Luminescent Enhancement for Combined Solar and Commercial Agriculture

Final Report

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Topic Area 12) Solar; e) Rural Solar
Energy Efficiency and Renewable Energy

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I). IDENTIFICATION AND SIGNIFICANCE OF PROBLEM

This proposal developed a new racking / mounting system combined with a new agriculture-tuned luminescent solar panel for low cost implementation in a hybrid high tunnel.

The US agricultural industry uses about 300 billion KW-hr of energy / year. Of this energy consumption, roughly 20% goes towards food production and 20% goes towards food processing. This proposal will allow farm land to simultaneously generate electricity and food. A cost effective and highly durable hybrid high tunnel greenhouse has been developed that generates electricity at *less than $3.00/watt INSTALLED cost* and can be used for production of high values crops. The high tunnel used a new design of Soliculture greenhouse integrated luminescent solar panels to selectively absorb the green portion of the solar spectrum that is not used by plants and convert the light to red light with higher photosynthetic efficiency. Green light is selectively downshifted to red light using luminescent materials that match the photosynthetically active region for plants and the efficiency maximum of Si photovoltaic cells. The color tuning associated with converting green light to red light has been shown to facilitate fruit production in commercial greenhouses growing cucumbers, lettuce and herbs. The current semi-transparent Soliculture product for this application has an efficiency of ~5% and a Si PV cell coverage of ~20%. Luminescent enhancement with bifacial cells adds up to 35% to the power output of the module relative to a panel with partial cell coverage and clear space between cells.

Figure 1: Soliculture Greenhouse Integrated solar panels installed on high tunnel grrenhouse frame. Half of the greenhouse was covered by 6kW of panels, the second half was covered with plastic greenhouse film as a control.

The hybrid power generating high tunnel greenhouse in this SBIR proposal is a completely different agricultural application than the climate controlled greenhouse market currently addressed by Soliculture and therefore requires a new development effort and new crop trials.

II) Project Progress:

Table 1 lists the project milestones as specified in the SBIR Phase I proposal.

Task	Description	Q1	Q2	Q3	Deliverable
1	Characterization of New Panel for High Tunnel / Open field application including power, efficiency and illumination uniformity under panel.				Efficiency measurements with clear and red backsheets, white reflective backdrop and a black absorbing backdrom. Quantifiy illumination uniformity 5 feet under panel. Cost of < $1/W.
2	Construct hybrid PV racking system / high tunnel greenhouse at Whiskey Hills Farm				Racking system for 30' x 65' hybrid high tunnel / PV array including power generation. Total Power of 10kW. Cost < $20/sq.ft.
3	Perform Crop Trials in greenhouse at Whiskey Hills Farm				Colect data on yield and internodal length for at least 4 different crops. Compare to outdoor grown crops.
4	Perform Uniformity tests and limited crop trials at NexTracker Solar Center of Excellence.				Compile data on uniformity of illumination throughout the day and season and measure growth rates for microgreens in 10 x 20' test plot.
5	Compile power output vs. illumination and compare to models.				Compile energy and radiation data. Compare to a conventional solar panel at the same location.

Table 1: Milestones for phase I combined agriculture and solar.

Task 1: New Panel Design for High Tunnels

This hybrid high tunnel greenhouse puts greater emphasis on power generation than the standard climate controlled greenhouse product from Soliculture. High tunnel greenhouses are commonly used in hot-dry climates where sunlight is abundant and lower levels of light transmission can be tolerated. Figure 2 shows a comparison of the two panel designs. Both panels utilize the Soliculture proprietary red luminescent backsheet that enhances both the current in the cells and red light for crop production. The enhancement from the red luminescent backsheet is due to the Luminescent Solar Collector effect in which green light is converted to red light using a luminescent dye and some of the red light is trapped within the front glass by total internal reflection and is then collected by the solar cells.

The greenhouse panel has a cell coverage of 27% and output power of 85W. The high tunnel panel has a cell coverage of 42% and power output of 110W. Both panels use bifacial cells that benefit from light reflected from the crop. The reflected light is captured both by the rear of the cell and by the luminescent backsheet resulting in a 15-32% enhancement in power output relative to a clear backsheet as shown in Figure 3.

