Energiteknologisk udvikling og demonstration

EUDP 64014-0508

SENSORPOWER

Bifacial PV Energy Reflector Tower

FINAL REPORT

PROJECT PARTNERS

SolarLab

AKJI

DTU Fotonik
Institut for Fotonik

Title:
SENSORPOWER
a highly aesthetic cost efficient PV integrated balcony

EUDP Project number
64014-0508

Project Partners
Solar Lab (project managers)
DTU Fotonik
AKJ Inventions

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Front page
Top: Sensorpower mast integrated at Risø Campus
Bottom: A series of Sensorpower masts integrated in living lab at Risø Campus side-by-side with solar irradiation measurement station.

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1.1 Project details

Project title	EUDP 14-II,Sensorpower – Bifacial PV Energy Reflector Tower
Project identification (program abbrev. and file)	64014-0508
Name of the programme which has funded the project	EUDP Solar Energy
Project managing company/institution (name and address)	SolarLab Gunnar Clausensvej 9, 8260 Viby J. Tlf.: 6019 8031 E-mail: pmr@solarlab.dk WWW: www.solarlab.dk
Project partners	DTU Fotonik AKJ Inventions
CVR (central business register)	34720975
Date for submission	2018, June 15th

1.2 Short description of project objective and results

English

The objective of the project has been to develop a solar powered sensor mast for powering instruments and provide data management which enables data to be sent to the cloud. The unit is demanded in e.g. remote areas where cabling is not feasible and measurement based remote monitoring of some kind is required. To improve winter performance a bifacial panel with a reflector was developed.

The project has during the project period achieved:

- An optical model for calculation the performance of the retro reflectors
- An thorough analysis of communication standards concluding in implementation of good communication method
- Prototypes of subparts
- 0 series functional model that has been proven in the field
- A living lab for testing Product integrated PV (PIPV) products with integrated communication.

All achievements can be used for future work. The 0 series and the findings leading towards that can be used by SolarLab to further develop and market the concept.

The living lab established at DTU Fotonik will provide a unique test site for field testing of PIPV product with integrated communication for the Danish industry and future development projects at DTU Fotonik. This is especially valuable at this time where outdoor product is expected to be part of the smart city concept and IoT is moving into almost all products requiring some kind of communication is available.

Dansk

Formålet med projektet har været at udvikle en soldrevet sensormast til strømforsyning og dataopsamling, der gør det muligt at sende målt data fra diverse sensorer op i skyen via forskellige kommunikationsplatforme. Enheder som denne er perfekte i f.eks. fjerntliggende områder, hvor kabling ikke er mulig, og målebaseret fjernovervågning af en slags er påkrævet. For at forbedre vinterpræstationen blev der udviklet et bifacialt solpanel med en reflektor.

Projektet har i løbet af projektperioden opnået:

- En optisk model til beregning af reflektorernes ydeevne
- En grundig analyse af kommunikationsstandarder, der indgår i implementeringen af god kommunikationsmetode
- Prototyper af underdele
- 0-serie funktionsmodel der er felttestet
- Et levende laboratorium til test af produkt integrerede solcelleprodukter (PIPV) indeholdende kommunikationsteknologier.

Alle resultater kan bruges til fremtidigt arbejde. 0-serien og opnåede resultater baseret herpå kan bruges af SolarLab til at videreudvikle og markedsføre konceptet.

Det levende laboratorium etableret på DTU fotonik vil give et unikt teststed for feltprøvning af PIPV-produkt med kommunikation integreret (IoT) til dansk industri og fremtidige udviklingsprojekter hos DTU Fotonik.

1.3 Executive summary

The objective of the project was to develop a solar powered sensor mast for powering instruments and data management which enables data to be send to the cloud. The unit is demanded in e.g. remote areas where cabling is not feasible and remote monitoring of some kind is required. To improve winter performance a bifacial panel with a reflector was used and developed.

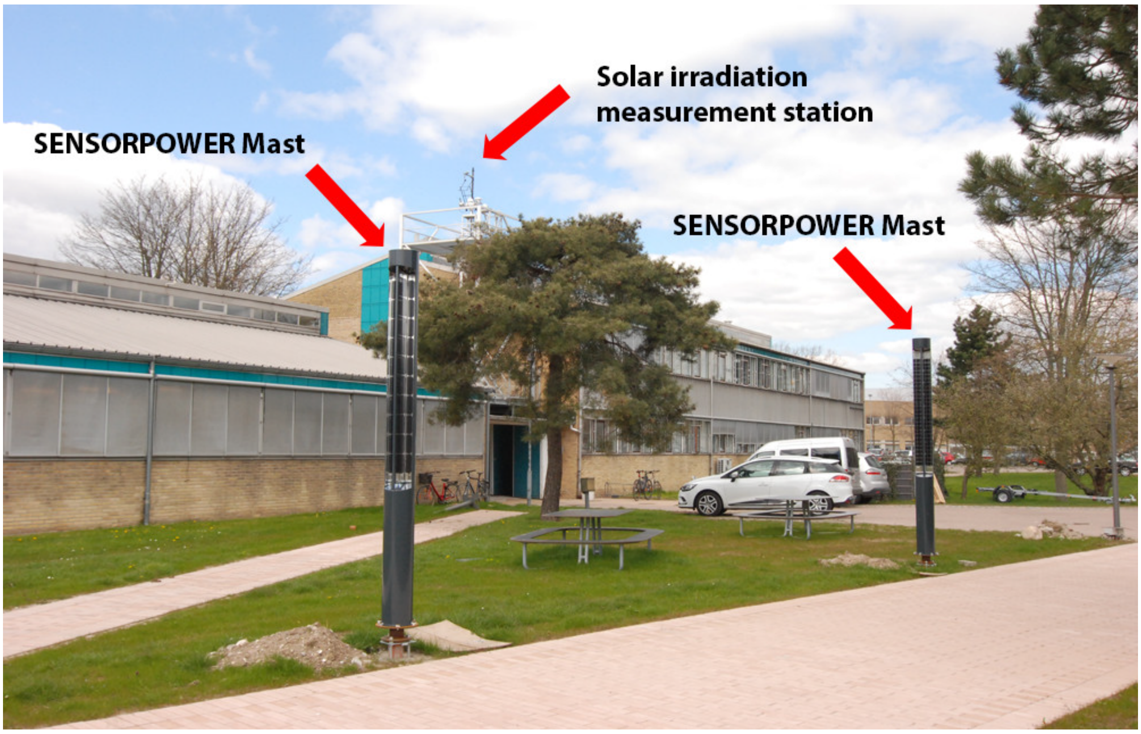
The project was divided into the following work packages:

WP 1 Project management
WP 2 Modelling and specification
WP 3 Development of the reflector
WP 4 Development of the bifacial panel
WP 5 Maturing and implementation of the controller
WP 6 Identification and implementation of wireless communication
WP 7 System integration
WP 8 Laboratory test
WP 9 Demonstration
WP 10 Field-test
WP 11 0-series fabrication
WP 12 Implementation of the mast in the PV-led Engine software

The overall goal of the project has been achieved and the product can enter the market. Particular WP 2 (Modelling and specification), WP3 (Development of the reflector), WP 6 (Identification and implementation of wireless communication), WP10 (Fieldtest) and WP 11 (0-series fabrication) has been successful.

