EUDP

Det Energiteknologiske Udviklings- og Demonstrationsprogram

EUDP 64018-0624
BiSun Boost

FINAL REPORT

PROJECT PARTNERS

EUROPEAN ENERGY

ISC International Solar Energy Research Center Konstanz

Startak

DTU Fotonik
Institut for Fotonik

Title:
BISUN BOOST

EUDP Project number
64018-0624

Project Partners
European Energy (project coordinator)
DTU Fotonik
Startak
International Solar Energy Research Center Konstanz

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Front page
Top: Bifacial solar panels with ground covers of respectively gravel and white tarp.
Bottom: The bifacial PV test-site at Risø campus used in the project for all experiments.

Final report

1. Project details

Project title	BiSun Boost
File no.	64018-0624
Name of the funding scheme	Solar Energy
Project managing company / institution	European Energy
CVR number (central business register)	18351331
Project partners	DTU Fotonik Startak International Solar Energy Research Center Konstanz
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2. Summary

2.1 English summary

The major objectives of the project has been:

1. Capturing backside irradiation
2. Increasing the reflection from the ground
3. Use substructures that track the sun along 1, 1.5 or 2 axis
4. Optimizing the tracker movement according to the actual received irradiation
5. Use validated simulation tools in the optimizing of components and overall design

Several groundcovers were tested to identify the bifacial gain of tracked and fixed tilt solutions showing values from 4-11% for 25° south facing fixed tilt solution and around 7-15% for 1-axis east-west tracked solutions.

We have assessed eight bifacial PV performance tools based on measurements made at the 420 kWp PV test site at Risø. Our results show that state-of-the-art bifacial performance models add **~0.5% uncertainty** to the PV modeling chain. Our results further show that – for the site investigated – 2D view factor fixed tilt simulations are within ±1 % of measured monthly bifacial gain. Simulations of single axis tracker systems are less accurate with 2D view factor simulations within approximately 2% and 3D ray tracing within approximately 1% of measured bifacial gain, respectively. The rather high degree of accuracy is crucial when planning and assessing new bifacial plan installation to ensure return on investment.

The overall conclusion of the project is very positive. European Energy and project partners have successfully completed the EUDP BiSun Boost project according to the original plans and ambitions. A strong, close, and well-functioning collaboration between research institutions, dedicated sensor and controller manufacturer and a PV project developer, have been instrumental in reaching these goals. The test-site at Risø and close collaboration with competent, engaged, and flexible scientific professionals, at both DTU as well as ISC Konstanz and Startak, have demonstrated to be a very fruitful team and provided important scientific results already taken into commercialisation.

2.2 Danish summary

De vigtigste mål for projektet har været:

1. Optimal solbestråling af solcellernes bagsider
2. Forøgelse af refleksionen fra jorden
3. Brug konstruktioner, der tracker solen i 1, 1,5 eller 2 akser
4. Optimering af trackerbevægelsen optimeret i forhold til den faktiske solindstråling
5. Brug af validerede simuleringsværktøjer til optimering af komponenter og overordnet design

Flere belægninger på jorden under solcellerne blev testet for at identificere den bifacielle sollysforstærkning af såvel trackerbaserede som fastmonterede bifacielle solcellesystemer. Der blev målt værdier fra 4-11% for 25° sydvendte fastmonterede løsninger og omkring 7-15% for 1-akse øst-vest trackede løsninger.

Vi har undersøgt og sammenlignet otte bifaciale PV-simuleringsværktøjer baseret på målinger foretaget på 420 kWp PV-testsitet på DTU Risø. Vores resultater viser, at moderne bifaciale simuleringsværtkøjer tilføjer ~ 0,5% usikkerhed til PV-modelleringskæden. Vores resultater viser yderligere, at - for det undersøgte system – at 2D-view faktor fast monterede simuleringer ligger inden for ±1% af den målte månedlige bifaciale gevinst.

Simuleringer af enkeltakse trackersystemer er mindre nøjagtige med 2D-viewfaktorsimuleringer inden for henholdsvis ca. 2% og 3D-ray trace modellering inden for ca. 1% af den målte bifaciale forstærkning. Den ret høje grad af nøjagtighed og ikke mindst kendskab til niveauet heraf er afgørende ved planlægning og vurdering af ny bifacial planinstallation for at sikre investeringsafkast herpå.

Den samlede konklusion af projektet er meget positiv. European Energy og projektpartnere har fuldt ud gennemført EUDP BiSun Boost-projektet i henhold til de oprindelige planer og ambitioner. Et stærkt, tæt og velfungerende samarbejde mellem forskningsinstitutioner, en dedikeret sensor- og kontrolsystemproducent og en PV-projektudvikler har været med til at nå disse mål. Testfaciliteten på Risø og et tæt samarbejde med kompetente, engagerede og fleksible videnskabelige fagfolk på både DTU såvel som ISC Konstanz og Startak har vist sig at være et meget frugtbart team og leveret vigtige videnskabelige resultater, der allerede har ført til kommercialisering.

3. Project objectives

The BiSun Boost project has been dedicated to the objective of “Boosting the energy harvesting from PV modules by:

6. Capturing backside irradiation
7. Increasing the reflection from the ground
8. Use substructures that track the sun along 1, 1.5 or 2 axis
9. Optimizing the tracker movement according to the actual received irradiation
10. Use validated simulation tools in the optimizing of components and overall design”

The experimental part of the EUDP industrial development project has been centered around the test-site build and financed by European Energy on DTU Risø campus as illustrated in the picture below. This test site located in Roskilde, Denmark (55.6°N, 12.1°E)

Figure 1 – the test facility at DTU Risø Campus used in the project

The test facility at this site consists of eight horizontal single-axis trackers (HSAT), labelled T1–T8 in figure 2 below and eight south-facing static-tilt structures, labelled T9–T16 in the same figure. All 16 substructures (including the south-facing units) are HSATs from the same manufacturer, but T9–T16 have been oriented southward and programmed for a static-fixed tilt. Tilt angles from 0° to 60° from horizontal are possible. Each PV substructure holds 88 PV modules, either monofacial or bifacial.

The cell types within modules are either 156 mm x 156 mm p-PERC or half-cell p-PERC. The 88 modules in each substructure are divided into 4 strings, where each string consists of 22 series connected modules. There is one 50 kW dual MPPT inverter for every two trackers (i.e. for every 8 strings) and therefore the operating point of the 88 panels on each substructure is determined by a single MPPT. As an advantage, all substructures at this site have dimensions analogous to those found in utility-scale PV installations.

The monitoring system provides maximum power point current (I_{MP}) and maximum power point voltage (V_{MP}) data from all 64 strings in the park at a one-minute sampling frequency using sensors with galvanic isolation. Digital filters are applied to the data to remove noise, such as fluctuations from inverter switching. Albedo data from upward and downward facing spectrally flat class A pyranometers, as well as from Class C photodiode sensors are available onsite.

The configuration of this grid-connected installation is given in the table below.

Substructure	Cell type	Module power [Wp]	Inverter brand and model	Nominal inverter power per unit [kW]	No of Inverters per subsystem	No of strings per inverter	No of modules per string	No of modules per subsystem	DC power installed [kWp]
1 ax tracker	Mono/Perc	305	Delta - RPIM50A	50	1	8	22	176	53,68
1 ax tracker	Bifacial/Perc	295	Delta - RPIM50A	50	3	8	22	528	155,76
Fixed tilt	Mono/Perc	305	Delta - RPIM50A	50	2	8	22	352	107,36
Fixed tilt	Bifacial/Perc	295	Delta - RPIM50A	50	2	8	22	352	103,84
1.5 ax tracker	Mono/Perc	305	Delta - RPI H4A	4	1	1	12	12	3,66
1.5 ax tracker	Bifacial/Perc	295	Delta - RPI H4A	4	1	1	12	12	3,54
2 ax tracker	Mono/Perc	305	Delta - RPI H4A	4	1	1	12	12	3,66
				412	10			1.444	432

An aerial view can be seen below.