Figure 2: Comparison of Soliculture high tunnel panel vs. the controlled environment greenhouse panel. Cell coverage of the high tunnel panel was 42% vs. 27% for the greenhouse panel. Dimensions were 39” x 52”, smaller than a standard 60 cell module.

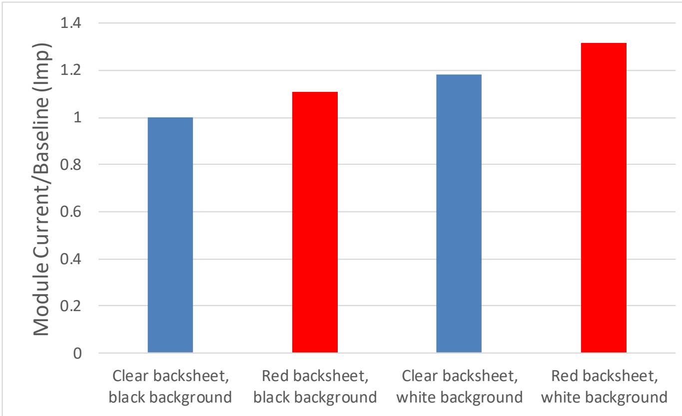


Figure 3: Comparison of maximum power point current for two types of bifacial modules with clear and luminescent backsheet with either a black absorbing backsheet or a white reflective backsheet. The combination of bifacial cells, luminescent backsheet and refetive background had a current enhancement of 32%

Panels for this project were produced at the Soliculture prototyping facility in Scotts valley with an output of roughly 7 modules / day. This is an expensive way to produce modules. The current cost of modules produced at one of our partner sites is $0.60/W for a standard 60 cell, 300W module. These Soliculture panels have half the power output of a standard module which would increase the $/W by 2x. However, the modules use 50% less silicon cells which currently cost $0.20/W or $60/module. Therefore, we expect the cost of a Soliculture agricultural module to be $30 less than a conventional 60 cell module that costs $180/module with an output of 150W (ignoring enhancements from the luminescent layer or bifacial cells). Therefore, the high volume cost of the module is expected to be $150 for a 150W panel or $1/W.

<u>Task 2: High Tunnel Racking System</u>

The test site for the hybrid Solar High Tunnel was Whiskey Hill Farms in Watsonville, CA. This is an active organic farm that grows produce both in greenhouses and open fields. Figure 4 shows a photograph of the greenhouse site before construction occurred. The site was cleared and leveled using Whiskey Hill staff and equipment. The growing area soil was prepared by adding organic biomass and other soil enhancements to a depth of 24” as shown in Figure 5. The high tunnel was 120’ long and 25’ wide with half covered by Soliculture panels and the other half covered by a semi-clear plastic film that would act as the control for crop growth studies.

The high tunnel base was built using 3” steel tubing pounded into the ground spaced at 80” intervals. The top of the high tunnel was built using standard 2” steel tubing. Soliculture got help from a local high tunnel manufacturing / installation company called Queidan that installed the high tunnel frame and plastic covering as shown in Figure 6. The 3” tubing base and 2” tubing frame is what is specified by the solar panel racking company IronRidge. Horizontal panel mounting bars were mounted to the 2” tubing of the roof frame as shown in Figure 7. Additional bracing was added to the roof structure to form a “queen” style truss and better support the weight of the panels shown in Figure 8. The soil was plowed to form 5 planting beds. Each bed was 120’ long and had 4 drip irrigation lines on top shown in Figure 9. This is standard practice for a commercial organic farm.

Making the racking system waterproof was more difficult than anticipated. Initially, foam weather stripping between the panels was used to form water tight seal but leakage occurred at the corners and where the top mounting bolts held down the panels. Expanding foam needed to be applied from below to seal the corners and the mounting bolts. Leakage between the panels caused significant erosion and flooding of the growth beds and could harm the crops.

Figure 4: Site prior to clearing and construction

Figure 5: Planting bed prepared with growing media

Figure 6: Construction of high tunnel with 2” and 3” tubing.

Figure 7: Installation of panels in roof.

Figure 8: “Queen” style truss support with 2” steel tubing.

Figure 9 planting beds, drip irrigation and climate monitoring station.

