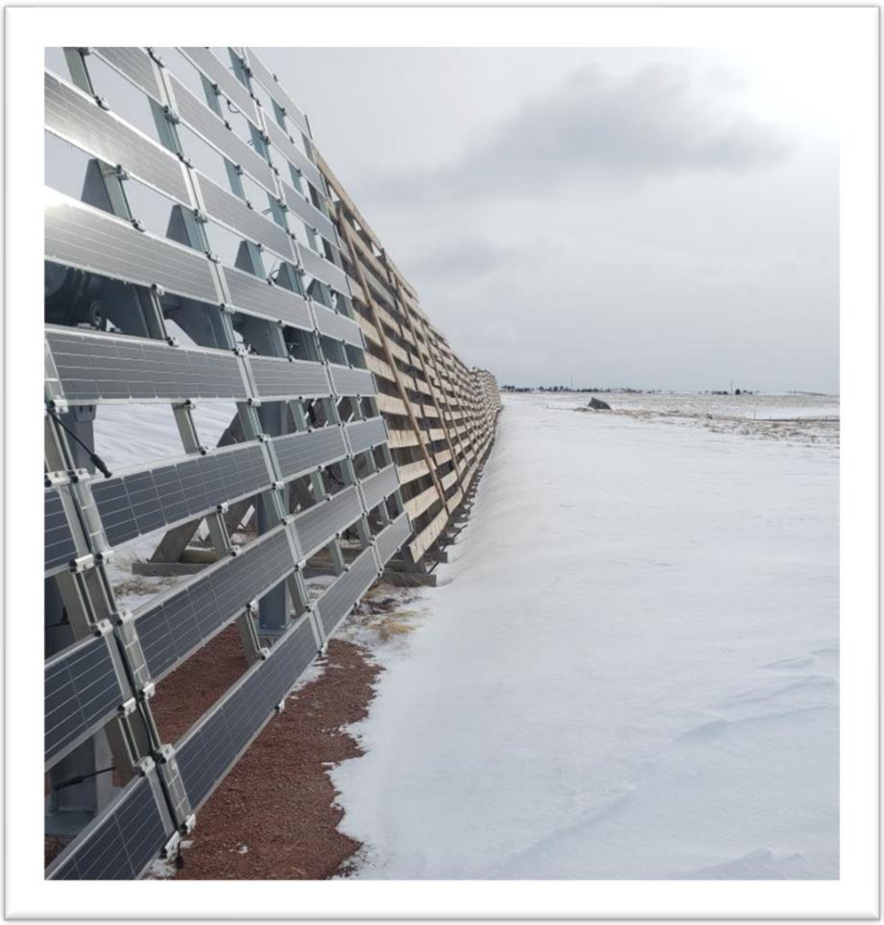


FIGURE 2: 12 foot (3.6 m) high solar snow fence co-located with a wooden snow fence.

INVESTIGATION

This project was designed to test and evaluate the functionality, effectiveness, and reliability of a prototype solar snow fence in real-world conditions. Project efforts were divided into two stages. The first stage consisted of constructing the solar snow fence prototype. The second stage focused on testing and evaluating the solar snow fence's capabilities, including solar tracking, autonomous operations, power production, snow fence effectiveness, integration with existing snow fences, and weather impacts to operations and maintenance.

FIRST STAGE: CONSTRUCTION

In the project's first phase, a prototype solar snow fence approximately 11.5 feet in height (3.5 m), 24.5 feet (7.5 m) in length, and a designed porosity of 43% was constructed on the north-end of an existing 12 foot (3.6 m) high by 300 linear-foot (91.4 m) long wooden snow fence with 47% designed porosity (*see figure 3*). *(4)*

WYDOT provided temporary use (from October 2021 through May 2023) of a site to construct, test, and evaluate the solar snow fence. Located in the median between the east and west bound lanes of Interstate-80 at mile marker 331.5 (approximately mid-way between Cheyenne and Laramie), the site is characterized as nearly level, with a slight high point on the southern end, and an average elevation of approximately 7,875 feet (2,400 m) (*see figure 4*). The ground consists of decomposing granite interspersed with native vegetation approximately 1 to 4 inches (2.5 to 10 cm) in height.

The surrounding area consists of an array of wooden and composite snow fences, 12 feet (3.6 m) in height with variable lengths (typically 300 linear feet (91.4 m)). The prevailing wind direction is from the west-south-west, with an annual average wind speed of 20.8 mph (33.5 kph). The average annual temperature is 42 °F (5.5 °C), with the area receiving approximately 58.8 inches (149.3 cm) of snow per year. *(5)* The average plane of array (POA) irradiance at the site is 6.0 kwh/m² per day. *(6)*

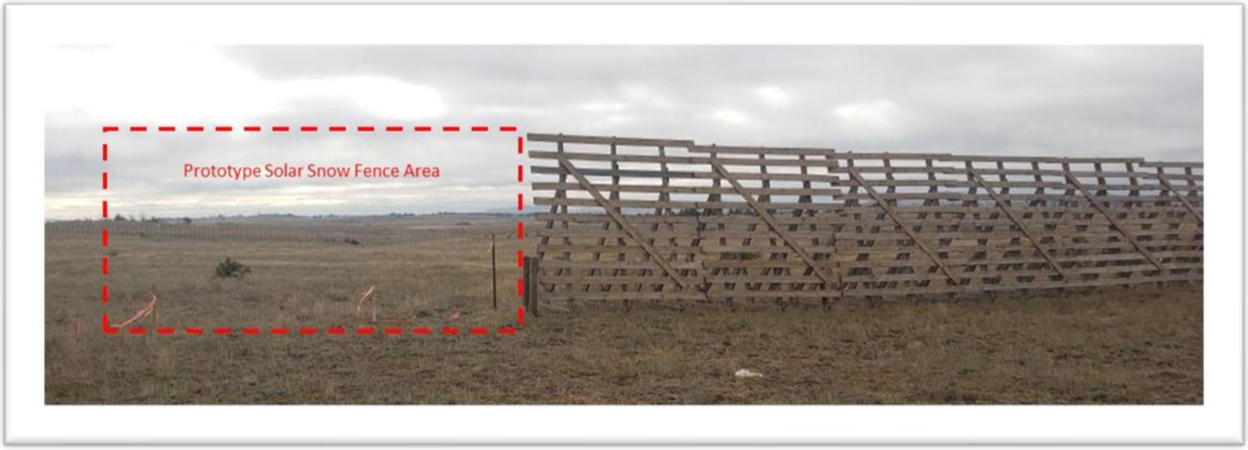


FIGURE 3: Elevation view to the east of the proposed solar snow fence location.

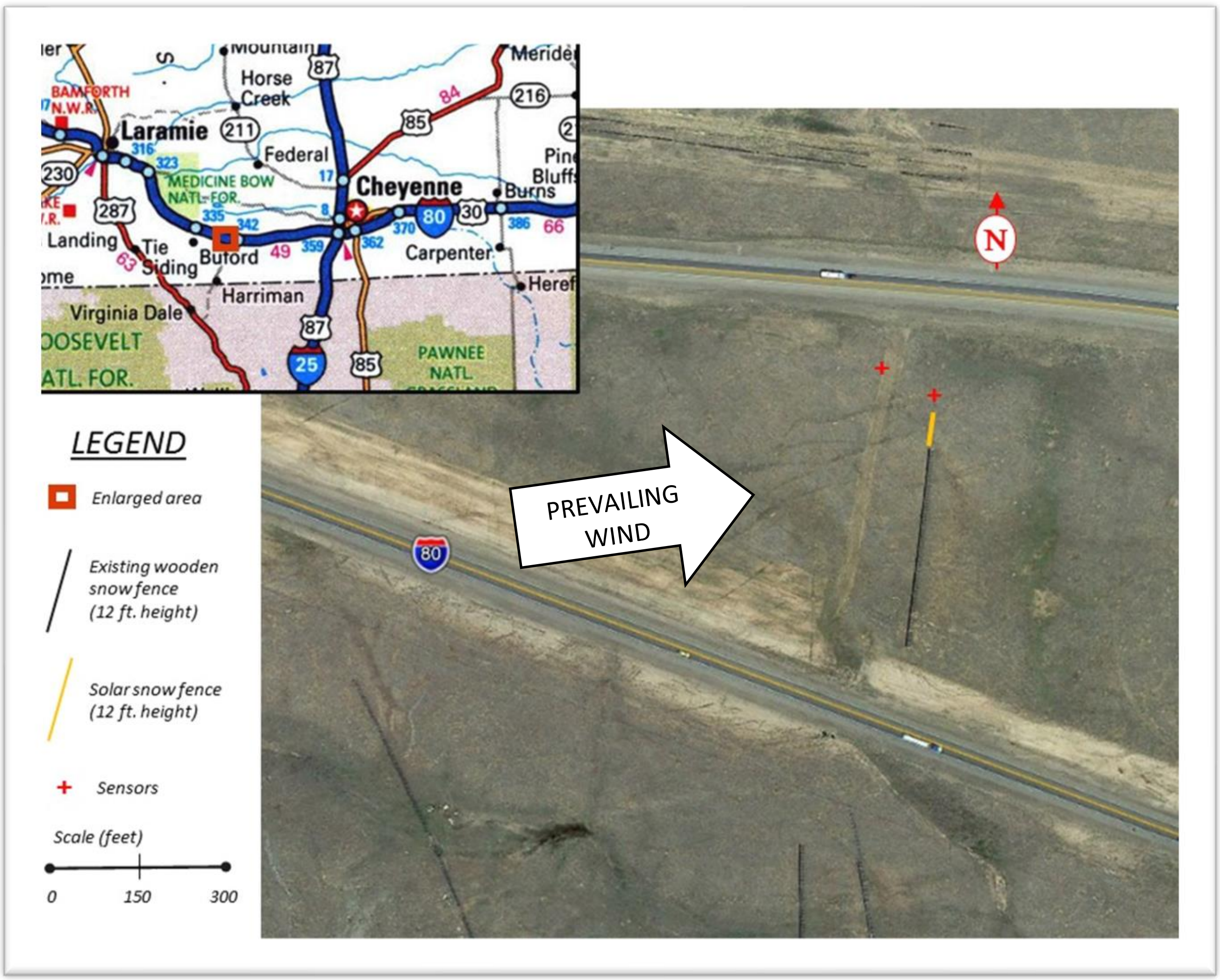


FIGURE 4: Map and plan view of the solar snow fence test site.