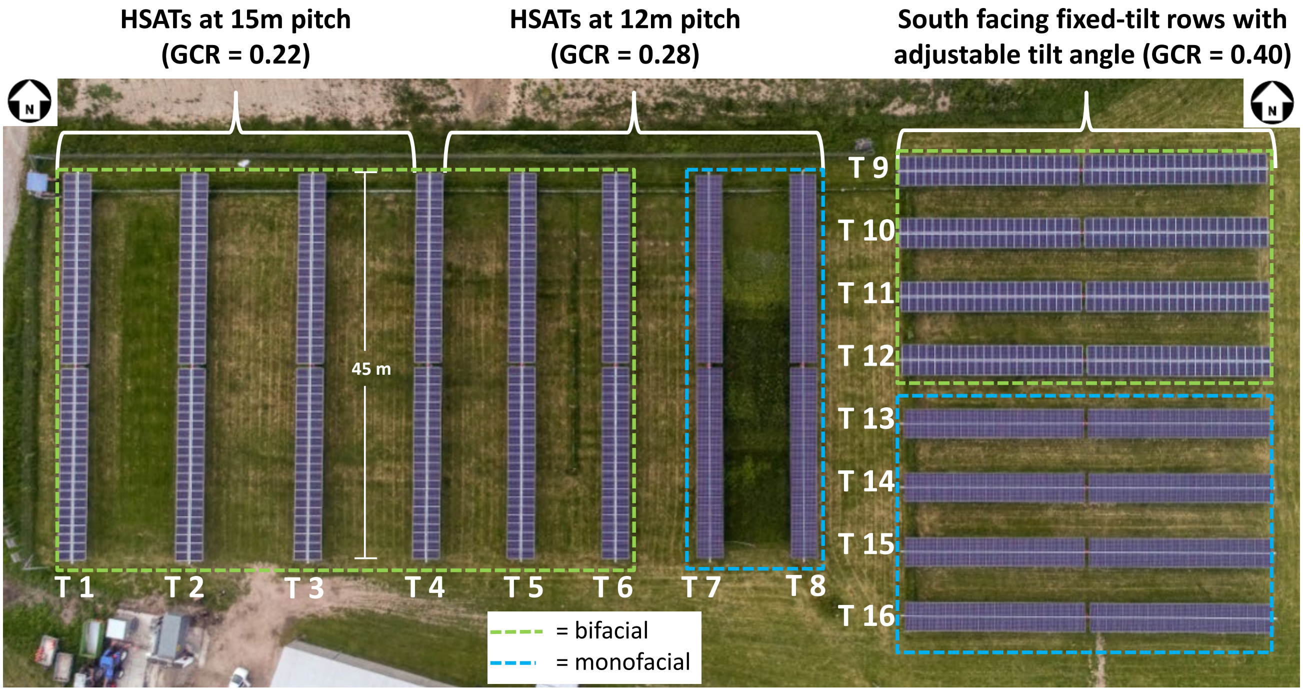


Figure 2. Aerial view of the bifacial test facility at DTU. Annotations show tracker number, substructure type, pitch, and module type.

3.1 Capturing backside irradiation

The solar modules used to capture sunlight from the backside was bifacial solar cells as shown below:

Figure 3 – backside view of bifacial PV panels.

Also optical sensors was used as a reference to measure the backside irradiance

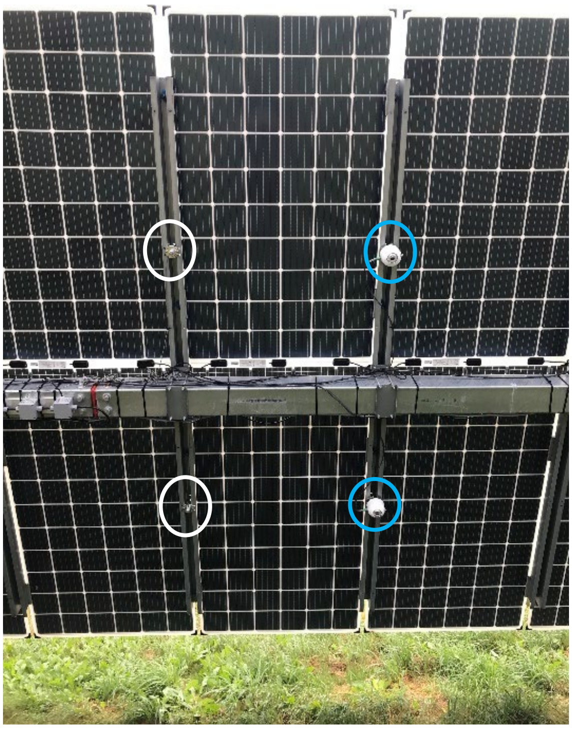


Figure 4 - Optical sensors mounted on the backside of T5. The Si photodiodes are circled in white and the pyranometers are circled in blue. The sensors are located 11 modules North of the array’s south edge. Note that sensor placement is similar on the fixed tilt system (T11).

The site also includes a custom-built high resolutions back-side irradiance monitoring setup that consists of forty large-area (156.25 cm^2) PV cells laminated into four separate PV panels. The custom panels are installed at four locations on T5, with two panels on the south edge and two panels toward the center (figure 5). This configuration was selected to investigate edge-brightening effects. The custom panels are moveable, which allows for investigations of the non-uniformity of light intensity and the subsequent impact on electrical mismatch as performed in

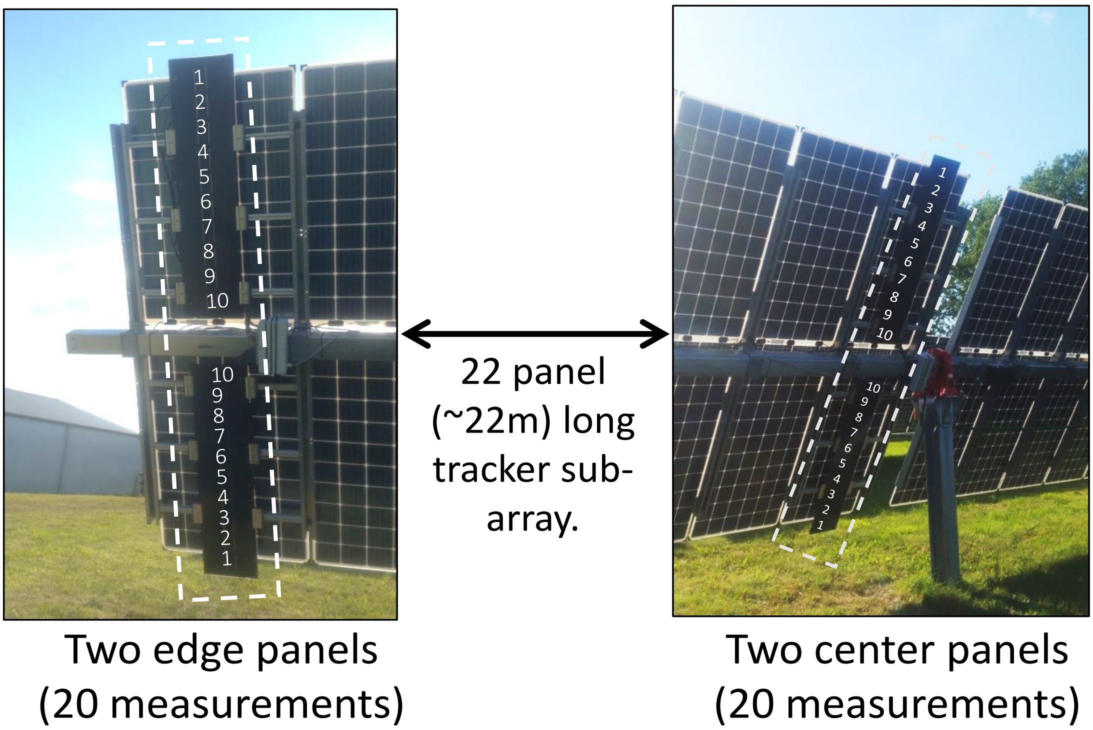


Figure 5 - Two 1x10 cell panels mounted on the east and west edges of the tracker (left) and the same panel type in the center of the tracker (right). Note that the black backsheet makes it difficult to see individual cells within panels.

3.2 Increasing the reflection from the ground

For increasing and comparing the ground reflections to grass several groundcovers was used. Figure 6 shows the albedo experiments on fixed-tilt and HSAT strings. A shortcoming of these experiments is that the experimental ground cover is not wide enough to be representative of uniform field conditions. In other words, a significant amount of the ground reflected light reaching the back side of the PV arrays comes from the grass, not the experimental cover. We have determined that for cells near the torque tube, roughly 80% of the ground reflected light comes from the experimental cover, but this amount can be as low as 50% for the cells highest (3m) from the ground. Therefore, these experiments have not proved to be useful for validating reduced-order models that do not have the capability to simulate such localized albedo enhancements. The utility of these experiments is therefore largely to observe energy production gains that can be achieved from modifying the ground.