SolarLab have established a solid demonstration of the principle and will use this data to further market this product and develop customized solutions for potential end-users. Several customers have already shown great interest and SolarLab is eager to pursue these paths.

DTU Fotonik has during the project build a living lab for performance testing of such products. This is now available for the industry for testing and is unique for testing product integrated PV Solutions with communication inside.



1.4 Project objectives

The objective of the project was to develop a solar powered sensor mast for powering instruments and data management which enables data to be send to the cloud. The unit is demanded in e.g. remote areas where cabling is not feasible and measurement based remote monitoring of some kind is required. To improve winter performance a bifacial panel with a reflector was used and developed.

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The execution of the project has been successful. Two 0 series masts were built and are still being tested at DTU Fotonik at Risø. During the project period, DTU Fotonik established a living lab with detailed datalogging for performance monitoring of these and other product integrated PV (PIPV) products.

1.5 Project results and dissemination of results

The overall goal of the project has been achieved and the product can enter the market. Particular WP 2(Modelling and specification), WP3 (Development of the reflector), WP 6 (Identification and implementation of wireless communication), WP10 (Field-test) and WP 11 (0-series fabrication) has been successful.

WP2 Mathematical model

A mathematical model has been developed and simulated for the retro reflector. It considers two types of optical losses:

- Fresnel losses, which are optical losses at interfaces between dielectric media, having different refractive indices.
- Material absorption losses, which are losses owing to the absorption in the bulk material and at metallic surface.

The Fresnel losses are determined by using the Fresnel equations, and here the reflection losses at an optical interface are calculated, and within this work averaging the transverse electric (TE) and transverse magnetic (TM) polarization reflection coefficients. Material absorption losses occur either due to absorption, when light propagates inside a transparent dielectric material, or due to absorption, when light is reflected at a metallic surface.

MODEL

Initially, a design according to Figure 1 is used for the raytracing model, and in the first design the mirrors are plane surfaces and thus provide no concentration of the sunlight. The system is comprised of a vertical bifacial panel which for simulation purposes is oriented east-west, and two reflector plates extending in angles (α = ±45 deg.) relative to the bifacial panel.

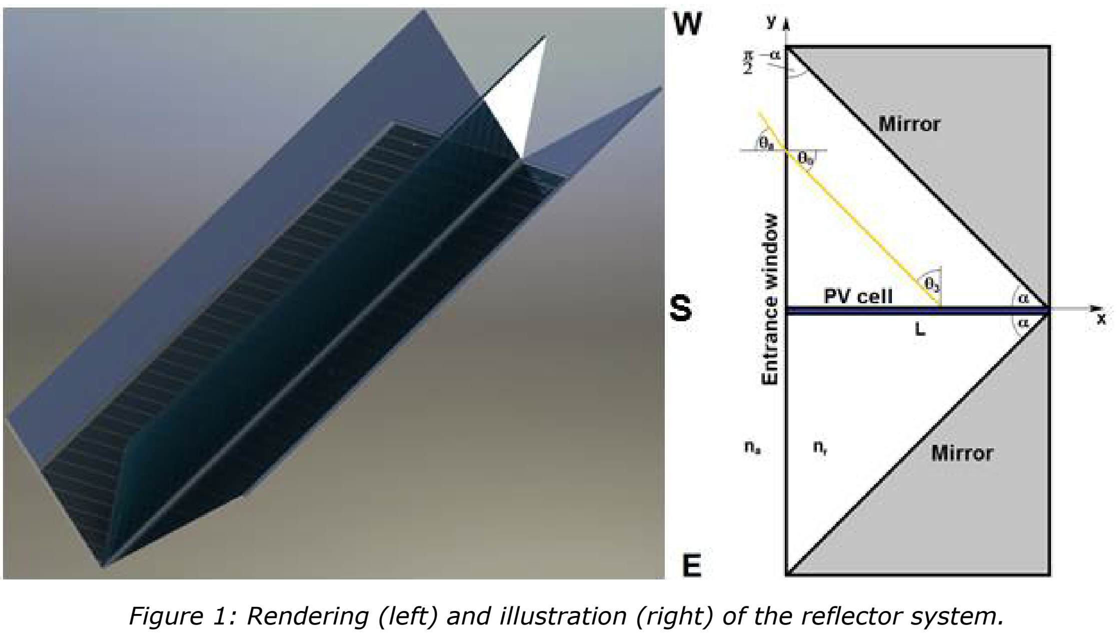

Figure 1: Rendering (left) and illustration (right) of the reflector system.

Ray tracing, where many optical rays are modelled and finally the weighted output is integrated, are performed on this system. The volume inside the reflector can be bulk and thus be filled with a transparent material with refractive index n_r. The material can be index matched to that of glass, where the Fresnel losses at the surface of the PV-module will be eliminated, or it can be air, removing the optical interface at the entrance window or any other transparent material.

We assume that all light incidents into the PV cell and its laminate of glass is absorbed. This allows us to consider only three paths of the incoming light, and these are illustrated in Figure 2. This allows us to omit surface reflections at the PV-module and to omit the optical paths derived from these reflections, which in fact are insignificant.

The paths are:

1. Refraction at the entrance window and then propagation to the PV-module where refraction occurs again - the direct path
2. Refraction at the entrance window, then propagation to the mirror, where reflection occurs and then propagation to the PV-cell, where refraction occurs again –the reflected path.
3. Refraction at the entrance window, then propagation to the mirror, where reflection occurs, then propagation to the entrance window, where refraction and reflection occurs and the reflected part propagates to the PV-cell, where refraction occurs again – the back multiple reflected path.