A site survey and geotechnical evaluation were conducted in September 2021, with permits secured prior to the start of construction.

Construction began on November 4th, 2021 with the installation of metal helical pier foundations. Metal helical piers allow for quick installation without the need for extensive site preparation (e.g. building access roads, excavating, form setting, rebar installation) or the use of heavy construction equipment. Metal helical piers have high strength and can immediately support full design loads after installation. They are also easily removed and can be re-used or recycled.

With expected extreme wind loads on the prototype solar snow fence calculated to be 46,475 Newtons (or 10,448 pounds of force), and a bending moment of 91,091 Newton-meters (or 67,189 foot-pounds), the foundation system design is a critical element to counteracting the forces exerted by high winds. A time-lapse video of the foundation installation can be viewed [HERE].

The solar snow fence was successfully assembled on November 9th, 2021, in accordance with the design drawings developed by Longboard Power. Half of the solar panels were installed at this time, as supply chain issues delayed the installation of the remaining panels until January 23rd, 2022 (*see figure 5*).

FIGURE 5: Partially assembled solar snow fence with monofacial solar panels attached.

Once electrical connections and safety systems were tested, the following parameters (*see figure 6*) were uploaded to the solar snow fence's automated controller:

PARAMETER	VALUE
Solar Tracking - East position limit	+65°
Solar Tracking - West position limit	-75°
Snow fence position	-75°
Overnight stow position	-75°
Loss of sensor/comms safety position	-75°
Wind threshold for snow fence position (mph/kph)	15/24.1

FIGURE 6: Solar snow fence programmed parameters.

On-site weather and power sensors were activated, calibrated, and tested for proper functioning in order to collect the following data: wind speed; wind gust; wind direction; temperature; precipitation; humidity; solar irradiance; direct current (DC) voltage, amperage, and power.

A weather station (identifier: KVDW) located approximately 1 mile (1.6 km) to the west of the test site provided additional data. (*7*)

SECOND STAGE: TEST & EVALUATION

Field testing and evaluation of the solar snow fence included validating solar tracking movement, autonomous transitions to-and-from snow fence position to solar tracking based on sensor inputs, measuring energy generation, analyzing snow fence performance, integrating operations with existing snow fences, and documenting extreme weather impacts to operations and maintenance. The duration of this stage was 12 months.

Validate System Movement & Autonomous Operations

The solar snow fence uses a programmable logic controller, associated sensors, and gear drive that allows nearly 180° range-of-motion and autonomous operation. Users are able to select solar tracking ranges and set stow positions based on weather parameter threshold values. The solar snow fence is equipped with integrated sensors to detect obstructed/blocked rotation. The system is designed to stop any additional rotation attempts until the obstruction is cleared – such as a snow drift.

For the test and evaluation, the solar snow fence's solar tracking range-of-motion was set at +65° to -75° (*see figure 7*; reference *figure 6* of this report for parameters programmed into the solar snow fence's controller). The total elapsed time for the solar snow fence to move from +65° to -75° is approximately 2 minutes. In coordination with WYDOT, the system was programmed to autonomously stow in snow fence position (selected as -75° from horizontal) when on-site snow was present and wind speeds reached or exceeded 15 mph (24.1 kph). Solar tracking operations would automatically resume once weather thresholds subsided.

FIGURE 7: Solar snow fence solar tracking range-of-motion.

On-site observations and time lapse camera video were used to validate the solar snow fence's range-of-motion and ability to successfully track the sun in the day sky. A short time lapse video of solar tracking operations can be viewed [HERE].

Automated transitions to-and-from solar tracking operation to snow fence position based on site weather conditions were also verified via on-site observations and time lapse camera video.

A 5-day time lapse video validating the solar snow fence's automated operations in varying on-site weather conditions can be viewed [HERE].

Validate System Power Generation

The use of integrated solar panels to generate electricity is the key feature which separates the solar snow fence from other types of snow fencing. Whether holding a fixed position as a snow fence or tracking the sun in the day sky, the solar snow fence can produce electricity in either configuration.

Maximum solar power generation occurs when a solar panel's surface is perpendicular to the sun's rays. Energy production significantly decreases as panel angles deviate from this perpendicular alignment. Power measurements were recorded and logged in order to validate the solar snow fence's generation capability in both snow fence position and solar tracking operation.

Two different solar panel designs were tested to determine optimum power generation characteristics. One panel design consisted of monofacial solar panels – with one side of the panel capturing solar energy. The second consisted of a bifacial design – with both the front and back sides of the panel able to capture solar energy (see *figure 8*).

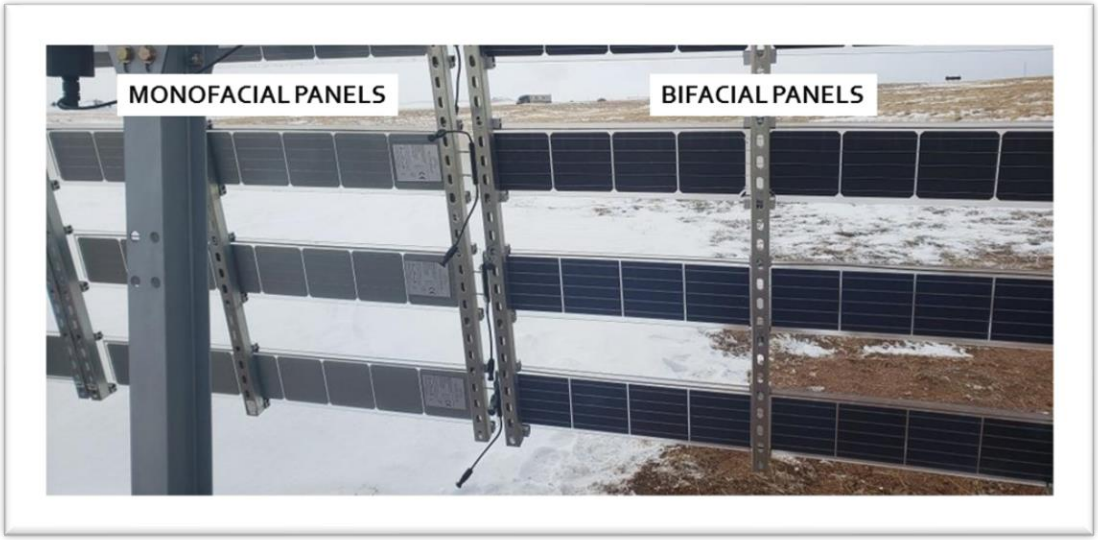


FIGURE 8: Rear view of the monofacial panels (left) and bifacial panels (right).

The monofacial panels were constructed with passivated emitter and rear contact (PERC) cells – which are commonly used in conventional crystalline silicon solar panels. The bifacial panels were constructed with Hetero-Junction Technology (HJT) cells. HJT cells combine crystalline silicon with amorphous silicon (i.e. thin-film) to produce a high-powered hybrid cell. This solar cell type is more shade and heat tolerant than conventional crystalline silicon cells (like PERC) and has a higher power output than thin-film silicon. *(8)* Details for each panel type are provided in *figure 9*; dimensions are provided in *figure 10*.

	Monofacial	Bifacial
Cell Type	PERC	HJT
Cell composition	monocrystalline	monocrystalline
Number of cells per panel	8	8
Cell size	M2	M2
Panel rated Power (Pmax) in *watts*	42	42
Voltage (Vmp) in *volts*	4.4	4.4*
Current (Imp) in *amperes*	9.54	9.49*
Panel length *(inches/millimeters)*	55/1400	57/1450
Panel width (*inches/millimeters)*	7.5/190	7.5/190

* Front side measurement only

FIGURE 9: Panel characteristics.

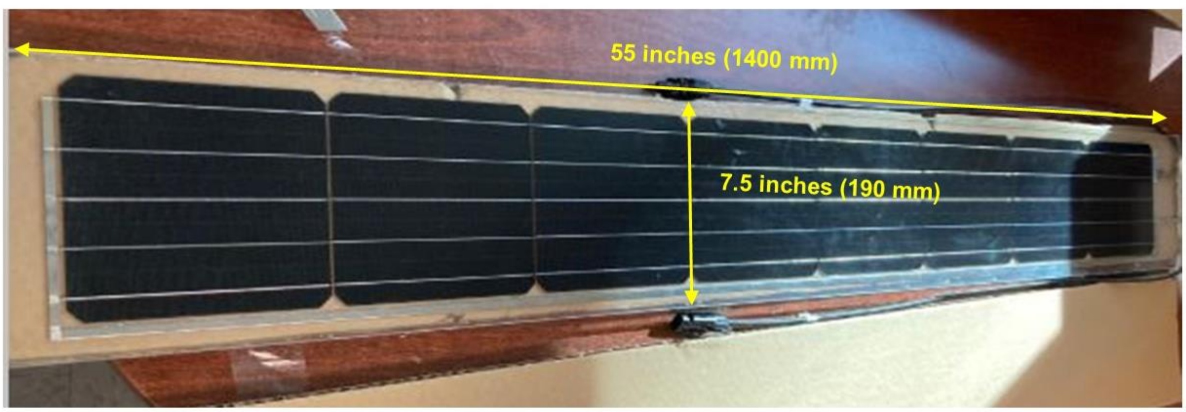


FIGURE 10: Single solar snow fence PV panel.