Figure 6 - Ground cover (albedo) experiments on fixed-tilt strings on T10 and T11 (left) and equivalent experiments on HSAT strings on T2 (right)

The DTU site is one of few in the world where continuous spectral albedo measurements are made. This measurement system allows for study of the spectral mismatch caused by the reflectance spectra of ground surfaces on different bifacial PV technologies. The horizontal upward- and downward-facing spectrometers are shown in figure 7. The campus solar radiation monitoring station has a spectrometer with a 5° field-of-view collimating tube, which provides the DNI spectrum. The diffuse spectrum is calculated as the difference of the GHI and cosine corrected DNI spectral measurements. The spectral reflectance, GHI, DHI and DNI can be used to calculate rear POA spectra.

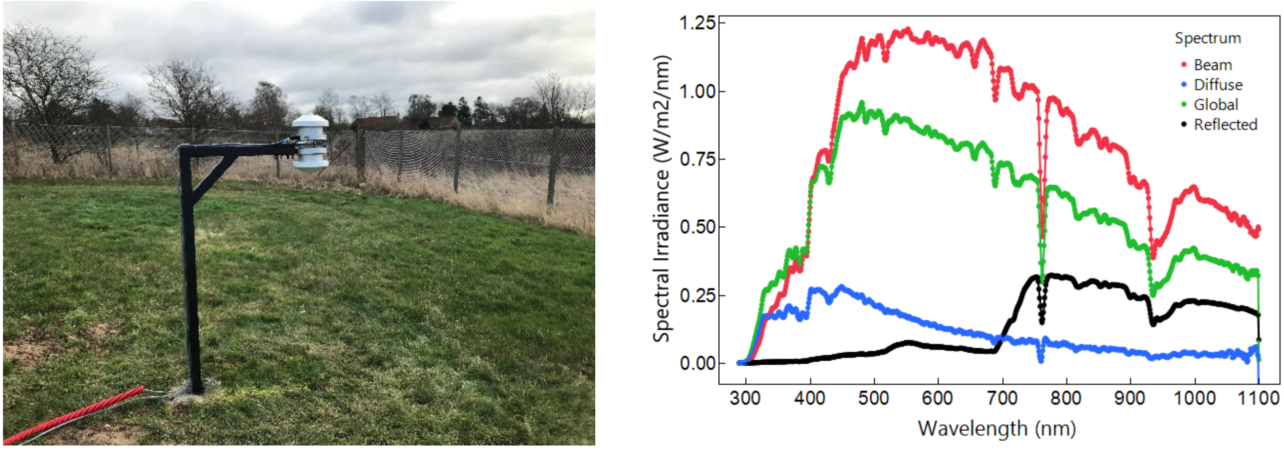


Figure 7 - Spectral albedo setup consisting of an upward and downward facing EKO MS 711 (left) and example data (right)

The impact that spectrally resolved albedo measurements have on bifacial gain calculations was performed in M. Ribaconka, “Impact of Spectral Albedo on Bifacial PV Performance Assessment,” Technical University of Denmark, Master's Thesis, 2020. In this work, the onsite spectral albedo, GHI, DNI and DHI measurements were used to calculate the spectral rear POA irradiance on fixed tilt and HSAT systems. This was done by modifying the open-source Python library *pvfactors* – which can only process broadband irradiance in its current version (1.4.1) – to process the spectrally resolved irradiance measurements made onsite at DTU. The bifacial gain was then calculated using various methods, which included the use of on-site spectrally resolved measurements weighted according to device-specific eQE, the use of reflectance spectra from the software SMARTs, the use of on-site broadband albedo measurements from pyranometers and reference cells, and the use of a single constant albedo value. The spectrally weighted bifacial gains were calculated for PERC+, n-PERT and IBC cells. The results showed that using spectral reflectance curves from databases (e.g. from SMARTS) can result in 2% differences in bifacial gain as opposed to using the onsite measured spectral reflectance for bifacial gain calculations.

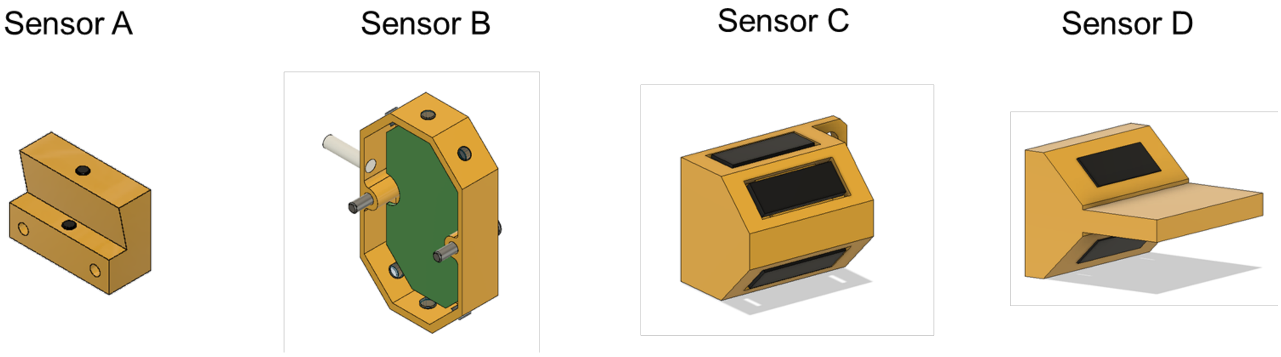
3.3 Use substructures that track the sun along 1, 1.5 or 2 axis

Figure 8 – different tracker configuration tested in the project. From left to right respectively the 1, 1.5 and 2 axis trackers are shown.

At the facility 3 different tracker types were tested as shown in figure 8.

3.4 Optimizing the tracker movement according to the actual received irradiation

For optimizing tracker movement for energy harvesting Startak tested different configurations of their diode sensor based tracker control systems compared with the passive astronomical solution used by the commercial solutions used in the 1-axis trackers on the site.



Sensor A

Sensor B

Sensor C

Sensor D

Figure 9 – Various sensor types with different diode configurations for optimal light monitoring and feedback to the control system.

Various configurations were tested in the project as shown in figure 9. The solutions were mounted on the edge of the PV panels as shown on the figure below.