Figure 10: Completed high tunnel with integrated solar for combined agriculture and solar

A modified racking system was built and tested at the Soliculture laboratory. The new racking system used mounting brackets that attached to the bottom of the frame only as shown in Figure 11. A rubber “T” gasket was inserted between the panels to form a continuous water tight seal. Installers will have easy access to the bottom of the modules from inside the high tunnel which makes this racking solution much easier to install. The racking system was tested with a hose to confirm that it forms a watertight roof for the high tunnel as shown in Figure 11. Attachment of the plastic film to the panels was done using an aluminum channel screwed into the panel frame and “wiggle wire” to hold the plastic film forming a water tight seal between the plastic film and the panels. The final high tunnel is shown in Figure 10.

Following is a cost summary of this prototype high tunnel. It is assumed that the full greenhouse is covered in panels (15kW) instead of half being a control space. The cost of the frame can be reduced through more efficient utilization of materials. The panels for this project were

(a) (b) (c)

Figure 11:Improved racking system test structure including (a) “T” style water proof gasket. (b) Bottom attached mounting brackets. (c) test of water-proof seal.

built at the Soliculture prototype laboratory in Scotts Valley. In the future, panels can be built with a contract manufacturing partner such as Auxin or Heliene for significantly less. The simplified second version of solar racking should simplify labor costs. Soliculture believes that it can achieve a cost of $10/sq.ft. or $2.00/W for these solar powered high tunnels. This cost is only for the structure and PV panels and does not include site preparation or items required for crop production.

	Prototype cost 3,000 SF, 15 kW	Estimated Future 3,000 SF, 15 kW
Frame (Quiedan, IronRidge)	$8,300	$5,000
Panels + BOS (Soliculture)	$24,000	$18,000
Labor (Quiedan)	$9,000	
Labor (Soliculture)	$8,000	$7,000
Total	$49,300	$30,000
Total ($/sq.ft.)	$15	$10
Total ($/W)	$3.15	$2.00

Added features were included in this experimental greenhouse to gain a better understanding of crop response and the impact of the solar panels on climate. Additions include the following.

1) Full climate monitoring including temperature and humidity in 4 regions of the high tunnels.
2) Light level monitoring under the red panels, under the clear plastic and outside.
3) Thermostat controlled sidewalls for climate control. Sidewalls roll up at 85^{o}F to prevent overheating and lower again at 75^{o}F to keep heat and humidity in at night.
4) Water flow monitoring to measure water consumption.

Light levels under the panels and in the control area are shown in Figure 24. The "clear" plastic contains a light diffusion pigment that reduces the light level by roughly 40%. The panels reduce PAR light levels by roughly 60%. Photosynthesis rates for lettuce saturate at about 300 uMOL/m2. Thus the lettuce is still receiving sufficient light levels even with a 60% reduction.

TASK 3: Crop Trials

Covered crop production is used for high value crops like berries, herbs and leafy greens. Soliculture contacted 6 different organic produce growers in the area for advice on what crops to test. We were constrained by the time of year when the high tunnel was ready for planting (November). The following crops were chosen based on the time of year and ability to collect data on crop growth by the end of the grant period

:

Strawberries (~480 plants)
Red Romaine Lettuce (~480 plants)
Butter Head Lettuce (~480 plants)
Cilantro (One 120' row)
Mustard Greens (~240 plants)
Kayle (~240 plants)
Tummeric (~480 root starts)


Figure 12: Strawberries planted in November


Figure 13: Lettuce planted in November

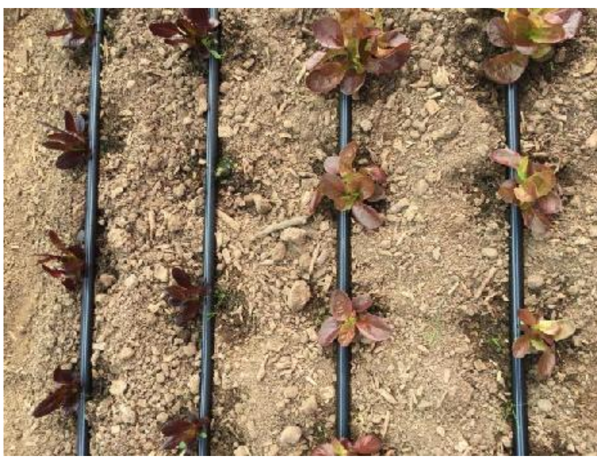


Figure 14: Lettuce under panels in January.