Two equal sections totaling 18 panels from each panel design type were used in the power generation tests (see *figure 11*). Each section is approximately 10 feet in length.

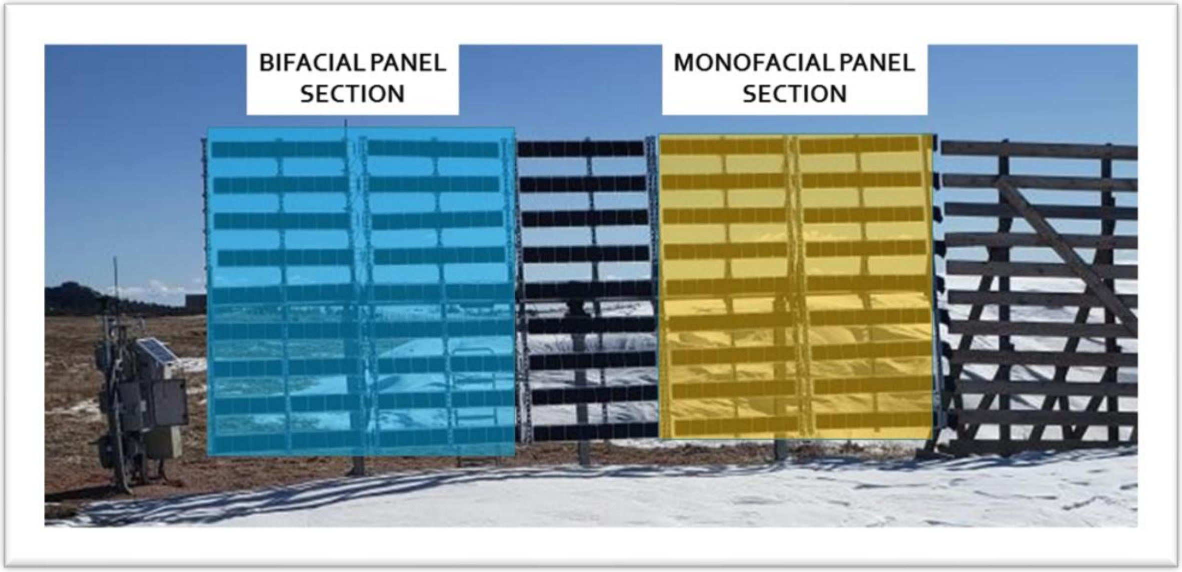


FIGURE 11: Panel type sections of the solar snow fence.

Each panel section was connected to a dedicated circuit, allowing for simultaneous power production measurements for both panel types. The schematic layout by panel type, including protection equipment, and power measuring device can be found in *figure 12.*

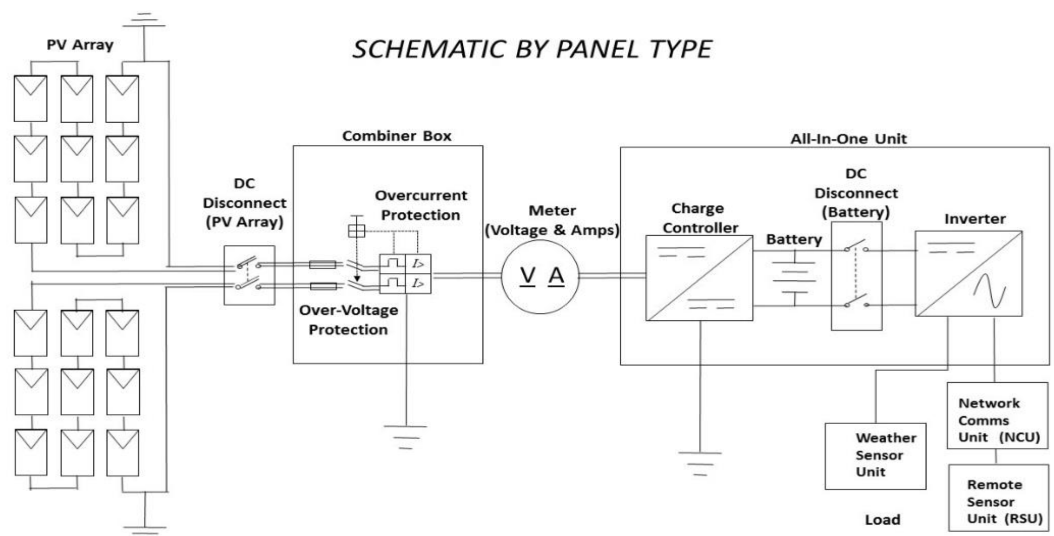


FIGURE 12: Electrical schematic for each panel type.

Power Production in Snow Fence Position

The average daily power production for both panel types in snow fence position is presented in *figure 13*. Analysis of the data shows the bifacial panels provided 10% more daily power production than the monofacial panels when in the snow fence position. The production difference between the two panel types was most pronounced during the first half of the day, with the bifacial panels producing 37% more power than the monofacial panels. This result was expected, as both panel types faced west – away from the rising sun. The bifacial panels were able to collect solar energy on both front and back sides, whereas the monofacial panels were limited to just the front side of the panel being able to harness solar energy. During the second half of the day, with the sun in the western part of the sky, the difference in performance between the two panel types was minimal with the bifacial panels producing approximately 5% more energy.

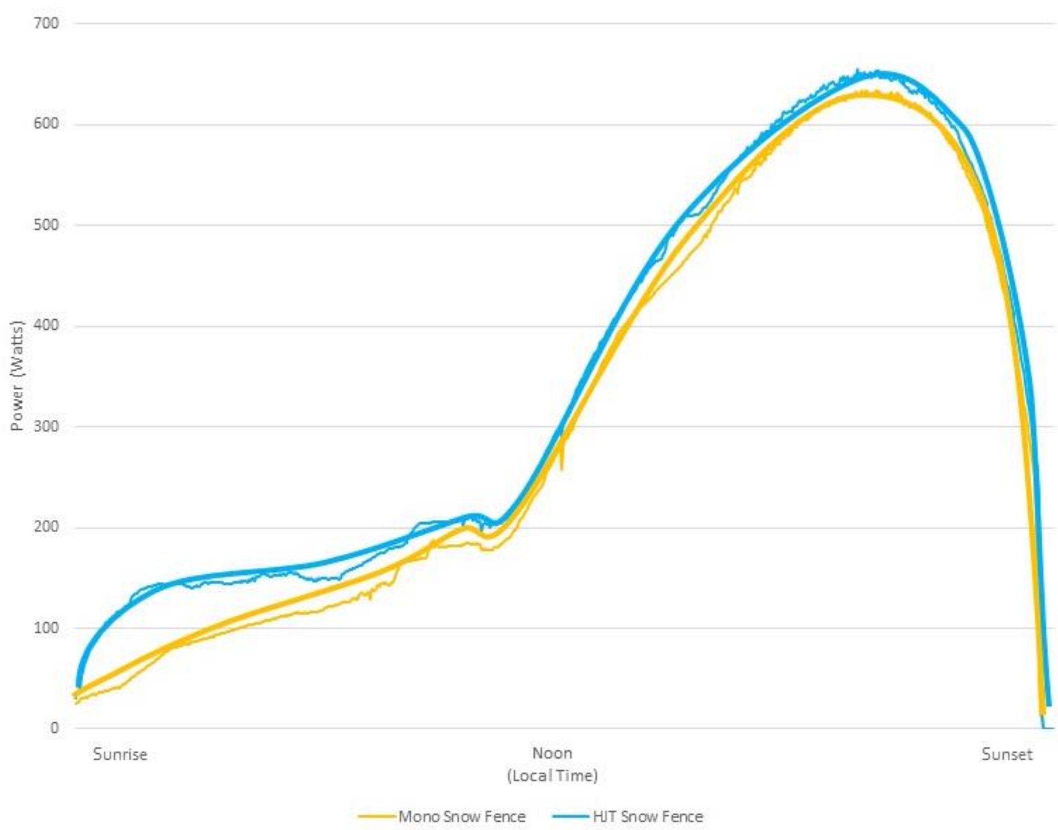


FIGURE 13: Solar snow fence daily power output curves for monofacial panels (yellow line) and bifacial panels (blue line) in snow fence position. Weighted lines overlaid atop raw production data represent ideal power production.

Given the site's solar irradiance profile coupled with the solar snow fence's north-south orientation, the average daily power production for a 10 foot section of solar snow fence in snow fence position was 3.8 kilowatt-hours (kWh) per day for the monofacial panels and 4.2 kWh per day for the bifacial panels.

Power Production in Solar Tracking Mode

Solar tracking power production curves for both panel types are represented in *figure 14*. Analysis of the data shows minimal production differences between the panel types, with the bifacial panels producing 5% to 14% more power.