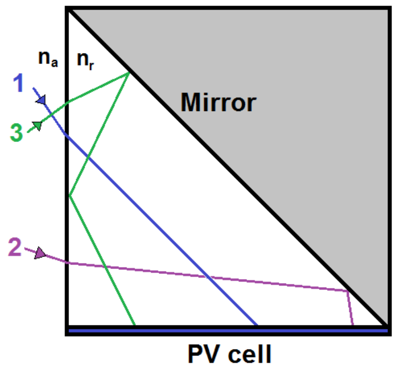

Figure 2: Relevant paths in one half of the retroreflector, when assuming that the PV cell and its glass laminate absorb all light.

When the ray intersects with a mirror interface we use a reflection coefficient of 95%, as an average value for the reflection coefficient of alumina throughout the spectral range of c-Si. The solar elevation (ψ) is determined from the local latitude (φ), the declination of the sun (δ) and the azimuth angle (θ) of the sun relative to the local true south:

$$\psi = \sin^{-1}\left[\sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\theta\right] \qquad (1)$$

The schematic of Figure 1 illustrates the model of the vertical retroreflector, and its orientation relative to earth. At the moment, the model does not include the diffuse solar contribution. The preliminary model does not include variations in sun intensity but considers only direct radiation and resulting scattering due to the Fresnel equations.

RESULTS

Four cities placed at different latitudes and very similar longitudes are chosen for the simulations: Trondheim (Norway latitude 63.5°N), Copenhagen (Denmark lat. 55.7 °N), Munich (Germany lat. 48.1 °N) and Rome (Italy lat. 41.9°N). The shortest and the longest days of the year are simulated and the relative irradiances as a function of azimuthal angle are used to normalize for the energy harvest.

As reference for the simulations, a monofacial panel facing south with the same area as a single side of a bifacial panel, is used. A reference scenario is calculated for each position. An example of a reference simulation is shown in Figure 3.

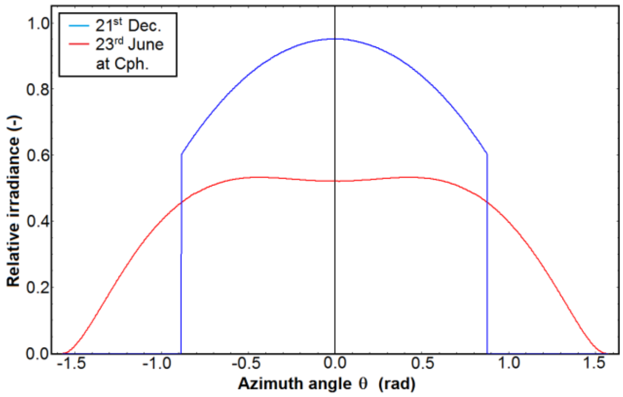

Figure 3: Reference simulation for Copenhagen

In Figure 4, two reflectors located in Copenhagen have been simulated. Left plot illustrates the simulation of a reflector filled with air (n_r = 1.0). The right plot illustrated the simulation for a reflector filled with acrylic (n_r = 1.49). The contributions from the three different ray paths are illustrated in Figure 2 with three different colors. The bulk optical absorption losses are omitted. As can be seen, the 3. ray path contributes significantly to the total light flux. The index matched reflector improves the energy harvest by 32%, when bulk losses are neglected.

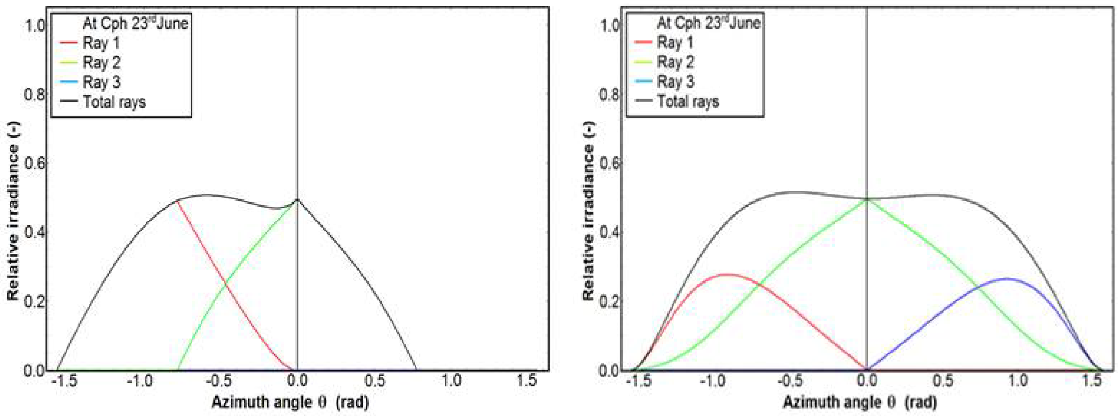

Figure 4: Ray contributions for a reflector filled with air (Left) and a reflector filled with acrylic (right).

The impact of optical absorption and non-ideal mirrors are considered in the following. Going from ideal glass to an acrylic filled reflector and with mirrors with a reflection coefficient of 95 % the power output is reduced by approximately 5 %, and hence fairly optimal materials give acceptable performance.

In Table 1, simulations comparing the energy harvest on the longest day and the shortest day of the year at four different latitudes are shown. Bulk optical absorption in the acrylic material is taking into account and the mirrors are assumed to reflect 95 % of the light.

Place	Latitude	Improvement			
		December		June	
		Air	Acrylic	Air	Acrylic
Trondheim	63.5	1.61	1.91	1.36	1.92
Copenhagen	55.7	1.45	1.91	1.35	1.92
Munich	48.1	1.39	1.91	1.33	1.92
Rome	41.9	1.38	1.92	1.35	1.92

Table 1: Simulation runs at 4 different latitudes, comparing energy harvest with an air filled reflector with an acrylic filled reflector.

It can be seen that the air filled reflector is performing significantly worse compared to the acrylic filled reflector and the performance of the air based is strongly dependent on the location and the time of year – i.e. the solar angles.

Opposite the acrylic reflector captures in all cases almost all the light entering the entrance window with a loss of less than 5 %, and the performance is almost independent of location and time of year – i.e. the solar angles.

Since it is not very practical to have a plastic filled reflector, a similar simulation on a circular reflector was made. As seen from below figures the circular reflector shape can obtain similar performance as the plastic filled linear reflector under realistic assumptions with reflection coefficients of 95% and realistic Fresnel losses.