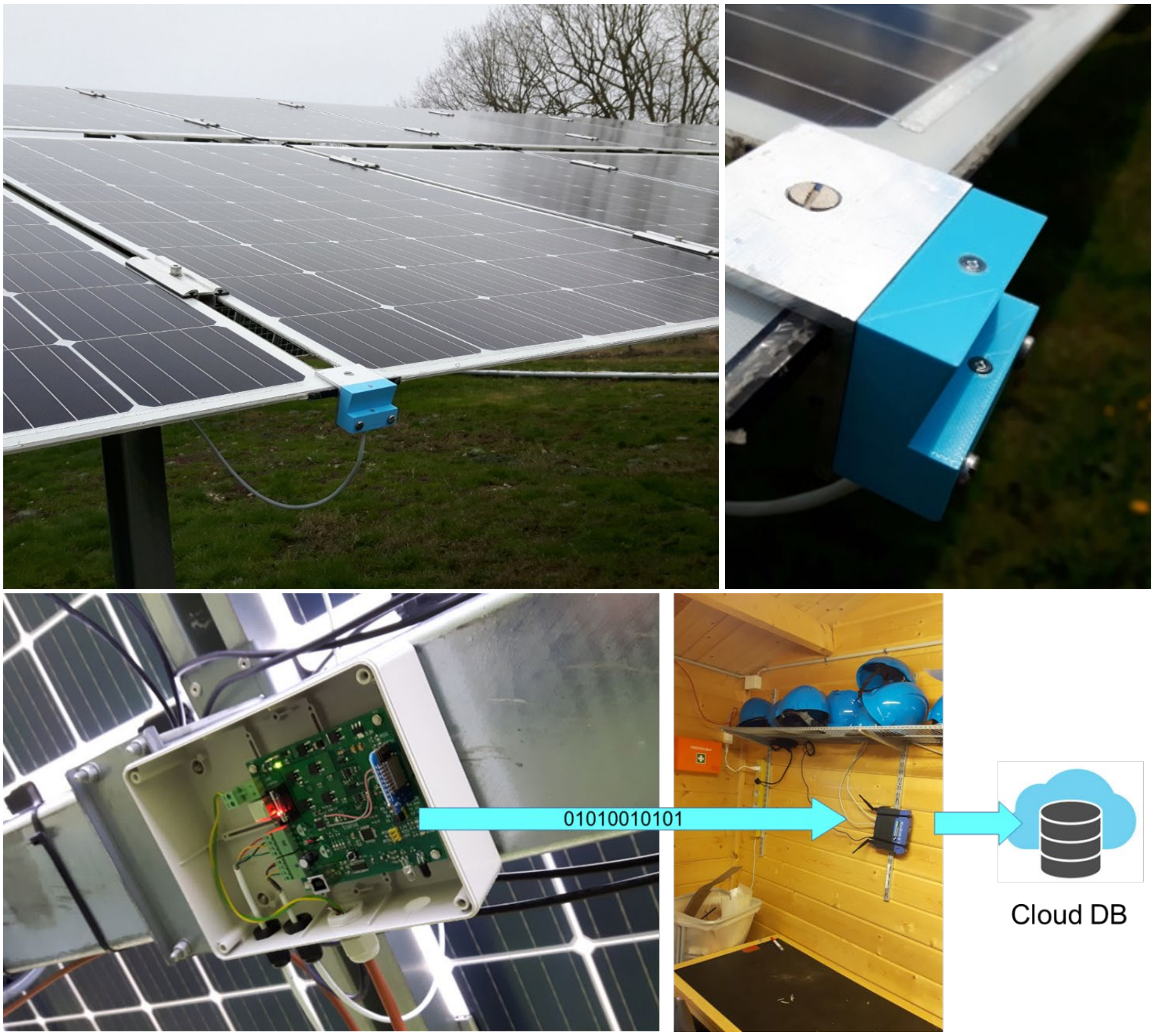


Figure 10 – Mounting of the different sensors on the PV modules and the infrastructure for transmitting measurement data. In the image it's the sensor A concept being tested from figure 9.

The sensors were wired to a control-box fixed to the mounting structure on the back-side of the PV system. The systems worked as control system for the tracking of the 1-axis tracker and transmitted wireless data to a hotspot and the data was collected in a database.

3.5 Use validated simulation tools in the optimizing of components and overall design"

One of the main objectives of the project was to validate the accuracy of bifacial PV simulations; investigate bifacial performance under various installation conditions of such factors as albedo, tilt angle, pitch; and test new bifacial PV technologies. The irradiation measurement on the test-site and the energy production from the panel was therefore compared with data from an on-campus metrological station dedicated for solar resource measurements. Broadband DHI, DNI, and GHI measurements from spectrally flat class A pyranometers are made onsite at the campus solar radiation monitoring station located roughly 400 m south of the bifacial test site (figure 11, left). These high-quality irradiance measurements - in conjunction with ambient temperature and wind speed - are used to create meteorological files for PV simulations of the test site.

Figure 11: Direct normal, diffuse horizontal, and global horizontal radiation measured at the campus solar radiation monitoring station (left). Spectrally flat class C pyranometers installed on the backside of a fixed tilt array T11 (right).

Several simulation tools were used to simulate the performance for the different experiments as shown in the table below and comparing with the real performance:

TABLE 1: Descriptions of the bifacial performance tools compared in this study. All tools implement the Perez transposition model for calculating GPOA,Front irradiance, although some use DNI and DHI for the transposition while others use GHI and DHI. Also, note that the sun position algorithm used among the tools is not always the same.

Bifacial PV Simulation Tool	**Version Used**	**Accessibility**	**$G_{POA,Rear}$ Method**	**IAM Model**	**Electrical Model**	**Thermal Model**
bifacialvf	0.1.7	Open source	2D VF	Physical	N.A.	N.A.
MoBiDiG VF	0.2.4	Proprietary	2D VF	Physical	De Soto 1-diode	Faiman
MoBiDiG Hybrid (RT)	0.2.4	Proprietary	3D RT	N.A.	De Soto 1-diode	Faiman
PlantPredict	8.7.0	Freeware	2D VF	ASHRAE	PVsyst 1-diode	Faiman
pvfactors	1.4.1	Open source	2D VF	Sandia	N.A.	N.A.
PVsyst	7.0.5	Licensed	2D VF	Physical	PVsyst 1-diode	Faiman
Solar Advisor Model (SAM)	2020.2.129	Freeware	2D VF	Physical	De Soto 1-diode	NOCT
SolarFarmer	1.0.187.0	Licensed	2D VF	Martin/Ruiz	PVsyst 1-diode	Faiman

The project partner ISC Konstanz has developed the MoBiDiG model tool for bifacial systems which was compared with other solutions. Results are shown in section 5.

4. Project implementation

The project evolved very well especially since all the partners was already very well acquainted with each others from prior work together. The project had some very precise and well-defined goals that all project participants were highly interested in working with, and the collaboration has therefore proceeded smoothly.

Commercially, European Energy had a great interest in investigating the bifacial solar cell technology on especially 1 and 1.5 axis trackers for use under Danish conditions to ensure that the company can offer increasingly low prices for the construction of national solar parks, as well as in areas of the same latitude. ISC Konstanz is a world leader in the modelling of bifacial photovoltaic systems and with the project received a unique large-scale experimental tool to validate their models. Furthermore, DTU had an overlapping interest and had a special interest in the experimental facilities to fuel research on larger PV systems in DK where the facility is unique of its kind. A large number of student projects at DTU were associated, as the amount of experimental data was overwhelming and posed one of the biggest risks in the project technically, which was then mitigated by raising resources by offering graduation projects to students. Startak's core business is the development and sale of control systems for tracker-based photovoltaic systems and the project provided a unique opportunity to test these on a large scale with access to several data that are not normally available. All of the above factors were crucial for the project to proceed successfully with very few delays.

A major risk of the project was, that its results might not turn out positive towards using bifacial PV systems on trackers in Denmark and modelling hereof even with high accuracy might not turn into any business opportunity. Luckily, the results showed the exact opposite and already in end of the first year of the project the results were used in tenders enabling lower cost of energy based on photovoltaics to the benefit of the danish society.

Another risk to the project was the COVID-19 pandemic which though had close to no impact to the project since most of the infrastructure was established exactly when the pandemic broke out in Denmark and therefore most of the work in that period was data treatment and modelling which was not influenced or delayed by the restrictions.

5. Project results

The BiSun Boost project has been dedicated to the objective of “Boosting the energy harvesting from PV modules by:

1. Capturing backside irradiation
2. Increasing the reflection from the ground
3. Use substructures that track the sun along 1, 1.5 or 2 axis
4. Optimizing the tracker movement according to the actual received irradiation
5. Use validated simulation tools in the optimizing of components and overall design”

All the listed topics have been addressed within this project and all with a successful outcome.

5.1 . Capturing backside irradiation

One fundamental precondition of the project is use of bifacial PV modules. When the project started such modules were still rare and not installed in any large scale commercial application in northern Europe. During the project a several different types of modules have been purchased, tested in the laboratory at Risø, installed and field-monitored for performance during this project. The basic understanding on this new module technology have been greatly deepened, also covering topics as thin glass backsheet or alternative transparent backsheets, encapsulation exchange from EVA to POE and glass backsheet with pre-painted white pattern to enhance reflection. All PV module investigated demonstrated significant bifacial uplift as tested in the lab under standard test conditions, and additional investigations into test-conditions applicable to backside performance which has not been covered by industry standards, had to be addressed in separate sub-research projects (with associated publications). Bifacial gains for the different materials tested can be seen figures 12 and table 2.

Figure 12 shows the daily bifacial gain recorded on all the bifacial arrays at the site from July to September 2019. Data from 24 individual bifacial (6.5 kWp) strings are presented in the plots. Please note that the HSAT monofacial reference systems (T7 and T8) are at a 12 m pitch. Therefore, the bifacial data from systems with a 15 m pitch have been removed, except for T2 where the white tarp and gravel are placed. The data points show the daily average bifacial gain for a given ground cover and substructure. The error bars represent the standard deviation of the daily bifacial gain when multiple strings are tested over the same ground cover. The highest bifacial gains occur under diffuse conditions when the daily DNI dose is < $1 \text{kWh}\cdot\text{m}^{-2}$. Table 2 shows a statistical summary of the bifacial gains observed over the three months. The 7.2% bifacial gain on the HSAT system above grass, versus the 5.9% gain on the fixed tilt system over the same albedo, is likely due to the fact that the HSAT system has a lower GCR and therefore experiences less self-shading.

Figure 12 - Daily bifacial gain of 35 individual 6.5 kWp bifacial PERC systems mounted on 25° fixed tilt (top) and HSAT (bottom) substructures. Results from testing three different ground covers during 2019 are shown.