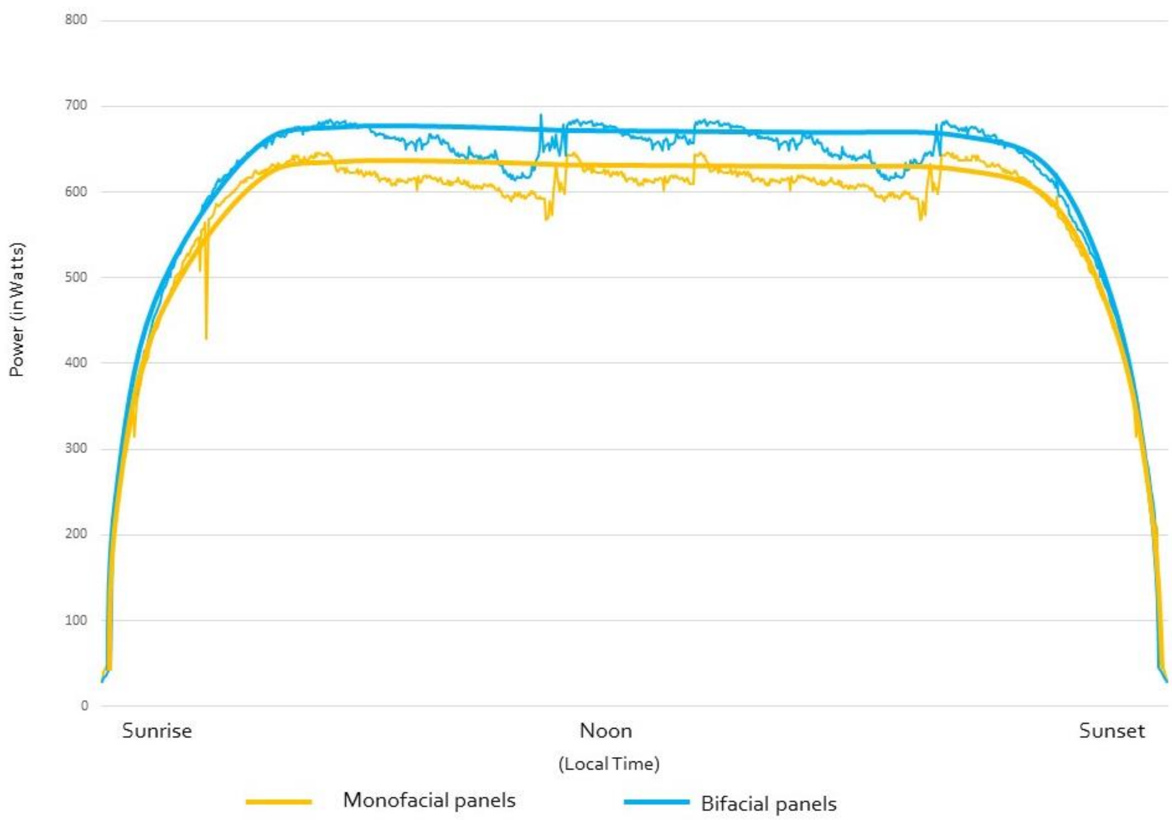


FIGURE 14: Solar snow fence daily power output curves for monofacial panels (yellow line) and bifacial panels (blue line) in solar tracking mode. Weighted lines overlaid atop raw production data represent ideal power production.

The height of the solar snow fence's axis-of-rotation above the ground coupled with its designed porosity allows for a significant amount of sunlight to reach the ground beneath the structure. Depending on the ground cover composition, the percentage of sunlight reflected from the ground surface (known as albedo) can increase power production in bifacial solar panels (*see figure 15*).

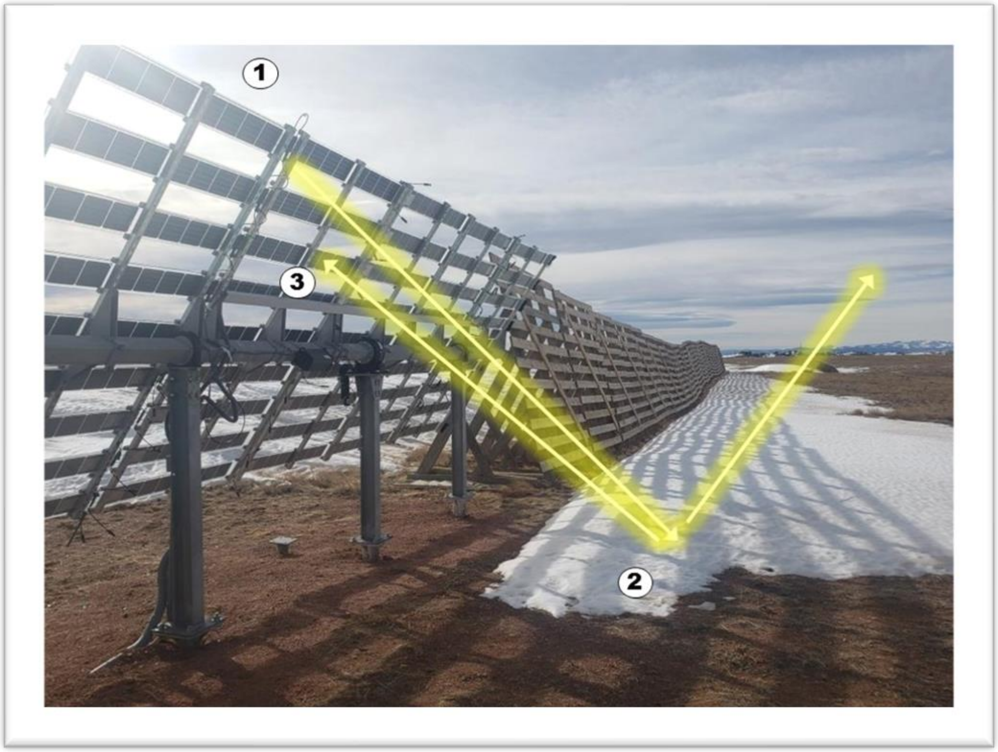


FIGURE 15: Illustration of albedo. Although a portion of the sun's light energy is absorbed by the front side of the solar panels (1), the gaps between the panels allow for additional solar energy to reach the ground (2). The amount of sunlight reflected from the ground depends on the albedo value of the ground surface. *(9)* **Snow can reflect up to 95% of sunlight and therefore has a high albedo value. The reflected light is scattered in multiple directions, with some of the reflected light directed towards the backside of the solar panels. Bifacial panels are able to convert this scattered light into electricity (3).**

The average daily power production for a 10 foot (3 m) section of solar snow fence during solar tracking operations was 4.4 kilowatt-hours (kWh) per day for the monofacial panels and 5 kWh per day for the bifacial panels.

Typical Power Production Profile

As snow fences are typically placed in areas prone to high winds, weather conditions favorable for solar tracking operations (i.e. wind speeds below 15 mph when snow is present) can be limited. However, seasonal and diurnal wind profiles still provide ample opportunities to maximize solar energy collection via solar tracking operations. At the test site, seasonal average wind speeds tend to be greatest during the winter and spring, with summer and fall experiencing the lowest average wind speeds. *(10)* In most locations, diurnal wind profiles are typically characterized by calm morning conditions with increased afternoon wind speeds. *(11)* *Figure 16* provides an illustration of the typical daily power production for the solar snow fence. Calm conditions in the morning allow for solar tracking operations. As wind speeds increase to pre-defined threshold levels by mid-day, the solar snow fence transitions into snow fence position. This automated functionality allows the solar snow fence to maximize solar energy production. An associated time lapse video to compliment the solar snow fence's power production in *Figure 16* can be viewed [HERE]. Additional information on wind conditions at the test site can be found in the *Extreme Weather & Impacts on Operations & Maintenance* section of this report.

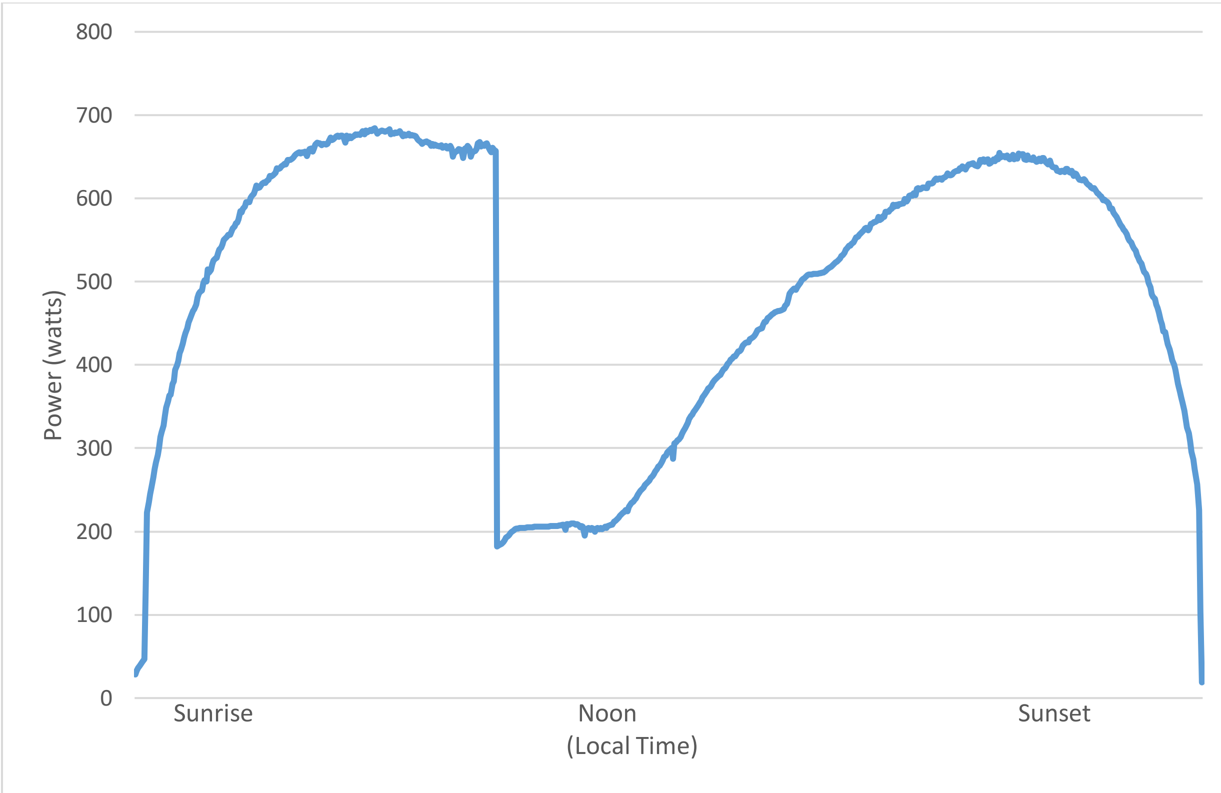


FIGURE 16: Typical power production curve for bifacial panels based on diurnal wind profiles at the test site. Calm mornings allow for solar tracking operations until just before noon. Increased wind speeds exceeded programmed threshold levels by mid-day, resulting in the solar snow fence autonomously transitioning into snow fence position for the remainder of the day.