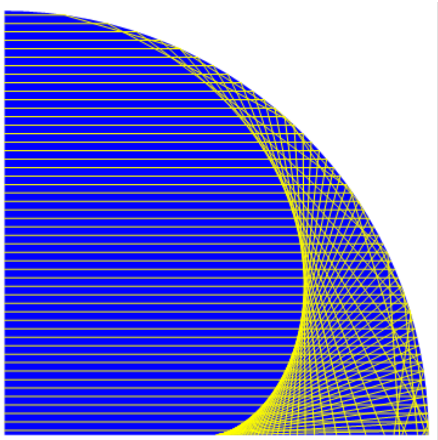

Figure 5: Ray paths for the circular reflector.

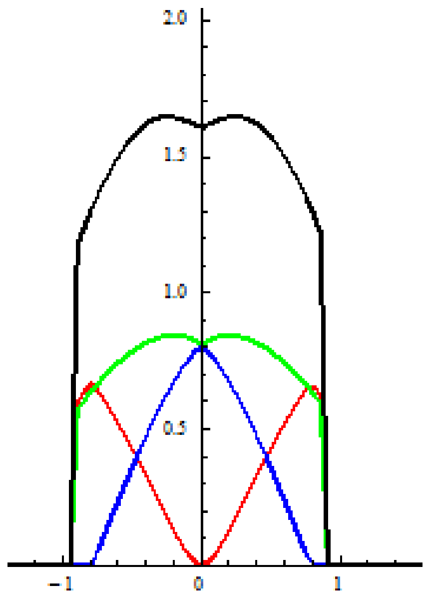

Figure 6: Simulation results for the circular reflector on Dec 31. Copenhagen. Total output 1.75. Red Curve, Direct beam from the sun, Blues curve, Sunny side reflection, Green curve Shady side reflection.

Dato:	Bifacial Reference:	Linear reflector gain without filling medium:	Circular reflector Gain:
21/12	1 (25 % of June)	2.17	4.1
10/4	1 (72 % og June)	1.08	1.59
23/6	1 (100 % og June)	0.74	0.89

Table 2: Reflector gain at different dates at latitudes similar to Copenhagen.

To summarize the above table shows the reflector gains for the two reflector design with reference to the raw vertically bifacial panel placed on a latitude similar to Copenhagen, and assuming no clouds. From this table it can be seen that both reflectors boost the energy gain in December however reduces the energy gain in June.

The circular reflector outperforms the linear significantly by doubling the winter boost and reducing the summer loss to 10 %.

WP 6 Identification and implementation of Wireless communication (AKJI)

There exist various different communication standards. In this project we need communication for three different purposes:

- Internal Wire-based, from sensors to controller
- External Wireless Point-2-Point, from one SensorPower unit to another
- External Wireless to the internet, from one SensorPower to the cloud

Based on these requirements we made an analysis of some available communication technologies to find the best solutions for each of the three purposes.

As the Internal Wire-based technology we selected RS232/RS485. This is a well-known and stable technology that has been on the market for more than 50 years. Almost all digital equipment can be connected easily to this technology. Either as point-2-point (RS232) or on a bus (RS485).

As the External Wireless Point-2-Point communication we selected two technologies: Wi-Fi and raw ISM band RS232 communication. Raw ISM band RS232 communication gives us great flexibility, and minimal power consumption. The disadvantage is that it is not a standard, so only SensorPower devices can communicate with each other, unless some development is made to make it talk to other devices. Wi-Fi is a well-known standard and makes it possible to communicate with other Wi-Fi enabled devices. The disadvantage is that Wi-Fi uses more power than the Raw ISM band RS232 communication.

As the External Wireless to the internet communication we selected two technologies as well: GSM/GPRS and Wi-Fi. GSM/GPRS, or better known as the 2G cellular network, has the big advantage that it is available almost everywhere. The disadvantage is that you need to pay a subscription to use it per month. But as IoT is getting popular these costs are decreasing rapidly for M2M communication. Wi-Fi on the other hand is free to use, but requires an internet connected Wi-Fi router within 400 m.

Developed electronics (AKJI)
Based on the requirements for the communications standards, we developed some control electronics based on the CUPU platform developed by AKJI. The PCB is called CUPU 5-0 and contains interfaces for RS232/RS485, HC-12 (raw ISM band RS232), GSM/GPRS and Wi-Fi. Beside of this it has several inputs for analog sensors, and PIR sensors (motion sensors). The controller contains a real time clock (RTC) to keep time for all data.