TABLE 2: Bifacial gain summary during three months of testing at the Risø site.

Substructure	Ground Cover	GCR	Mean Albedo [%]	N Strings Tested	Bifacial Gain Mean [%]	Bifacial Gain Std. Dev. [%]
25° Fixed Tilt	Natural Grass	0.40	22%*	8	5.89	2.65
	Gravel Type 1	0.40	20%†	2	3.73	2.24
	White Tarp	0.40	60%*	2	11.02	3.82
HSAT	Natural Grass	0.28	22%*	8	7.23	3.84
	Gravel Type 2	0.22	26%†	2	9.32	2.87
	White Tarp	0.22	60%*	2	15.37	3.98

* Albedo measured with pyranometers.

† Albedo measured with Si photodiodes (reference cells).

The white tarp had a substantial higher bifacial gain than grass and gravel though was also the most material with most maintenance associated.

In focus was the bifacial gain field performance of these modules where also new methods to determine and describe the irradiation received on the backside of the module with dependence of module location within a substructure (edge vs. central; upper vs. bottom) had to be quantified based on innovative measurement and data-analysis methods (dedicated homebuilt sensor-array had to be installed). Results from measurements of edge and center modules at different configurations can be seen in figure 13 and 14.

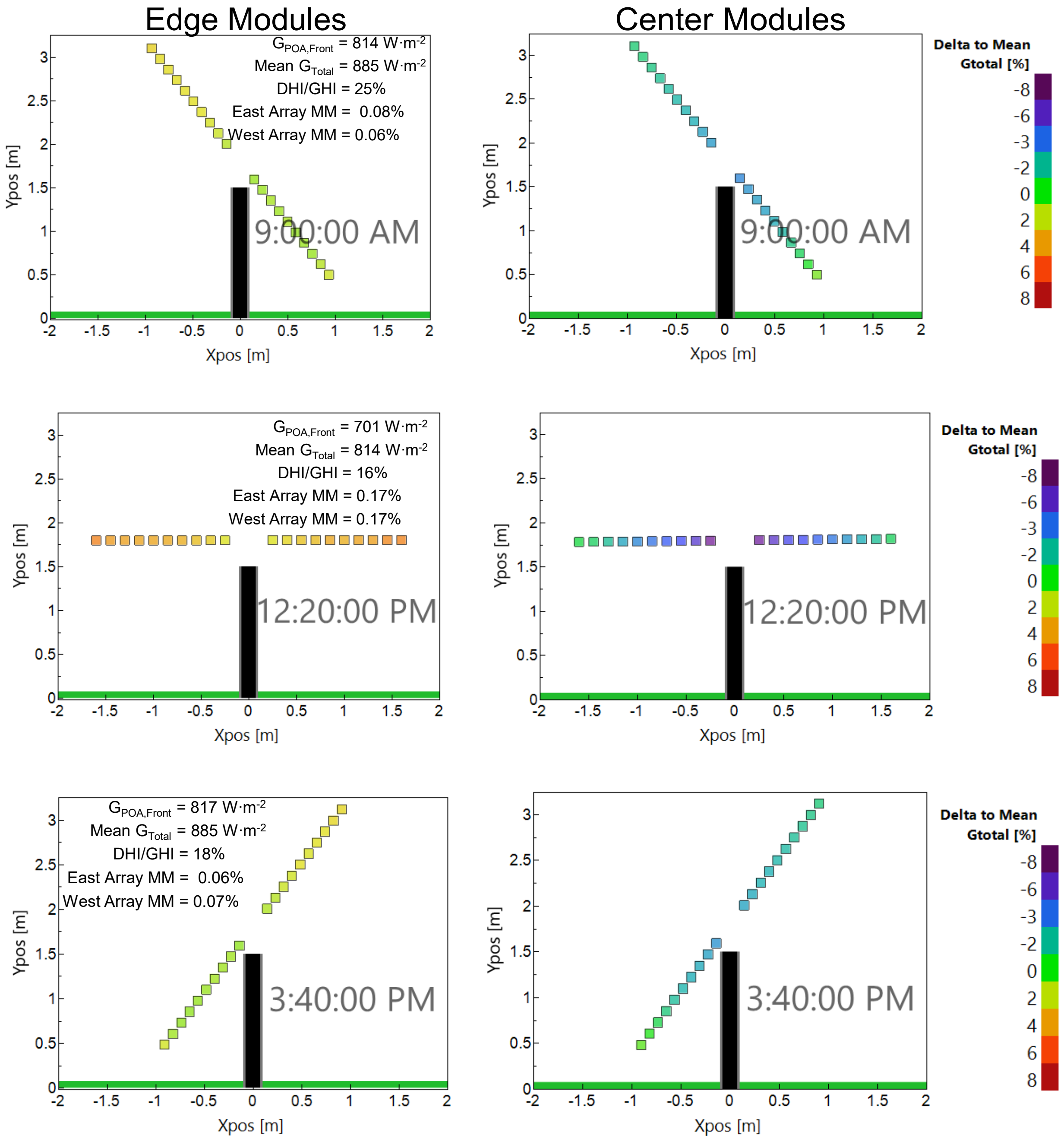


Figure 13. High resolution rear POA measurements on the back of a 2-in-portrait HSAT during a clear-sky day (albedo = 0.22). The left column of images show measurements from the edge panels and the right column shows measurements from the center panels. The dimensions are representative of the tracker position at each timestamp. The array-level non-uniformity induced electrical mismatch for the eastern and western arrays is displayed in the text boxes.

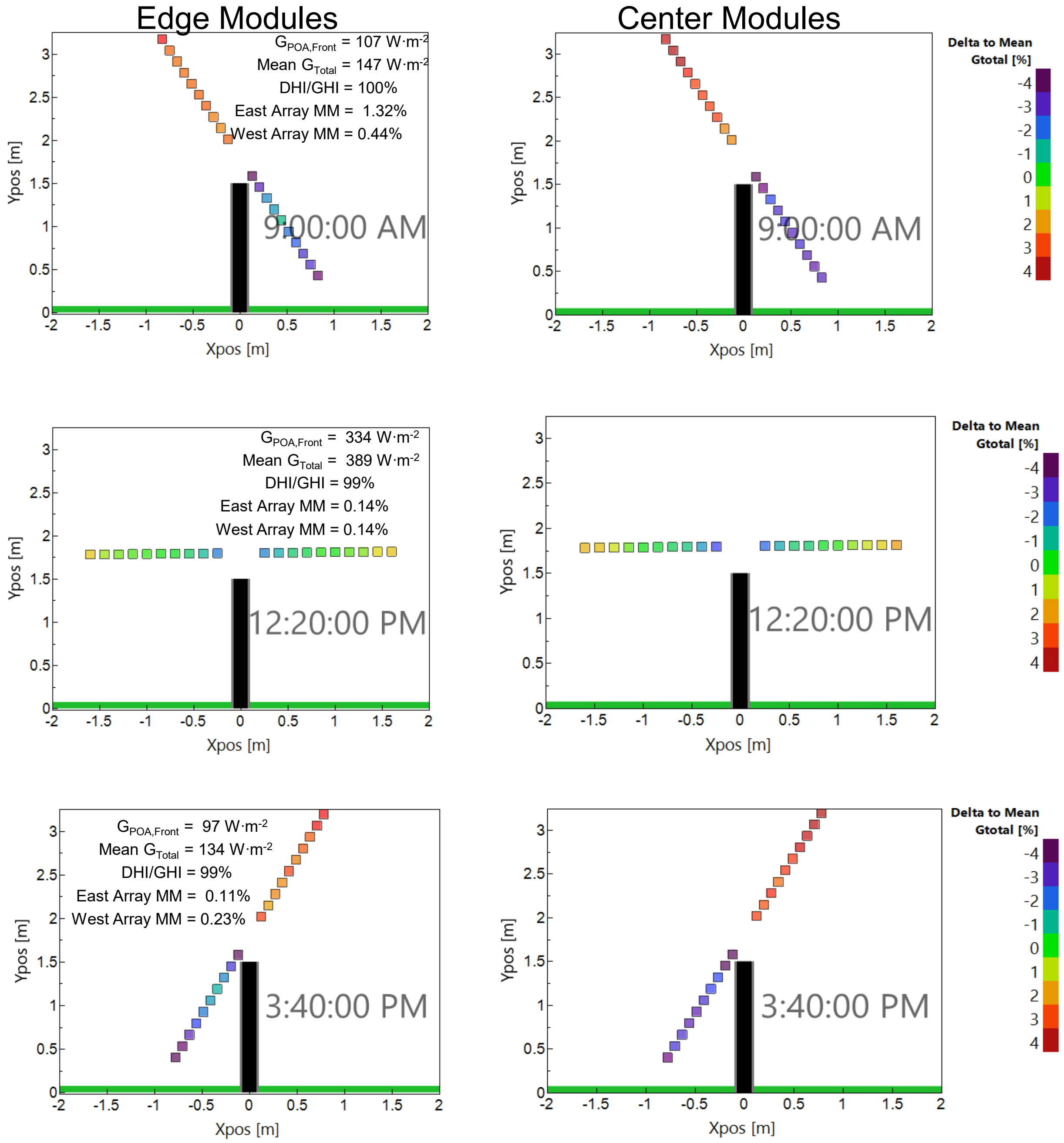


Figure 14: High resolution rear POA measurements on the back of a 2-in-portrait HSAT during a cloudy day (albedo = 0.22). The left column of images show measurements from the edge panels and the right column shows measurements from the center panels. The dimensions are representative of the tracker position at each timestamp. The array-level non-uniformity induced electrical mismatch for the eastern and western arrays is displayed in the text boxes.