Validate Snow Fence Performance

Downwind snowdrift dimensions were compared to validate the solar snow fence's capability to trap and store blowing and drifting snow on par with existing snow fence designs.

Multiple on-site ground measurements over two winter seasons, and one aerial light detection and ranging ("LiDAR") survey were utilized to measure, map, and compare snowdrifts formed behind the solar snow fence to a co-located wooden snow fence. The multiple measurements documented snowdrift genesis from new snowfall events as well as drift decay from snow melt and sublimation.

Since the solar snow fence is only twenty-five linear feet and located on the north-end of an existing 300 linear foot (91.4 m) wooden snow fence, measurements and comparisons were focused on snowdrifts formed on either end of the snow fence. This approach takes into consideration the solar snow fence's position in relation to the existing wooden snow fence, and accounts for the shorter and rounded downwind snowdrift formed at the ends of snow fences (known as "end-effect"; *see figure 20*). *(12)*

Two additional factors were also considered when comparing the downwind snowdrifts: terrain variation and bottom-gap dimensions.

Terrain Variation: although the test site is relatively flat, there are slight changes in the terrain which affect snowdrift formation. This includes non-linear slope profiles in both the windward approach and leeward side of the snow fence.

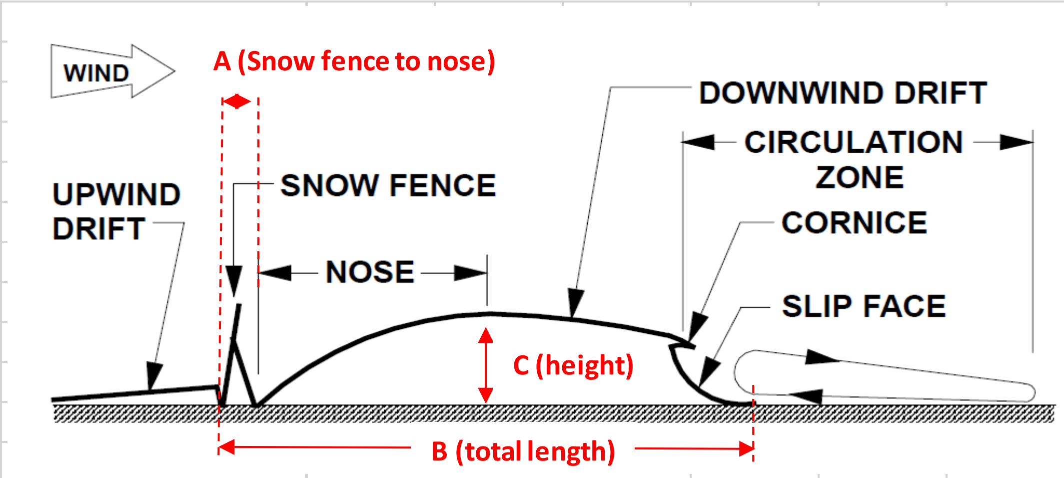
Bottom-Gap: The bottom gap is the open distance as measured from the tip of any ground vegetation to the first horizontal plank of the snow fence. A bottom gap of approximately 12.5% of the total fence height is recommended in the design of a snow fence. *(12)* A bottom gap less than the recommended design reduces overall snow trapping capacity and causes the downwind drift to form and encroach on the snow fence itself – which can lead to fence damage and reduce the overall useful life of the structure. The on-site wooden snow fence has a bottom gap of less than 12 inches (30.5 cm); equal to < 8% of the fence height, while the solar snow fence has a bottom gap of approximately 18 inches (45.7 cm); equal to 12.5% of the fence height and within WYDOT's *12 Foot (3.6 m) Wood Snow Fence Standard Plan*. *(4)* Of note, the solar snow fence design allows for vertical rail adjustments (in 2 inch (5 cm) increments) to account for undulating terrain variations.

Three snowdrift dimensions were recorded during each on-site ground measurement:

Snow Fence to Nose: The distance from the centerline of the snow fence to the start of the downwind snowdrift (denoted as "A" in *figure 17*).

Total Length: The distance from the centerline of the snow fence to the end of the downwind snowdrift (denoted as "B" in *figure 17*).

Height: The maximum height of the downwind snowdrift (denoted as "C" in *figure 17*).



	Solar Snow Fence			Wooden Snow Fence		
Date	A	B	C	A	B	C
March 3, 2022	*23*	*125*	*7*	*17*	*119*	*8*
March 14, 2022	*24*	*137*	*10*	*15*	*126*	*12*
March 25, 2022	*21*	*114*	*11*	*18*	*95*	*13*
April 7, 2022	*33*	*90*	*4*	*33*	*76*	*4*
April 29, 2022	*No drift behind fence end*			*No drift behind fence end*		
February 10, 2023	*17*	*115*	*7*	*0*	*100*	*10*

FIGURE 17: Comparison of downwind snowdrift sizes (in feet) for the solar snow fence and wooden snow fence (illustration adapted from *(12)***).**

The recorded snow fence-to-nose measurements (measurement “A”) for both fence types illustrates the impact the bottom gap has in determining where the downwind snowdrift starts to form. As predicted and observed, the shorter bottom gap in the wooden snow fence resulted in the downwind drift forming closer to the fence, and at times encroaching on the structural support members (*see figure 18*).

FIGURE 18: Snowdrift creep and glide onto the existing wooden snow fence at the test site.

After accounting for variations in the bottom gap, the measurements indicate comparable snowdrift formations on either end of the snow fence. By subtracting measurement "A" from "B", the length of the snowdrifts on either end are nearly identical (see *figure 19*).

	Solar Snow Fence	Wooden Snow Fence
Date	**B - A**	**B - A**
March 3, 2022	*102*	*102*
March 14, 2022	*113*	*111*
March 25, 2022	*93*	*77*
April 7, 2022	*57*	*43*
April 29, 2022	*NA*	*NA*
February 10, 2023	*98*	*100*

FIGURE 19: Downwind snowdrift length (in feet; measure from nose to end).

FIGURE 20: Side-view (top) and front-view (bottom) of the downwind snowdrift behind the solar snow fence (top photo taken March 2022, bottom photo taken December 2022).

A combination of the sun's gradually increasing elevation (from winter to summer solstice) and the alignment and geometry of the snowdrift may account for the more rapid snowdrift melt on the south-end (as observed in the recorded data). This section of the snowdrift has a greater surface area more directly exposed to solar irradiance than the north-end snowdrift.

A LiDAR survey of the downwind snowdrift was conducted on March 3, 2022 (see *figure 21*). The survey image provides a plan view of the downwind snowdrift, and captures the end-effect on snowdrift formation. The LiDAR data compliments and is in agreement with the on-site ground measurements, to include bottom gap impact on downwind drift formation and overall similarity in downwind drift lengths on either end of the snow fence.

FIGURE 21: Plan view of snowdrift formation taken by an unmanned aerial vehicle.

By accounting for the difference in the bottom gap dimensions and evaluating end-effect results, the data reflects the solar snow fence captured and stored blowing and drifting snow as effectively as the co-located wooden snow fence. WYDOT staff conducted their own surveys and evaluations of the snowdrift and reached the same conclusion. *(13)*

Integration with Existing Snow Fences

The point of connection between the two dissimilar fences (i.e. the solar snow fence and the co-located wooden snow fence) was studied to determine how this potential gap may impact snowdrift formation and solar tracking operations. Gaps as small as 6 inches (15.2 cm) between snow fence sections can reduce overall fence effectiveness, resulting in reduced snow capture capacity and induced blowing snow in the gap spaces (see *figure 22*). *(12)*

FIGURE 22: Effect of a 6 inch gap between snow fence panels on downwind snowdrift formation; resulting in reduced fence efficiency. (Image from *(12)*).

To mitigate the effects of gap spacing and to allow for unobstructed range-of-motion operations, the solar snow fence design incorporates the use of end-brushes. These brushes are located on the end of solar snow fence adjacent to the existing wooden snow fence. The end-brush design allows for unimpaired solar tracking operations. When the solar snow fence moves into snow fence position based on site weather conditions, the end-brushes close the gap and provide a physical point of contact between the two dissimilar fences (see *figure 23*).

On-site observations of the downwind snowdrift located between the two dissimilar fences were recorded during regular site visits from January through April of 2022. Analysis of those observations did not show evidence of snowdrift erosion caused by open gaps.

A combination of time-lapse camera recordings and on-site observations were used to determine end-brush impacts on solar snow fence solar tracking operations. Those recordings and observations did not reveal any obstructed or impaired solar tracking movement from the use of end-brushes. Routine inspections of the solar snow fence and wooden snow fence conducted during each site visit also did not show signs of damage to either fence from end-brush use.