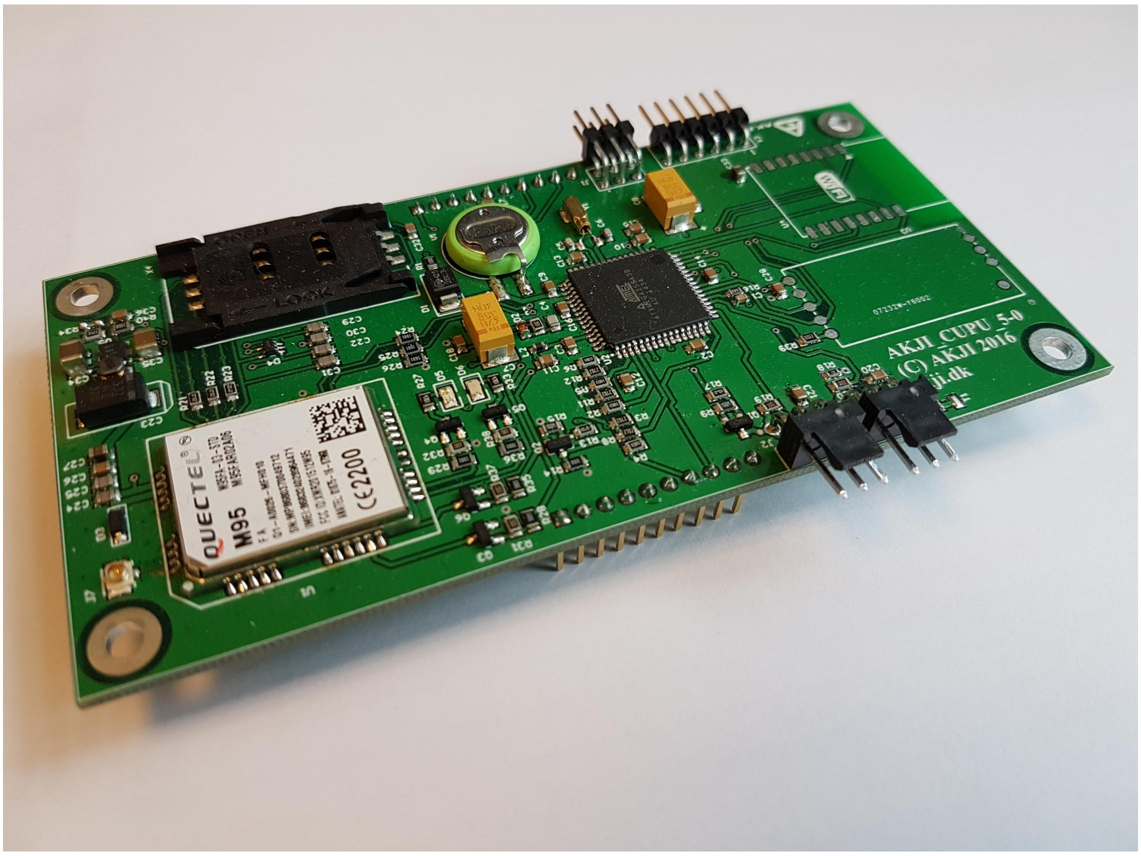

Figure 7: Electronics for the sensor mast

Data from the sensors can be send to a cloud database via the internet. This cloud database is called CUPU Cloud, and is designed to collect large amount of data from various distributed sensors. Each device can be seen on a Google map, as seen below:

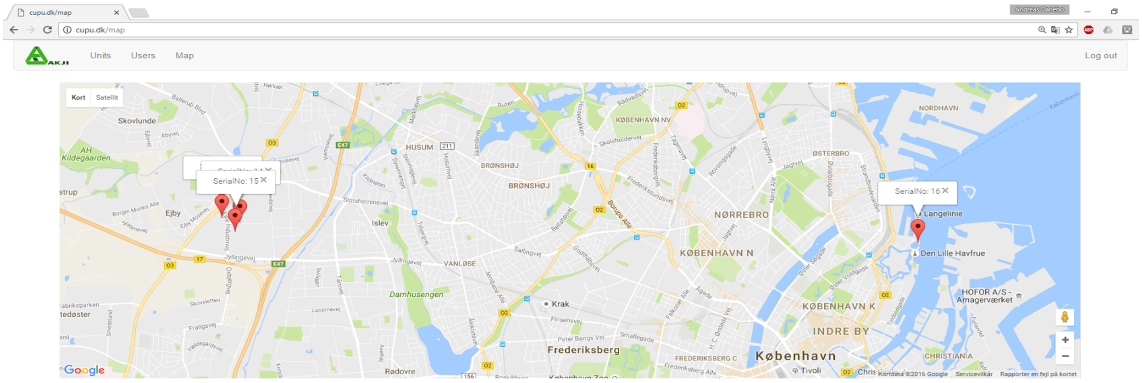

Figure 8: CUPU Cloud – where the sensors can be seen on a map.

All products are also listed as seen below

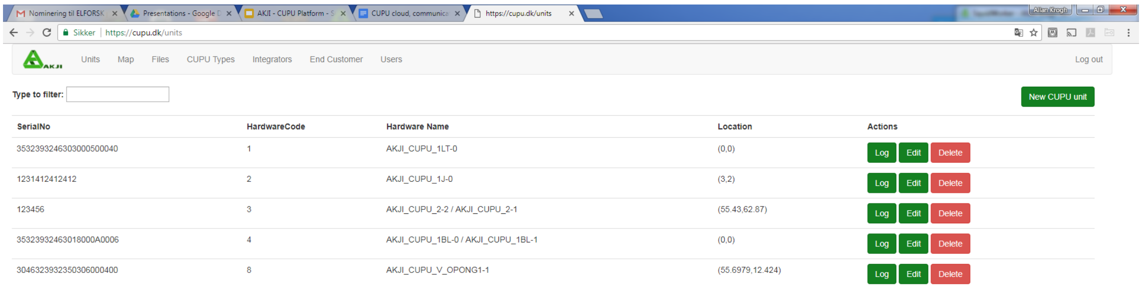

Figure 9: CUPU Cloud – Data from and control of each mast.

All available data from each sensor can be viewed on a graph as seen below. Here it is for instance the temperature that is shown but could be any data

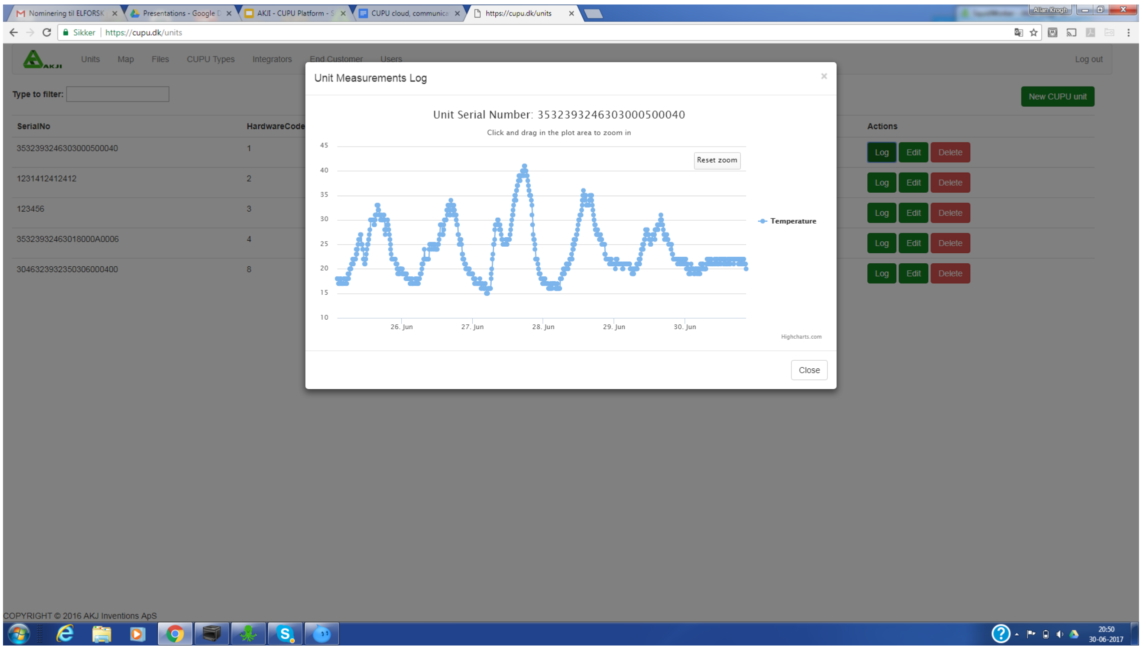

Figure 10: CUPU Cloud – Graphical presentation of data.