Figure 15: Lettuce under clear plastic in January.


Fig. 16: Herbs of Cilantro, Mustard Greens, Kale under red January.


Fig. 17: Herbs of Cilantro, Mustard Greens and Kale under clear January.

Figure 18: Lettuce under panels on 2/28/20.

Figure 19: Lettuce under clear plastic on 2/28/20

Figure 20: Herbs under panels on 2/28/20.

Figure 21; Herbs under clear on 2/18/20

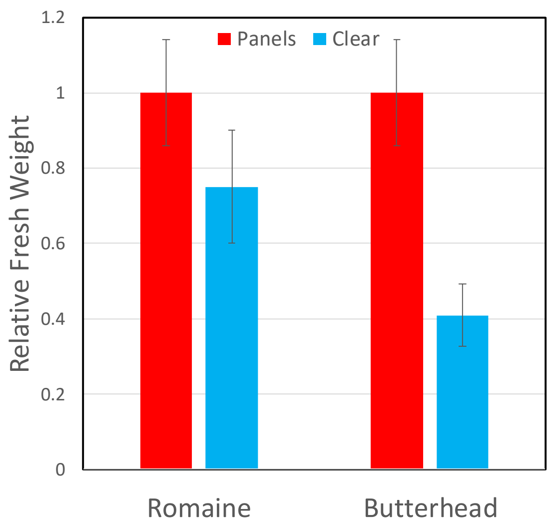
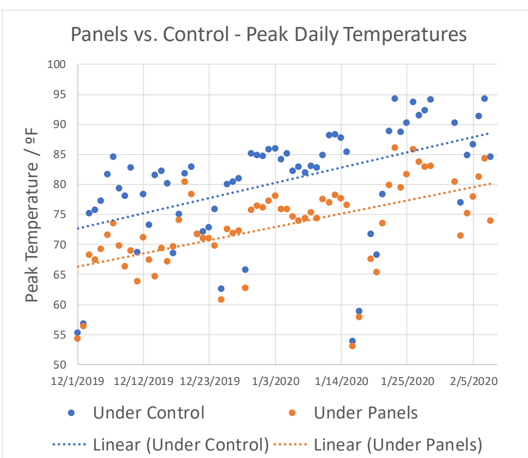
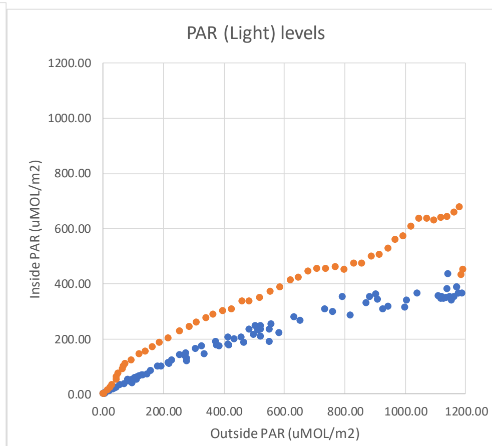


Figure 22: Fresh weight of Romain and Red Butter lettuce grown under red panels relative to clear plastic. Fresh weights were 30% and 140% higher under red panels.

liquid organic fertigation. It is essential that commercial growing methods are used to assure that results can be translated to commercial crop production. Environmental conditions were monitored throughout the growing period and temperatures were maintained at less than 90°F using sidewall vents.

Crops were started in mid-November. Lettuce normally matures in 60 days, but early growth was very slow for the first month of the crop trial as seen in Figures 12-15. A soil test was performed in January and nitrogen levels in the soil were found to be very low. A strong dosing schedule was established with organic fertilizers to replenish nitrogen in the soil. Crop growth improved immediately for late January and February. Figures 12-21 shows pictures of the crop growth at various stages. Both the red romaine and butter head lettuce did much better under the red Soliculture panels relative to the clear area. The fresh weight under the red panels was 30% for the red romaine and 140% greater for the butterhead lettuce relative to the clear plastic film area as shown in Figure 22. Data on cilantro, kale and mustard greens is pending but is expected to show a similar trend.