FIGURE 23: End-brushes in contact with the wooden planks of the co-located snow fence.

The use of end-brushes successfully bridged the gap between the two dissimilar fences without impacting solar tracking operations, snow fence storage capacity, or causing damage to either fence. This functionality allows the solar snow fence to integrate seamlessly with existing wooden or composite fences, enabling segments of solar snow fence to be placed within existing snow fence rows if desired.

Extreme Weather & Impacts on Operations & Maintenance

Snow fences are designed to operate in extreme weather conditions. During the winter, snow fences must be able to withstand hurricane force winds, blizzards, freezing rain, ice build-up, heavy snow fall, and extreme cold temperatures. During the remainder of the year, these same structures are exposed to rain, lightning, hail, heat waves, blowing dust, and intense solar irradiance. The extreme range of weather coupled with the duration of the extreme weather events requires snow fences to be robust and durable in order to survive for decades in the field.

To validate the solar snow fence's ability to operate in extreme weather conditions, a combination of on-site weather instrumentation and a nearby weather station were used to collect and record the following weather parameters: sustained winds, wind gusts, temperatures, precipitation type, and totals. Physical inspections of the solar snow fence were conducted during site visits to record any damage and document any unscheduled maintenance. Time-lapse camera recordings provided additional data on solar snow fence operations during and after extreme weather events.

The collected weather data was analyzed to derive monthly extreme values for maximum sustained winds, maximum wind gusts, maximum temperature, and minimum temperature (see *figures 24 & 25*).

High Wind Events

During the 12 month testing period, the solar snow fence was exposed to maximum sustained wind speeds of 58.4 mph (94 kph), and a maximum wind gust of 67.7 mph (109 kph). A total of 42 High Wind Warnings were issued by the National Weather Service during the same time frame for the affected test site area. *(14)*

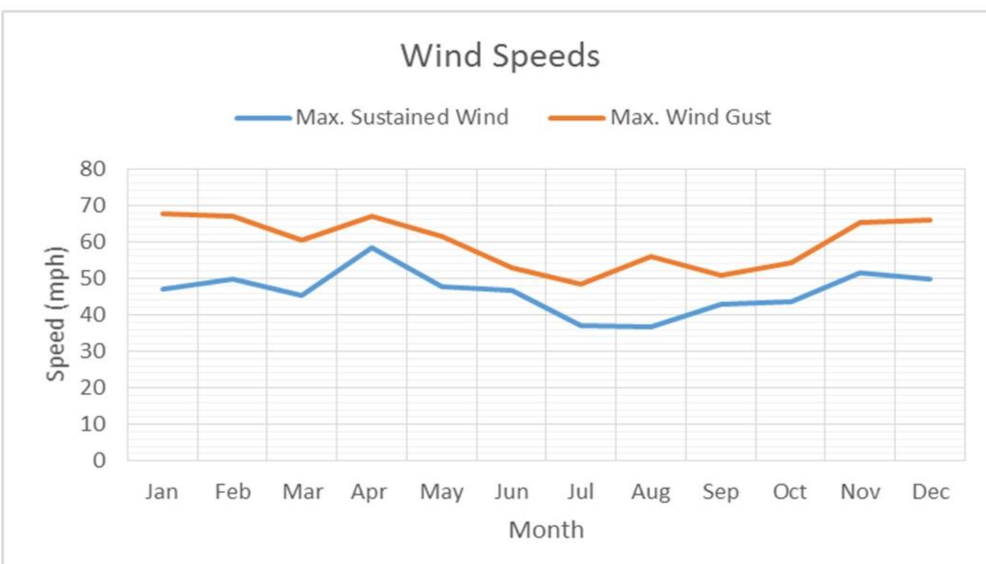


FIGURE 24: Maximum monthly sustained wind speeds and wind gusts at the test site for 2022.

Extreme Temperatures

An extreme high temperature of 84.2 °F (29 °C) was recorded in July 2022. An extreme low temperature of -23.8 °F (-31 °C) was recorded in December 2022. The extreme low temperature occurred during a prolonged cold snap, when temperatures remained below freezing for 14 consecutive days, including a 32 hour period of sub-zero temperatures. *(7)*

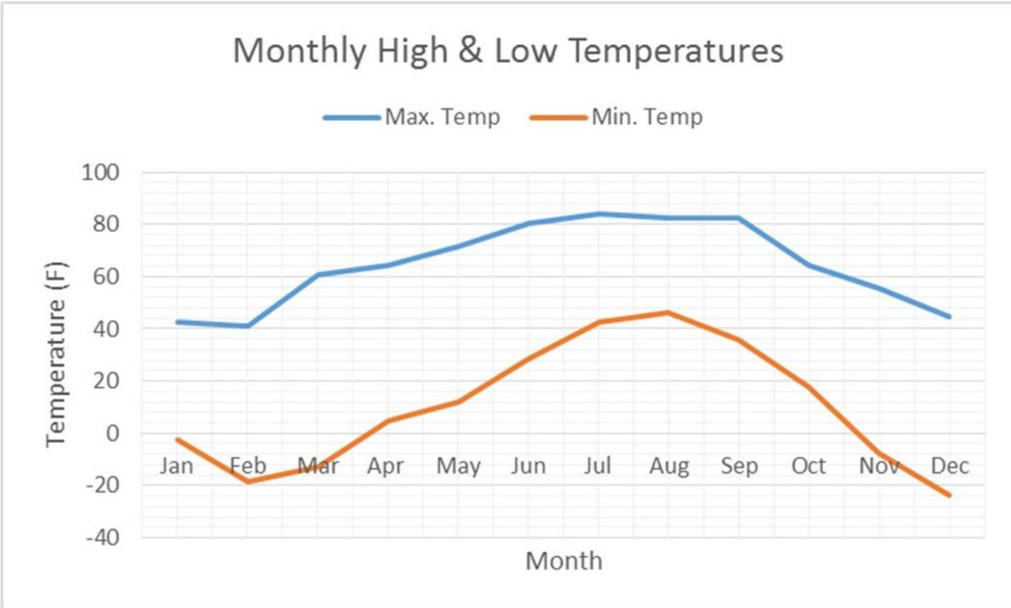


FIGURE 25: Monthly high and low temperatures at the test site for 2022.

Winter Storms

During the 12 month test period, the National Weather Service issues 28 Winter Weather Advisories/Winter Storm Watches/Winter Storm Warnings, 7 Snow Squall Warnings, and 2 Blizzard Warnings for the affected test area. *(14)* A total of 63 snow fall days resulted in 65 inches (165.1 cm) of snow accumulation in the region. *(7)* Freezing rain/drizzle events were also recorded at the site, with ice forming on the solar snow fence (*see figure 26*).

FIGURE 26: Freezing drizzle accumulating on the underside of the solar snow fence.

Severe Thunderstorms

21 Severe Thunderstorm Warnings were issued by the National Weather Service for the affected test area. This included 5 associated hail events in July and August, with hail stone sizes ranging from half inch to 1 inch (1.2 to 2.5 cm) in diameter (radar indicated). *(7) (14)*

Impact on Solar Snow Fence Operations

Regular inspections of the solar snow fence were conducted during each site visit. The inspection consisted of examining solar panels for damage and dirt/grime accumulation; checking electrical systems and the metal structure for ground faults and short circuits; verifying structural components and foundation system were not damaged and in proper alignment; inspecting bolts for proper torque values; verifying sensors and software are working properly; and confirming the system is producing, storing, and discharging energy safely. Time lapse camera recordings were downloaded to analyze solar snow fences operations.

During the 12 month test and evaluation period, routine inspections did not reveal any damage to the solar snow fence. The solar snow fence was able to maintain normal operations through high wind events, blizzard conditions, extreme low temperatures, and severe thunderstorms. The extreme weather conditions did not impact the solar snow fence's ability to autonomously transition to-and-from solar tracking operations to snow fence position. Range-of-motion operations were unimpaired. Snowfall events coupled with tracking movements kept the solar panels free of accumulated dirt and grime (*see figure 27*). *(15)*

A time lapse video of the solar snow fence's operations during a 72 hour extreme weather event can viewed [HERE].

Figure 27: Wind-driven snow accumulating on the front side of both snow fences.

Other Observations

Although not within the scope of the original test and evaluation project tasks, vegetation growth and wildlife observation were noted and recorded via on-site security cameras and during site visits. A cost analysis was also performed to compare the CAPEX of a solar snow fence to a similar sized wooden snow fence and comparable solar array.

Vegetation Growth

Images gathered from the on-site security camera provided documentation of native vegetation regrowth following construction activities. As detailed in previous sections of this report (pages 4 and 8), low impact construction and installation techniques were utilized to minimize disturbances to soil and vegetation. *Figure 28* provides a snapshot of vegetation growth during different project stages. From the images, native vegetation was able to reestablish itself to near pre-construction levels without the use of reseeding within 7 months of installation.

FIGURE 28: Native vegetation prior to the start of construction (left – photo taken first week of November 2021); area around the solar snow fence immediately after construction (middle – photo taken the second week of November 2021); and revegetation without reseeding (right – photo taken in June 2022).

Wildlife Observations

Over the project's 15 month duration, the on-site security camera captured several images of wild rabbits around the solar snow fence. A prairie dog was also observed and photographed during the summer of 2022. The operation of the solar snow fence did not seem to deter these animals from foraging in and around the solar snow fence area (*see figure 29*).