WP 8 Prototypes with measurements

The performance of the two bifacial reflector prototypes was monitored from March to June 2017 in DTU Fotonik's Living Lab (Figure 11). The short circuit current (I_{SC}) of both reflector columns was sampled every 10 seconds in conjunction with solar irradiance data from the nearby Solar Monitoring Station. The I_{SC} was chosen as the parameter of interest because I_{SC} is linear with respect to the amount of light generated carriers. In other words, I_{SC} gives the best indication of the optical gains received by the PV device.

Figure 11: The curved mirror (foreground) and linear mirror (background) reflector columns in DTU Fotonik's Living Lab. The Solar Resource Monitoring Station is in the tower in the top left of the photo.

The communication electronics were attached as a load to the linear mirror reflector column on May 2, 2017. The PV cells in the linear reflector prototype no longer operated at I_{SC} once the load was attached. Therefore, the side by side comparison of the two reflector designs was limited to a 2 month period. The comparison is further limited to clear sky days as direct beam light is needed to validate the effect of the mirrors.

Figure 12 shows a typical performance profile of the reflector prototypes on a clear sky day (April 30, 2017). The angle of incidence (AOI) is shown on the secondary y-axis. The AOI represents the angle between the sun's rays and the glass surface of the PV cells; the East facing cells are used for the AOI calculation before noon and the West facing cells for the afternoon calculation. Note that the I_{SC} measurements on the primary y-axis in Figure 12 are normalized to the daily maximum. The normalization is done because the curved reflector column contains PV cells with a 243 cm^2 area while the linear reflector column contains cells that are one third this area. The morning performance data of the linear reflector is truncated from 8:00 to 11:00AM due to a significant shadow profile to the East.

The afternoon data show that the two designs have a peak performance roughly one hour (i.e. 15° in solar azimuth) from each other. The performance of both designs is the lowest midday since the sun is due south (i.e. AOI equals 90°) and no direct sun light can reach the PV cells at this time. The 25 to 30% relative output midday is therefore driven by scattered light within the reflector column. One can see that PV output increases rapidly as the AOI decreases from noon to about 15:00. This trend indicates that the primary source of energy output comes from the direct beam irradiance component from the sun's rays on the PV cells. The curved reflector data show that the morning peak in performance is about 95% of the afternoon peak. In bifacial PV cells, the bottom cell never produces as much as the top cell and the difference between the top and bottom cell is referred to as the bifaciality factor. Figure 2 indicates that the bifaciality factor of the cells used in this experiment is roughly 95%. This level of bifaciality is near ideal since it can be as low as 70% in lower performing bifacial cells.

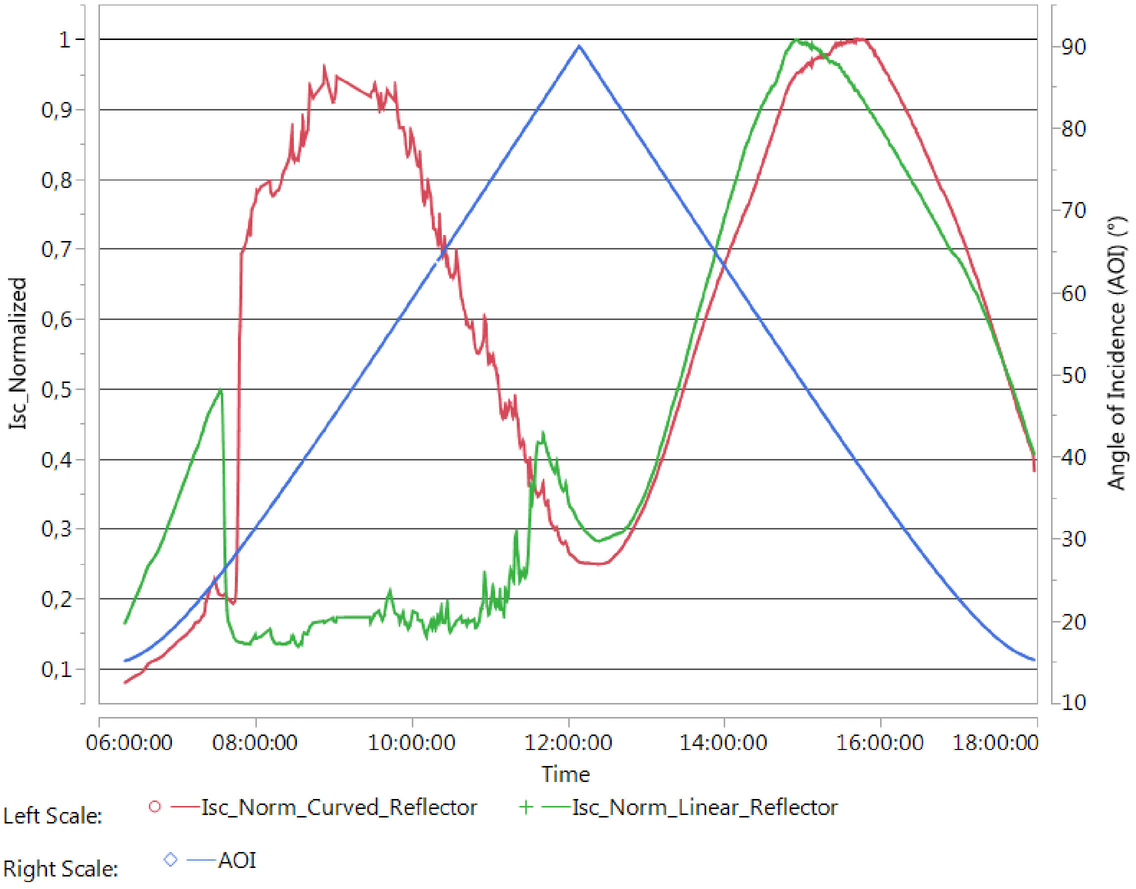

Figure 12: Clear sky I_{SC} measurements of the two reflector prototypes as a function of time. The I_{SC} data are normalized to the daily maximum.