For the whole range of tested albedo (from 0.22 to 0.80), the edge modules power mismatch is lower than 0.3%. Studying inner modules now, the albedo reaches a maximum of 1.5% at an albedo of 0.80. Around solar noon, the mismatch increases more steeply with the total irradiance relative standard deviation. Also, the highest mismatch values are reached around solar noon, hence at low tilt.

5.2 Increasing the reflection from the ground

An essential element of the scientific analyses is related to an understanding of the albedo effect, i.e. the reflection of direct and indirect sunlight reaching the ground grass coverage back onto the backside (and front) of the PV panels. This parameter which is dependent on the geometry of shading obstacles, incidence angle and detailed spectral transfer function of the reflector, is quite complicate to calculate. To address these issues optical modelling in terms of raytracing modelling has been developed and compared to faster and more simplistic view-factor models. Model validation based on actual seasonal and spectrally resolved measurements of incoming and reflected light has been carried out. Several different approaches have successfully been tested to identify materials and solutions that may enhance the ground reflection and thereby the energy production. Among these have been foils delivered by the Danish solar technology company Heliac and Swedish manufacturer of white reflecting tarp as well as various types of local sand and gravel. Due to handling complexity during installation and maintenance as well as associated costs it was demonstrated and published that only very minor economical advantages were to be expected by these solutions.

5.3 Use substructures that track the sun along 1, 1.5 or 2 axis

The modules have been installed on 16 full utility-scale trackers, each holding 88 modules. Half of these structures have followed the sun-path from east to west during the day whereas the remainder 8 trackers have been mostly kept at a fixed angle facing south. Thereby it’s been possible to quantify both the tracker gain and the synergy between tracker and bifacial modules that have been able to increase the bifacial gain above the gain observed for standard fixed tilt installations. Also 3 additional smaller substructures each carrying 6 modules on a tracking substructure of both 1.5 and 2-axis have been investigated. Both solutions have as expected demonstrated to perform better than the standard fixed-tilt and Horizontal Singla Axis Trackers, for both mono- and bifacial modules, although the actual substructure solutions may not be immediately useful in a Danish context due to limitations in the mechanical design of the specific solutions tested.

5.4 Optimizing the tracker movement according to the actual received irradiation

A sensor based tracking system was designed and manufactured by Startak to control the movements of the 1,5 axis solar tracker designed by European Energy and installed at Risø. While this system only looked at the front light, it allowed to put the tracker in service in a short time without having to deal with the complex math to take into account the geometry of the solar tracker unique kinematics, where the slope of the axis and the angle around the axis are related by a rigid lever-arm mechanism, powered by a single motor. The tracker followed the Sun movements appropriately during Sunny as well as cloudy weather, increasing the frequency of the movements proportionally to the Sun radiation. Unfortunately, a mechanical failure shortly after the installation of the bi-facial panels on the solar tracker prevented further experimentation. A single axis horizontal tracker (HSAT) was designed and installed shortly after.

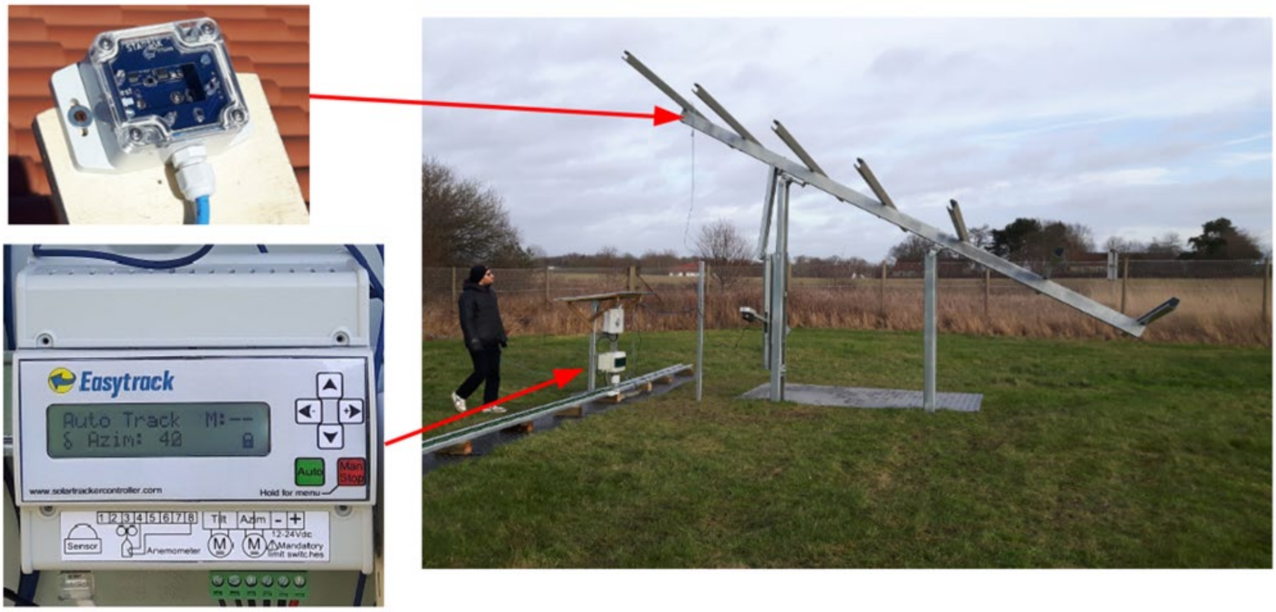


Figure 15 – Startak Easytrack solution installed on the 1.5 axis tracker.

In close collaboration with Startak, a new specially designed sensor solution has been developed and integrated into the control system. The intelligence is capable of overriding a more mechanistic tracking algorithm that aim to position the panel perpendicular to the Sun’s position even when other parts of the sky may demonstrate a high irradiation resource potential (as under overcast conditions where a horizontal positioning of the panels may be advantageous as compared to an east/west orientation).

Thanks to the project we documented that there is a potential for improving the energy production of bifacial single axis solar trackers by using light sensors.

One of the challenges to test the last version of the sensor was to use the information coming from the sensor in the existing control system made by Soltec. Therefore, we have re-designed a control board, that would accept the light sensors inputs, where we can personalize the software to a full extent. So far, we implemented the Sun Position Algorithm, which has shown to be very accurate respect to the Soltec trackers.

The next step for Startak is to manufacture the sensor (version D in figure 9) and develop the hybrid tracking strategy. We plan to install the controller on the EE HSAT at Risø and compare the astronomic to the hybrid tracking strategy in terms of energy production.

As the difference object of the investigation is quite small, comparable to the size of the measurement errors and external imperfections like different level of soiling between two solar trackers, a single solar tracker will be used for the investigation, changing the tracking strategy periodically, like every 60 seconds, from “astronomic” to “bifacial light optimization”.

5.5 validated simulation tools in the optimizing of components and overall design

Based on the extensive collection of data from field-performance during a full year of operation of the many different technologies, it’s been possible to validate both the advanced Ray-tracing and the simpler View factor modelling tools for both optical and electrical performance. Hereby the overall project objective has been successfully met, and it’s now possible to provide solar PV park investors with accurate Energy Yield Assessments based on modelling tools that have been scientifically validated.