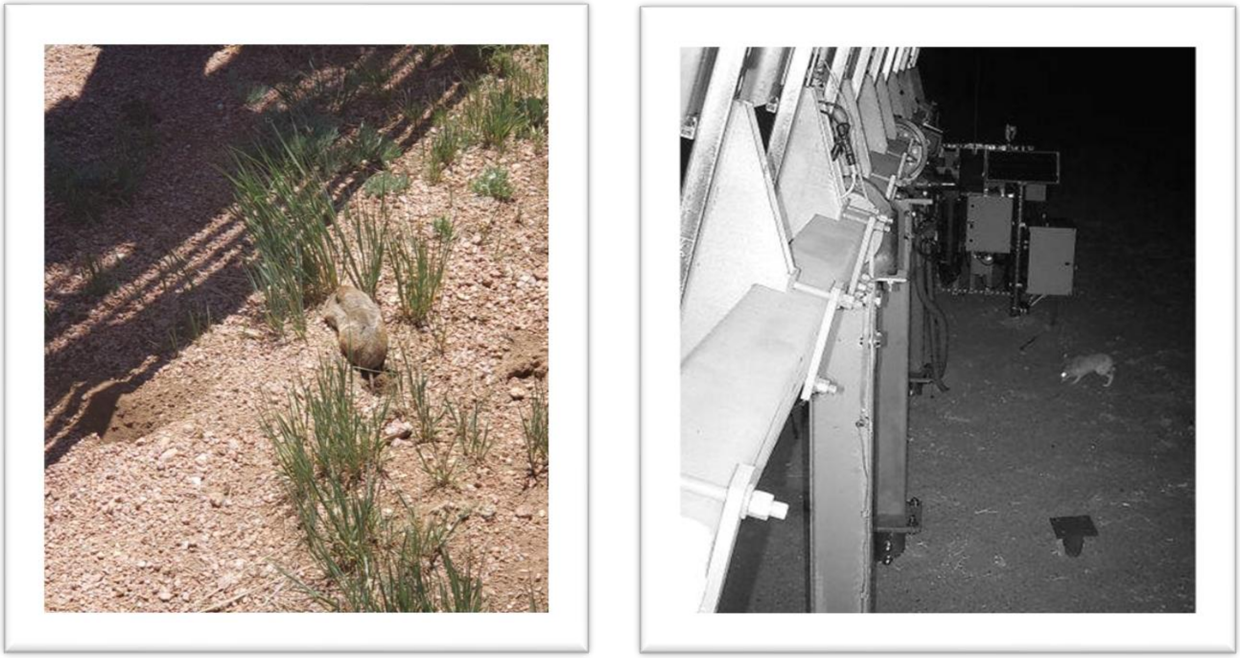


FIGURE 29: Photograph of a prairie dog (L) foraging beneath the solar snow fence, and a night time image of a rabbit (R).

Cost Analysis

Dual use structures typically utilize less material and occupy a smaller footprint when compared to the two single purpose structures incorporated into the dual use structure's design; in this case a snow fence and a solar array. Likewise, the economic and financial benefits of a dual use structure are realized if both of the intended uses of the dual use structure are required by an end user.

By comparing the CAPEX of a structural snow fence and a solar array to the estimated CAPEX of a solar snow fence of similar size and solar output, a determination can be made if the dual use structure provides any financial advantage over the single purpose structures.

A notional 100 linear foot solar snow fence, 12 feet in height and 50% porosity, with a rated output of 8 kW is estimated to cost around $20,000 to $25,000 (estimates are based on an installed price of $200 to $250 per linear foot).

A 100 linear foot wooden snow fence, 12 feet in height and 50% porosity, is estimated to cost between $2,500 to $6,000 (estimates are based on an installed price of $25 to $60 per linear foot). *(1)*

An 8 kW solar array (roof mounted) is estimated to cost around $23,305 (estimate is based on an installed price of $2.95 per Watt DC). *(16)*

Figure 30 provides a CAPEX comparison for the solar snow fence to a wooden or composite snow fence and solar array.

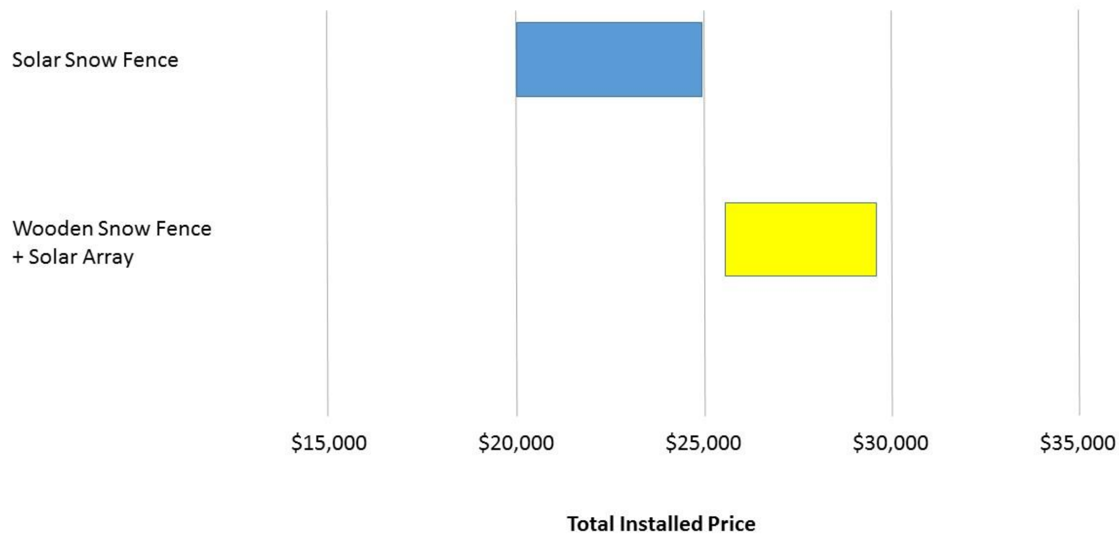


FIGURE 30: Range of CAPEX comparison of a dual use structure (solar snow fence – blue bar), a wooden snow fence and associated roof mounted solar array (yellow bar).

Overall, the CAPEX of a dual use structure like the solar snow fence provides savings when compared to the CAPEX required to install two single-purpose structures (e.g. snow fence and solar array).

An 8 kW solar array is estimated to produce approximately 15,500 kWh per year (based on solar irradiance values for Wyoming & Colorado). Assuming a retail energy price of $0.085 per kWh, an annual electricity savings of $1,317.50 can be realized if an 8 kW solar array is utilized to offset a user's electricity consumption. With the application of the 30% federal tax credits to the overall system CAPEX, a simple payback calculation for an 8 kW solar array is approximately 10.6 to 13.3 years.

PLANS FOR IMPLEMENTATION

With favorable test and evaluation results in hand, outreach efforts to Agencies is underway. Agencies represent a majority of the snow fence customer base, and are therefore the focus of the implementation plan.

The plan consists of two main components: 1) communicating test and evaluation results to the broader highway transportation sector, and 2) development of a full-scale solar snow fence demonstration project.

COMMUNICATE TEST & EVALUATION RESULTS

Agency representatives participating in the expert panel have been receiving quarterly updates on test and evaluation results, which are presented in this report. Broader information dissemination will be achieved by 1) providing a final report to Agencies, 2) posting the report online for interested parties to download, and 3) presenting information at appropriate industry forums (e.g. Transportation Research Board Annual Meeting) and to interested parties.

FULL-SCALE DEMONSTRATION PROJECT

In coordination with an Agency partner, a larger demonstration project is in the planning. The demonstration project will provide a practical example of the solar snow fence's ability to either power ITS equipment, offset Agency electricity usage (if net-metering policies are available), or to power other electrical loads (which may include homes or equipment for landowners hosting solar snow fences on their property).

EXPANDED FUNCTIONALITY

Longboard Power is currently developing a system which pairs the solar snow fence with a direct current fast charger. This integrated system can provide cost-effective electric vehicle fast charging options in remote areas.

Finally, additional functionality is being added to the integrated battery energy storage system and power conversion equipment to enable virtual power plant (VPP) operations. This functionality would allow grid-tied systems to store and discharge energy via signals provided by the utility; resulting in expanded grid reliability and resiliency.

CONCLUSIONS

This test and evaluation project provided real-world data confirming the dual-use functionality of the solar snow fence to generate power and store blowing snow.

The ability to generate electricity year-round is a unique function which separates the solar snow fence from other snow fence designs. Power generation profiles during the test and evaluation stage confirmed the solar tracking design provides a significant advantage in boosting power production versus fixed position designs.

The solar snow fence was as effective at trapping and storing blowing and drifting snow as a wooden snow fence of similar dimensions. This result should alleviate concerns about potential snow storage degradation should Agencies opt for the use of solar snow fencing.

Overall, the results demonstrate the solar snow fence can provide year-round service – by collecting solar energy and providing winter season protection to roadways by trapping and storing blowing snow (*see figure 31*).

This capability can be monetized to provide a broad range of benefits to include, but are not limited to: transforming budgeting processes for winter road maintenance activities into revenue generating endeavors; expanding public-private partnership opportunities for infrastructure development; powering highway ITS infrastructure (either for remote, off-grid application or grid-tied) with renewable energy; and providing expanded benefits to landowners hosting snow fencing on their property.

The solar snow fence can provide Agencies with another tool to manage winter road maintenance efforts, enable energy management strategies, and achieve sustainability goals.

FIGURE 31: Solar snow fence in solar tracking operation (left) and snow fence position (right).

GLOSSARY

Agencies – Collective term encompassing state highway agencies, tolling agencies, and any public entity or enterprise responsible for winter road maintenance.

Albedo - The percentage of light that a surface reflects. For example, snow has an albedo of 80% - 95% while a blacktop asphalt road has an albedo of 5% - 10%.

C - celsius

cm - centimeter

End Effect - the rounding of the downwind snowdrift near the ends of a snow fence; resulting in shorter drifts.