WP 9 Demonstrator

Two demonstrator towers were designed and build by SolarLab. The reflectors were designed based on the simulations, and since it is not very practical and too expensive for production to have a filled air space both a linear and a circular reflector were made. The circular reflector can if proper dimensioned ensure that most of the rays that hit the reflector is directed into the Cell, and thus not need a third reflection at the Air Medium interface. These were designed for manufacturability and were assembled at DTU Fotonik.

Figure 13: Photo of Sensorpower mast installed at DTU Fotonik in Roskilde.

WP 10 Field test

The two demonstrators were placed at the Living lab at DTU Fotonik in Roskilde. Here efficient infra structure for datalogging is created close to the most advance solar resource monitoring station in the Nordics. Here on mast where fully equipped with the developed electronics, battery and charge regulator. As a demonstration the temperature inside the mast has been logged and sent to the CUPU cloud every 10 minutes. This mast is still operational and has send temperature data to the cloud for almost 11 months.

The other mast equipped with the circular reflector has been logging short circuit data for the same period of time, in order to test the performance of the circular reflector.

The performance data for the circular reflector can be seen in Figure 14, the cumulative energy harvest for the period is plotted on the left axis expressed in Amp hours, and the actual current is plotted on the right axis. The average daily harvest is 17 Amp hours.

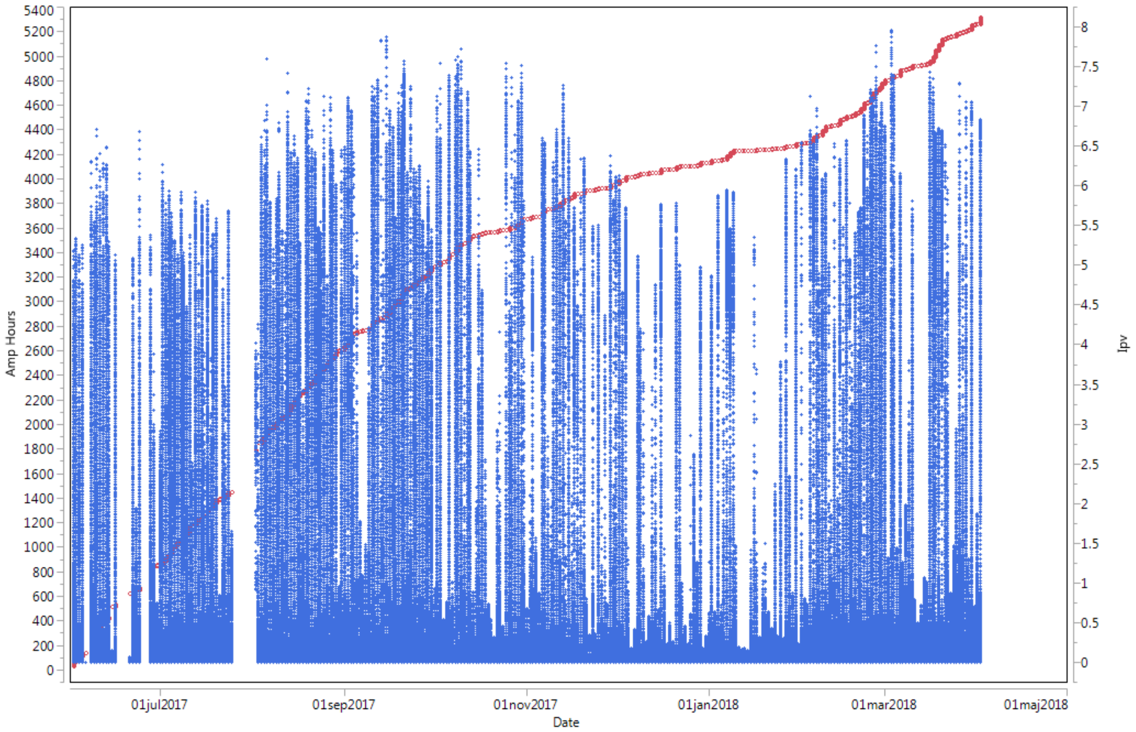

Figure 14: Plot of performance of the circular reflector for 290 days. Blue dots is the actual current, Red Cumulative Amp hours during the period.

The mast with the linear reflector was connected to a complete powersystem and have during the period of 10 months sent temperature data to the cload via a 2 or 3 G cellular networks. The data frequency is every 10 minutes at the temperature data can be seen in figure 15, with a logging period long enough to see the seasonal variations in temperature.

The temperature sensor is places inside the mast and is not representative for the ambient air temperature.

The graph in figure 15, shows that a reliable systems fullfillng the specifications is succeeded.

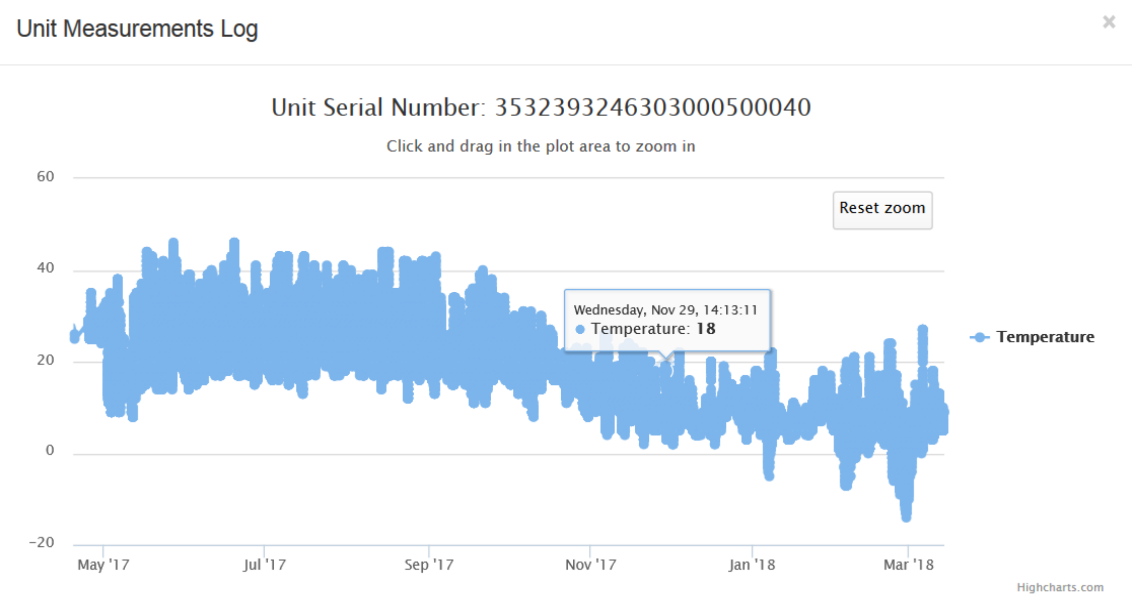

Figure 15: Temperature data for the sensor mast.