(b)

Figure 23: Peak daily temperature under panels vs. under clear plastic. Average is a 7 degree difference..

Figure 24: Light levels under clear plastic vs. red panels for one day. Transmission of the red panels is ~60% and the red panels is ~40%.

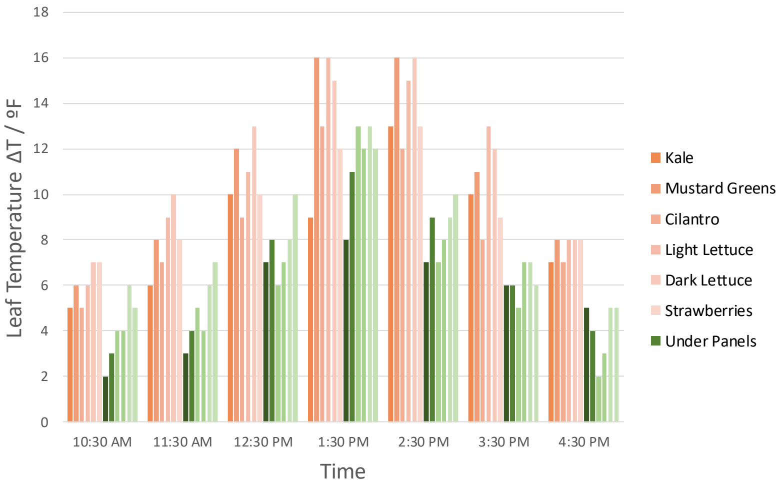


Figure 25 Leaf temperature rise above plants under shade. all crops vs time. Leaf temperature is higher under clear plastic

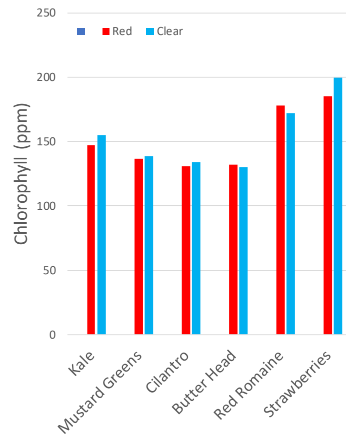


Figure 26: Chlorophyll levels under red panels vs. for clear plastic. Levels showed no difference.

The improved growth under the red Soliculture panels is likely due to reduced stress levels from the lower intensity of light under the panels and the enhanced red light. The daily peak temperature in the clear region of the greenhouse was on average 7 degrees higher than in the region under the panels as shown in Figure 23. Lettuce is known to become stressed above 85^{o}F and the higher temperature might have reduced growth. Sunlight that is too intense can also increase the temperature of the leaves to above the ambient temperature of the air, therefore causing additional stress. Figure 24 show shows the light intensity difference between the red portion of the high tunnel and the clear portion. The Lettuce photosynthesis saturates at about 300 uMOL/m^2-s so light intensity higher than this level does not result is greater growth and only causes crop stress. Light levels in both sections of the high tunnel are greater than 300 uMOL/m^2-s for most of the day. Excess light intensity can cause crop stress by increasing the temperature of the leaves above the ambient air temperature. Figure 25 shows the temperature difference between leaves that are under sunlight in the high tunnel relative to leaves that are shaded for both regions of the high tunnel. The temperature difference between a leaf in the sun and a leaf in the shade can be as large as 15oF at peak times under the clear plastic. Under the panels, the leaf temperature increase from the sun is roughly 5^{o}F less, as expected from the lower intensity of light. Ideal growing conditions should minimize the increase in leaf temperature above the ambient air temperature. Figure 26 shows the chlorophyll levels for all crops grown under the panels vs. those grown under the clear glass. Both sections had statically equivalent chlorophyll levels for all crops which is an indication of a healthy crop. Taste tests were performed of the lettuce crop with family members and and friends with no difference detectable.

Cilantro, mustard greens and kale will all be harvested in April 2020 for quantitative crop results reported in the Phase II proposal. The strawberry plants have started to produce fruit. Fruit output will be monitored and reported in April.

TASK 3: Open field tests

The initial SBIR plan included tests at the NexTracker Solar Center of Excellence in Fremont, CA. Further discussions with NexTracker CEO Dan Shugar revealed that this would not be possible due to other work being done at the sight. It was decided to wait until the results from this phase I project are complete before starting open field tests.