5.5.1 Model Input Data

Measurements of the broadband diffuse horizontal irradiance (*DHI*), direct normal irradiance (*DNI*), global horizontal irradiance (*GHI*) and albedo are collected onsite with spectrally flat class A sensors. The *DHI*, *DNI*, and *GHI* are filtered according to recommendations published by the Baseline Surface Radiation Network (BSRN). We have calculated the expanded U_C of each sensor following the Guide to the Uncertainty in Measurement (GUM). Measurement uncertainty (U_C) of pyranometers and pyrheliometers is not a constant value, but rather changes according to the prevailing environmental conditions (e.g. diffuse ratio, sun position, solar variability index etc.). The U_C of the *GHI* is heavily affected by the instrument's cosine response, but only when direct beam light is present. Therefore, the *GHI* increases with decreasing sun elevation angles. We estimate that the expanded (k = 2) U_C of the hourly averaged *GHI* is about ±4.0 % at solar noon on a clear summer solstice, and about ±7.3 % on a clear winter solstice. The uncertainty of the hourly averaged *DNI*, on the other hand, is significantly affected by inter-hour irradiance variability. During hours with little to no variability, the uncertainty of hourly averaged *DNI* is as low as ±2.2 %, but under high solar variability the uncertainty can be as high as ±10.0 %. Such uncertainties of the meteorological data ought to be considered when validating PV performance models, which will be done in a future work.

The seasonal albedo at the site shows little seasonal variation, but monthly average albedo is used in the simulations nonetheless (*min* = 0.192, *mean* = 0.214, *max* = 0.229). Some tools shown in Table 1 are capable of sub-hourly simulations, whereas others are limited to hourly resolution. Hence, all simulations shown here are performed using hourly averages of the *GHI*, *DHI*, *DNI*, ambient temperature and wind speed measured onsite.

For the bifacial performance tools that include an electrical model, we use the following data and assumptions for DC performance, AC performance and DC losses. Low irradiance efficiency is determined by the 1-diode parameters used in each performance tool (fitting of I-V data is only at STC). The inverter performance behavior is taken from the manufacturer's datasheet. In each simulation, the total DC loss applied is 2.3 %. This includes losses from light-induced degradation (LID), wiring, and module mismatch.

5.5.2 Model Validation Data

The electrical monitoring system at the test site is independent of the inverter measurements. Every minute the maximum power current (I_{MP}) and voltage (V_{MP}) of each string are measured. Digital filters are applied to the data to remove noise. The expanded uncertainty of the P_{MP} measurement is 0.5 % of full scale.

5.5.3 Rear Plane of Array Irradiance

The fundamental challenge in bifacial – as compared to monofacial – PV performance modeling is estimating $G_{POA,Rear}$. Therefore, the discrepancies in simulated bifacial energy production are likely to occur in the derivation of $G_{POA,Rear}$ values. Figure 16 shows one year of simulated $G_{POA,Rear}$ values as a function of the average simulated value. The dispersion of simulated values is nearly the same for the fixed tilt and HSAT system. The range of simulated values among software correlates with the frontside irradiance (R^2 = 0.81–0.85). The range of simulated $G_{POA,Rear}$ values is approximately 20 $W \cdot m^{-2}$ at 1000 $W \cdot m^{-2}$ frontside *POA* irradiance. In other words, the range of $G_{POA,Rear}$ is about 2 % of $G_{POA,Front}$. SolarFarmer is highest in this comparison because its integrated approach does not currently consider the obstruction of sky diffuse irradiance caused by neighboring PV rows. Therefore, the ground reflected irradiance between PV rows is over estimated. To our knowledge, this detail is currently being revised and is expected to be implemented in SolarFarmer versions greater than 1.0.191.2.

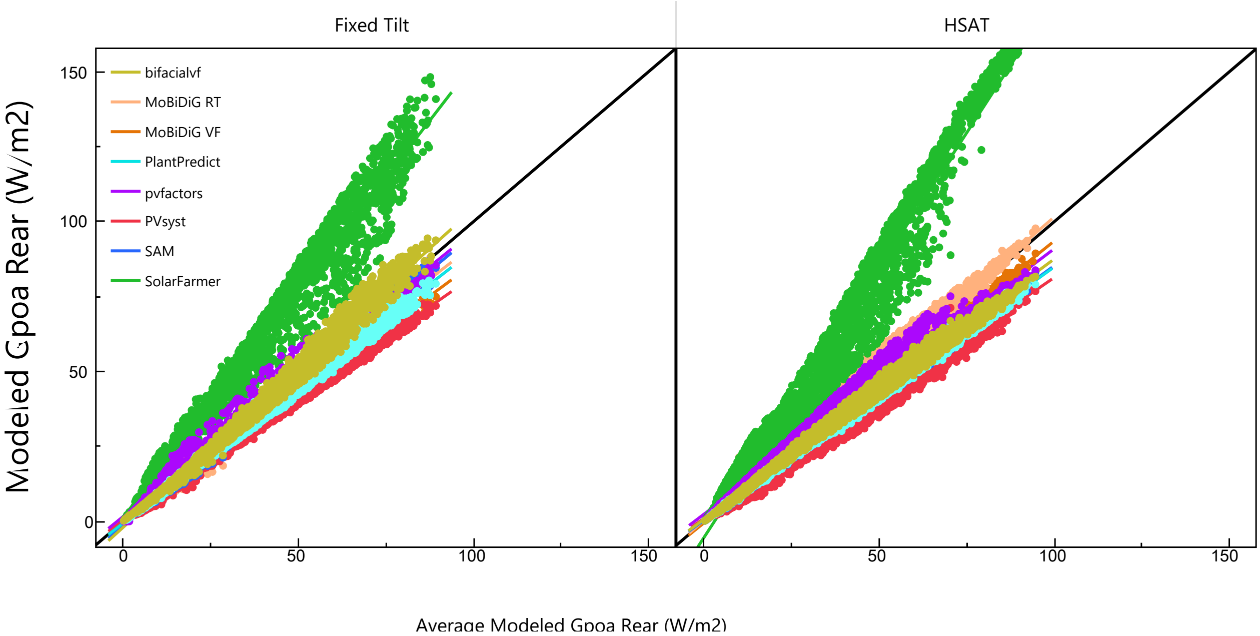


Figure 16 - Simulated rear plane of array irradiance as a function of the average of the eight simulation tools. The solid black line is unity to the average.

A comparison of modeled $G_{POA,Rear}$ during five weeks (Feb 21st – Mar 30th, 2020) where measured $G_{POA,Rear}$ data are available on the fixed tilt and HSAT system are shown in figure 17 and figure 18 respectively. The simulated results include reflection losses at the PV glass-air interface according to the IAM model implemented in each software. The solid black 45° degree lines in figure 17 and figure 18 represent unity to the measurements. The measurements are the average of two EKO MS-40 pyranometers mounted on the backside of the structure: east and west in the case of the HSAT, top and bottom for the fixed tilt. Ray trace simulations have shown that this 12 m distance into the 45 m long array should be sufficient to remove edge brightening effects and to be representative of the semi-infinite assumption that is common among 2D VF models.

We see that trendlines from seven of the eight software agree well to pyranometer measurements. The mean absolute error (MAE) of said group is 2.3–5.2 $W \cdot m^{-2}$. The peak total irradiance (i.e. sum of $G_{POA,Front}$ and $G_{POA,Rear}$) measured during this period was approximately 1000 $W \cdot m^{-2}$. When the magnitude of total irradiance is considered, the MAE of $G_{POA,Rear}$ contributes roughly 0.5 % uncertainty to the bifacial PV modeling chain.

During clear sky (i.e. low diffuse fraction) days, we observed that the bottom pyranometer can receive nearly twice as much irradiance as the top pyranometer. Therefore, the black unity line in figure 17 – which represents the average measurement from two sensors – can at times have error bars on the order of ±15 $W \cdot m^{-2}$. On such clear sky days, seven of the eight software studied give $G_{POA,Rear}$ results that are within that range. In other words, when the vertical spatial non-uniformity of irradiance is considered, the reduced-order complexity 2D VF models perform reasonably well for fixed tilt simulations.