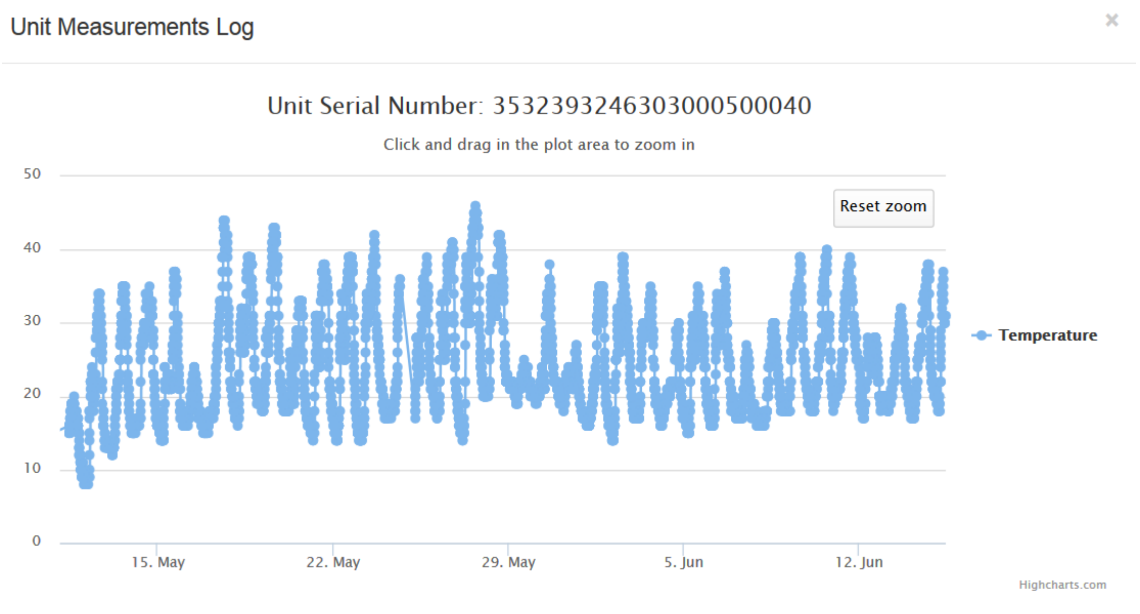

Figure 16: Zoomed data, where daily temperature variations are visible.

Demonstration and marketing

Solar lab has together with Banedanmark installed an initial prototype of the product close to Høje Taastrup station, where Banedanmark currently is investigation which sensors can be driven by the PowerPilar. Initial results are gathered and so far the results looks promising, however no finite conclusions yet.

Furthermore, Skov og Natur styrelsen has expressed interest in being able to provide services in the new national parks together with being able to count visitors. Solarlab is currently in a dialog with the supplier of these service stations to provide a power solution for these services. So far the dialog is positive and this seems promising.

Dissemination

The project has been disseminated at relevant scientific conferences:

2016:
Ray Tracing Modelling of Reflector for Vertical Bifacial Panel
Jakobsen, Michael Linde ; Thorsteinsson, Sune ; Poulsen, Peter Behrensdorff ; Rødder, Peter Melchior ; Rødder, Kristin
Proceedings of the 2016 European Photovoltaic Solar Energy Conference and Exhibition 2016, 2016,
Presented at: 32nd European Photovoltaic Solar Energy Conference and Exhibition, 2016, Munich

Vertical reflector for bifacial PV-panels
Jakobsen, Michael Linde ; Thorsteinsson, Sune ; Poulsen, Peter Behrensdorff ; Rødder, Peter Melchior ; Rødder, Kristin
IEEE 43rd Photovoltaic Specialist Conference 2016 (ISBN: 9781509027248), pages: 2678-2681, 2016, IEEE,
Presented at: 43rd IEEE Photovoltaic Specialists Conference , 2016, Portland, Oregon
DOI: http://dx.doi.org/10.1109/PVSC.2016.7750136

2017:
Bifacial PV cell with reflector for stand-alone mast for sensor powering purposes
Jakobsen, Michael Linde ; Thorsteinsson, Sune ; Poulsen, Peter Behrensdorff ; Riedel, Nicholas ; Rødder, Peter Melchior ; Rødder, Kristin
Presented at: 13th International Conference on Concentrator Photovoltaic Systems , 2017, Ottawa

Bifacial PV cell with reflector for stand-alone mast for sensor powering purposes
Jakobsen, Michael Linde ; Thorsteinsson, Sune ; Poulsen, Peter Behrensdorff ; Riedel, Nicholas ; Rødder, Peter M. ; Rødder, Kristin
Journal: Aip Conference Proceedings (ISSN: 0094-243X) (DOI: http://dx.doi.org/10.1063/1.5001437), vol: 1881, 2017

1.6 Utilization of project results

SolarLab have now established a solid demonstration of the principle and will use this data to further market this product and develop customized solutions for potential end-users. Several customers have already shown great interest and solar lab is seeding market potential with with BaneDanmark and Skov og Naturstyrelsen. Skov og Naturstyrelsen find this product very interesting, since the can use the masts to provide interactive information visitors in the national forests, the new natural nature parks or other nature recreative areas.

DTU Fotonik has during the project build a living lab for performance testing of such products. This is now available for the industry for testing and is unique for testing product integrated PV Solutions in the sense that a unique data logging infra structure is available together with the close proximity to the most advanced solar resource monitoring station in Scandinavia. DTU Fotonik uses this lab for other projects and offers it to the industry already.

Figure 17: Picture of the build living lab taken from the solar resource monitoring station.

Additionally DTU Fotonik will continue used the experience and knowledge gained with bifacial panels and reflectors in this project to boost the research of application of bifacial panels, and how optical reflectors can boost the energy harvest, - also for grid connected systems. Collaboration with a large partner on this topic is already established and a test site at Risø is already projected.

1.7 Project conclusion and perspective

The project has been successfully solved and all the technical challenges have found good solutions, and SolarLab have together with DTU Fotonik developed a product with a high market potential in a market with little competition.

I addition DTU Fotonik have built a living lab for testing PIPV products with integrated communication and IoT for the Danish industry and future R&D projects.