TASK 4: Power output

The array consisted of 58 panels, 110W each for a system power rating of 6kW. The panels were connected as three strings to a SMA 7kW Sunny-Boy inverter. The AC power was fed into the farm power system in parallel to an existing 5kW conventional solar array on site. The orientation was SW or about 225 degrees. Figure 26 shows a typical daily output. Shading occurs in late afternoon due to neighboring greenhouses.

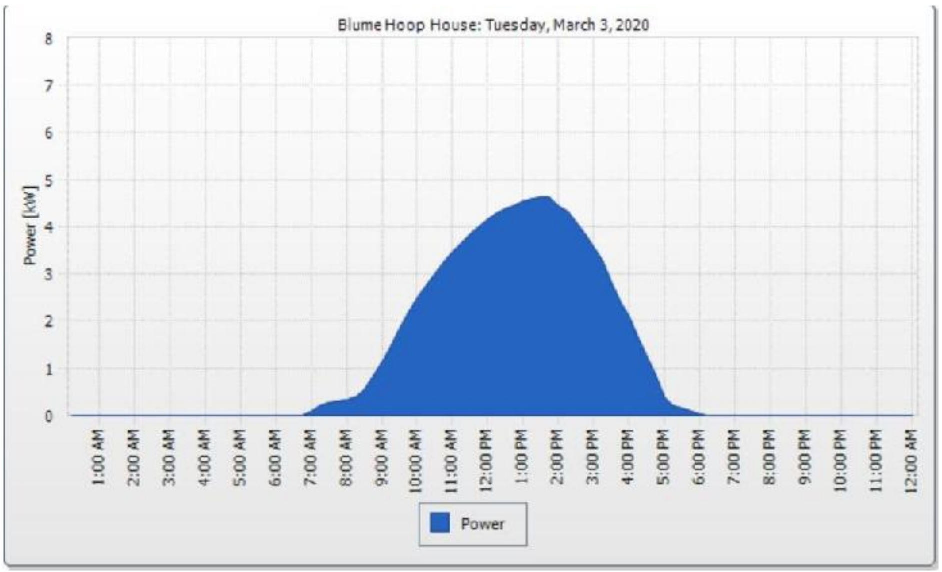


Figure 26: Typical output on overcast day from red panel array.

The efficiency of the panels under outdoor conditions was measured using a light meter and full array power output measured from the inverter for both the high tunnel panels and the array of conventional panels on site. Table 3 summarizes the efficiency measurements.

Panel	Rated efficiency at STC	Measured efficiency at operating conditions	Cell coverage	Cell efficiency at operating condition	Relative gain for high tunnel efficiency
Standard	17%	15.6%	95%	16.4%	
Soliculture	8.4%	8.3%	41%	19.6%	19%

We expect the high tunnel panels to have an enhancement from the bifacial nature of the cells, the luminescent backsheet and reflected light from the greenhouse. It is difficult to break out the different contributions in real world conditions. Enhancement in power for the high tunnel panels. It is well know that efficiency drops by ~10% in standard operating conditions due to heating in the sun. If we correct for the cell coverage of the high tunnel modules vs. conventional modules then we obtain a cell efficiency of 19.6% for the greenhouse panels vs. 16.4% for a conventional panel. This efficiency includes the losses due to reflection, glass, EVA and AC/DC conversion. The cells that were used on the module had a rated efficiency of 19%. Therefore, it is quite encouraging that we are still able to get a 19% efficiency of the cells even with all of the losses at operating conditions. This is a 20% power enhancement over a conventional module and is close to what was expected in the laboratory experiments shown in Figure 3.

III) CONCLUSION

This phase I project has shown that solar electricity production can be combined with commercial agriculture with significant IMPROVEMENTS to crop yields, depending on crop. The combined high tunnel and solar panels can achieve an installed cost of $2/W of $10/sq.ft., excluding land and agriculture preparation. A conventional high tunnel with no solar panels costs about $2/sq.ft.. The solar panels add considerably to the cost of the high tunnel but the incremental cost will be less than $2/W making the installation competitive with a commercial ground mounted solar installation without the loss of productive crop land.