F - Fahrenheit

HJT – Hetero-Junction Technology. A solar cell design combining crystalline silicon with amorphous silicon thin-film to produce a high-power hybrid cell. This solar cell type is more shade and heat tolerant than conventional crystalline silicon cells (like PERC), and has a higher power output than thin-film silicon.

Imp – Current at maximum power. An electrical performance parameter for a solar panel denoting the maximum amperage when the panel is connected to a load.

ITS – Intelligent Transportation System. The application of sensing, analysis, control, and communications technologies to ground transportation in order to improve safety, mobility, and efficiency.

Kph – Kilometers per hour.

Km - Kilometers

Kwh –Kilowatt hour. Unit of power production.

kwh/m² per day – kilowatt-hours per square meter per day. Standard unit of measurement for solar power calculations.

LiDAR - aerial light detection and ranging. A method of conducting high resolution mapping and surveying through the use of lasers

m - meter

mph – Miles per hour.

Net-metering - a metering and billing arrangement between a utility provider and a customer with a distributed energy generation system installed by and for the customer's use; designed to compensate the customer for any excess energy generated by the customer that is exported to the utility grid.

PERC – Passivated Emitter and Rear Contact. A modified conventional crystalline silicon solar cell with the addition of passivated rear contacts to boost power production (typically by 10% - 12%). These are the most common type of crystalline cells used in today's solar panels.

POA Irradiance – Plane of array irradiance. The total irradiance incident on a panel; comprised of the sun's position, the orientation of the solar array (fixed or tracking), irradiance components (direct and diffuse), albedo, and nearby shading.

PV – Photovoltaics.

Vmp – Voltage at maximum power. An electrical performance parameter for a solar panel denoting the maximum volts produced when the panel is connected to a load.

VPP – Virtual Power Plant: A collection of small-scale energy resources that, aggregated together and coordinated with grid operations, can provide the same kind of reliability and economic value to the grid as traditional power plants while increasing resiliency.

WYDOT – Wyoming Department of Transportation

Wyoming Snow Fence – A snow fence design characterized by evenly spaced horizontal wooden planks affixed to a 15° from vertical wooden frame, typically 10 to 12 feet in height. First developed for use in Wyoming in the 1970's.

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APPENDIX: RESEARCH RESULTS

Sidebar Info

Program Steering Committee: NCHRP IDEA Program Committee

Month and Year: May 2023

Title: Field Test & Evaluation of a Solar Snow Fence

Project Number: #234
Start Date: October 7, 2021
Completion Date: May 25, 2023

Product Category: New or Improved Tool or Equipment

Principal Investigator:
Tibor Hegedus, General Manager – Longboard Power LLC
E-Mail: tibor@longboardpower.com
Phone: (719) 232-0531

TITLE:
Solar Snow Fence Field Test & Evaluation

SUBHEAD:
This project constructed, tested, and evaluated the functionality, effectiveness, and reliability of a prototype solar snow fence in real-world conditions.

WHAT WAS THE NEED?
Blowing and drifting snow onto roadways poses a safety concern to motorists, with state highway agencies bearing the responsibility to keep roadways clear and passable. When compared to the more costly option of plowing and mechanically removing snow, state highway agencies use snow fences as a cost effective alternative to control blowing and drifting snow.

With an estimated installed price of $25 - $60 per linear foot, and annual operating expenses of $0.20 - $1.20 per linear foot, state highway agencies must budget for both capital expenditures and operating expenses in order to purchase, install and maintain structural snow fencing – which provides only seasonal-use.

By fully integrating photovoltaics into the design, snow fences can continue to perform their originally intended purpose while simultaneously providing the benefit of harnessing power from the sun. Transforming snow fences into dual-use structures creates year-round value and revenue-generating potential for state highway agencies.

WHAT WAS OUR GOAL?
The development of the solar snow fence is intended to integrate winter road maintenance operations, energy management practices, and sustainability initiatives – allowing state highway agencies to save money and optimize resource allocation while keeping roadways clear and safe for drivers in the winter.

The goal of this project was to construct, test, and evaluate the functionality, effectiveness, and reliability of a prototype solar snow fence in real-world conditions. This included validating the solar snow fence's dual-use functionality to generate electricity year-round in addition to protecting roadways from blowing and drifting snow.

WHAT DID WE DO?

Project efforts were divided into two stages. The first stage consisted of constructing the solar snow fence. With the assistance of the Wyoming Department of Transportation, a test site located along Interstate 80 in Wyoming was selected. A 25 linear-foot section of solar snow fence was constructed next to a co-located 300 linear-foot wooden snow fence of similar dimension.

The second stage focused on testing and evaluating the solar snow fence's capabilities. Designed to operate autonomously, the solar snow fence tracks the sun in the day sky. When blowing and drifting snow conditions are detected by on-site sensors, the solar snow fence will cease solar tracking operations and move into to a near-vertical position to act as a snow fence. Solar tracking operations resume once blowing and drifting snow conditions have passed.

This stage involved operating the solar snow fence in the field for one year to gather real-world data on its functionality, effectiveness, and reliability. This included validation of solar tracking, autonomous operations, power production, snow fence effectiveness, integration with existing snow fences, and survivability in extreme weather conditions.

WHAT WAS THE OUTCOME?

Over the course of the testing period, the solar snow fence was able to trap and store blowing and drifting snow as effectively as a co-located wooden snow fence. In addition, the 25 linear-foot section of solar snow fence generated 7½ to 15 kilowatt-hours of electricity per day over the course of the test and evaluation program. The system operated autonomously to the changing weather conditions, with no maintenance required despite being exposed to multiple winter storms, near hurricane force wind speeds, and temperatures as low as -23.8 °F.

WHAT IS THE BENEFIT?

The solar snow fence provides state transportation agencies with another tool to manage winter road maintenance efforts, enact energy management strategies, and achieve sustainability goals. This includes transforming winter road maintenance activities into revenue generating endeavors; expanding public-private partnership opportunities for infrastructure development; powering state highway agency infrastructure (either for remote, off-grid application or grid-tied) with renewable energy; and providing expanded benefits to landowners hosting snow fencing on their property.

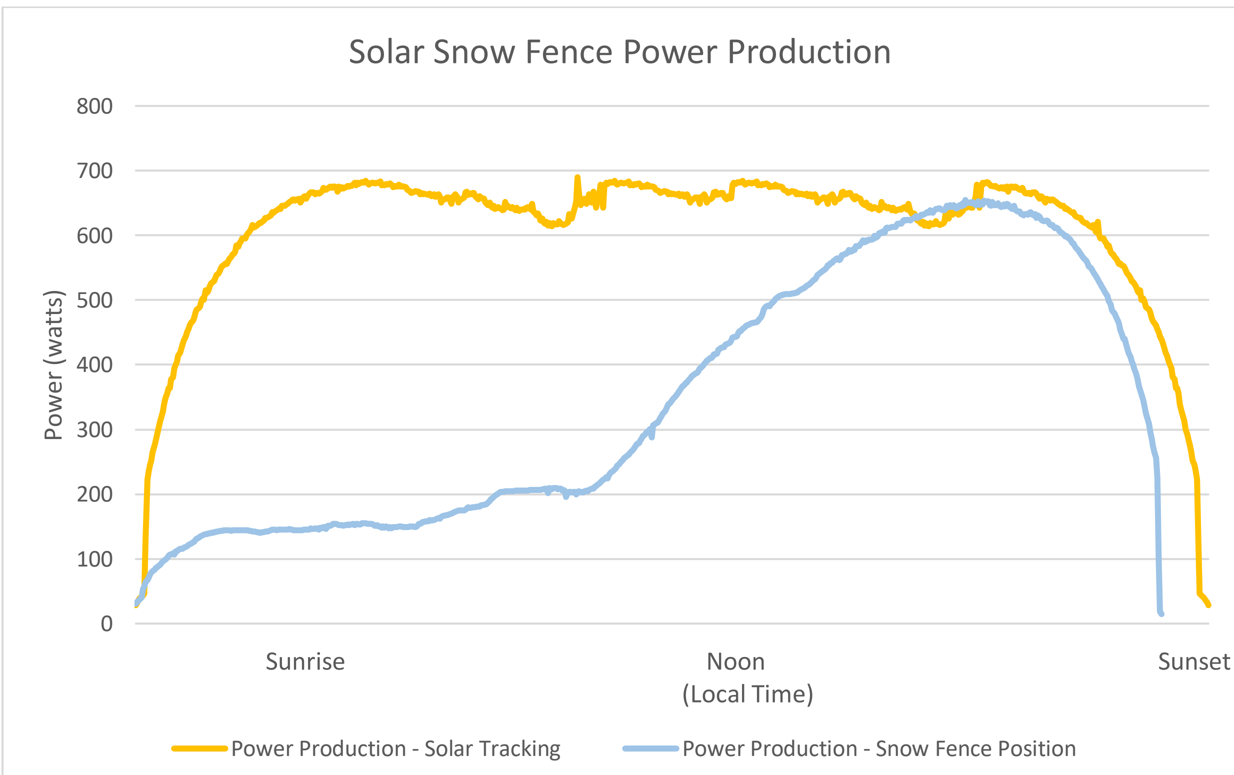
LEARN MORE

www.longboardpower.com [link to report posted on the bottom of the webpage]

To view the evaluations:
tibor@longboardpower.com

IMAGES

Solar snow fence in solar tracking operation (left) and snow fence position (right).



Power production curve (raw data) for a 10 linear-foot section of solar snow fence in solar tracking mode (orange line) and snow fence position (blue line). The solar snow fence autonomously transition between these two modes based on site weather conditions.