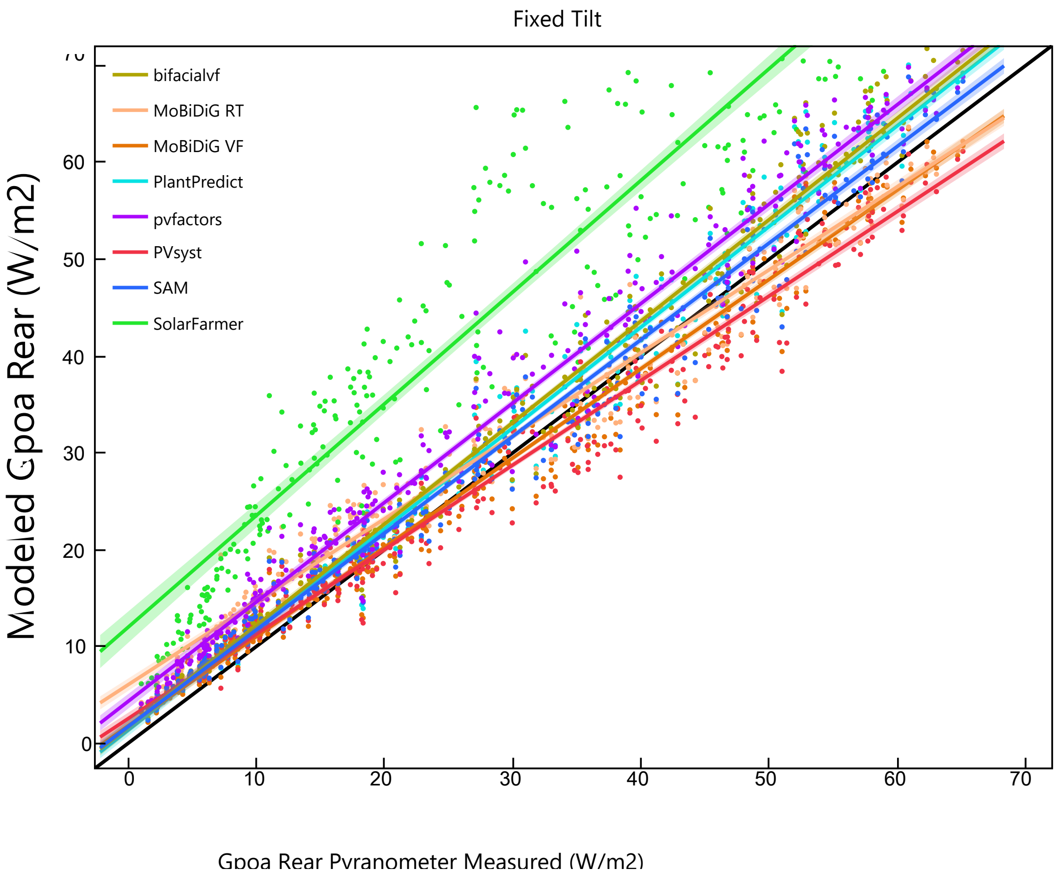


Figure 17: Simulated rear plane of array irradiance on the fixed tilt system as a function of measured for a 5-week period. The solid black line represents unity to the measurements. The shaded areas around each regression line indicate the 95 % confidence intervals. The measurements are made 17 m into T11

The simulated $G_{POA,Rear}$ values on the single axis tracker mostly under estimate the pyranometer measurements. Additionally, the agreement to measurements is not as good as the fixed tilt scenario. The MAE of the 3D RT model and six out of seven 2D VF models is between 3.5–6.7 W·m^{-2}. This result makes sense considering that the HSAT system introduces additional complexity – and thus additional degrees of freedom for error – at two levels. First, the tracker algorithm implemented by the software is introduced to the comparison and second, the VFs in HSAT simulations are calculated for each change in tilt angle whereas the VFs in fixed tilt simulations are calculated once for the entire simulation. Note that the 3D RT simulation over predicts $G_{POA,Rear}$ in the HSAT scenario, which could be due to the fact that this model currently does not incorporate backside IAM losses.

Our $G_{POA,Rear}$ measurements over grass have shown that – under most conditions – the tracker side that is farthest from the ground receives more irradiance than the side closest to the ground. In other words, in the morning the western sensor typically reports higher measurements than its eastern counterpart, whereas the trend reverses in the afternoon. We found that the differences between eastern and western $G_{POA,Rear}$ pyranometer measurements on the HSAT system were not as extreme as differences between the top and bottom $G_{POA,Rear}$ measurements on the fixed tilt system. On a clear sky day, we observed differences on the order of 10 W·m^{-2} between western and eastern pyranometers. Although five of eight software agree within 5 W·m^{-2} of each other, none of the same five tools overlap the measurement uncertainty bars. This result likely could change if alternative backside pyranometer locations were chosen. Therefore, the PV industry could benefit from a standardized best-practice protocol for mounting rear plane of array irradiance sensors in bifacial PV monitoring systems.

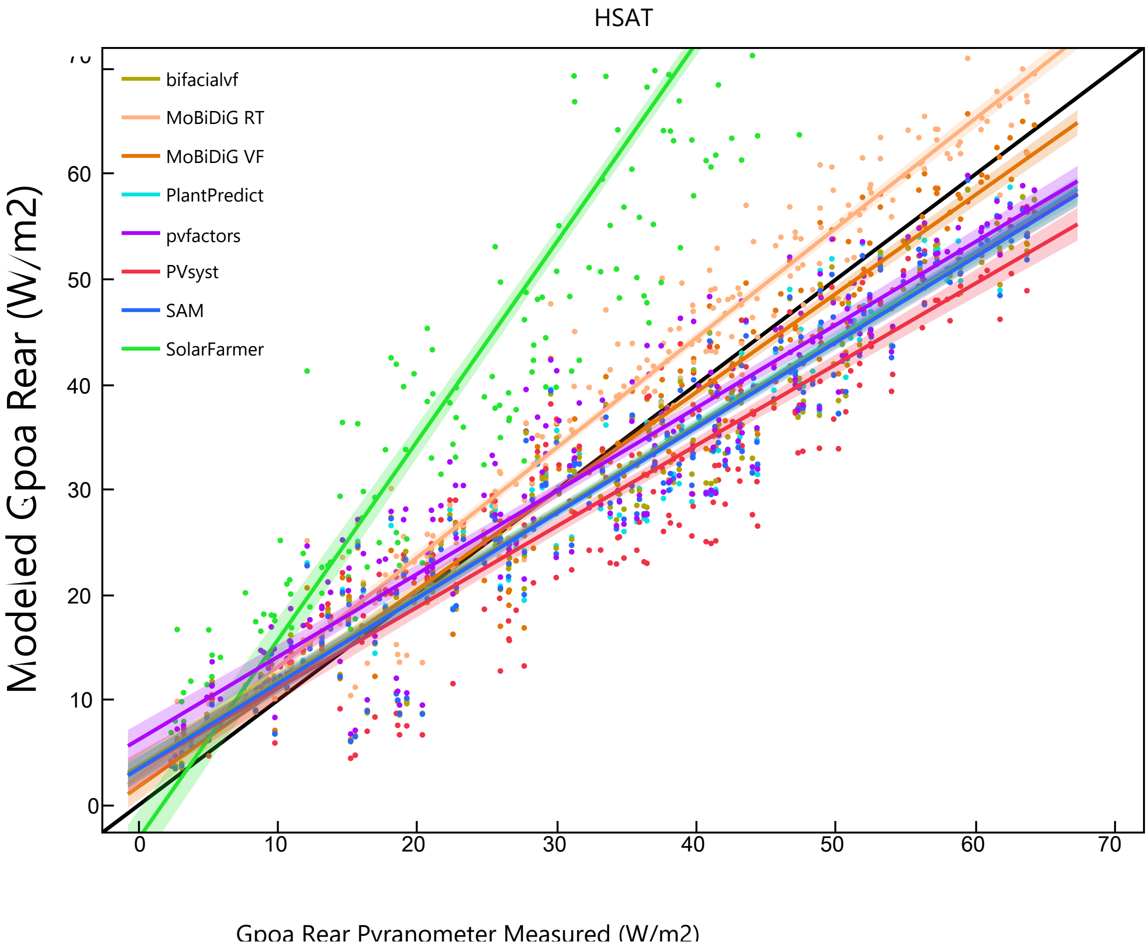


Figure 18 - Simulated rear plane of array irradiance on the HSAT as a function of measured for a 5-week period. The solid black line represents unity to the measurements. The shaded areas around each regression line indicate the 95 % confidence intervals. The measurements are made 12 m into T5.

5.5.4 Bifacial Gain

Figure 19 shows the monthly bifacial gain from software with capability of simulating electrical performance. The black lines in each plot show the results from the DC string measurements. Recall that the measured results are normalized with the I-V measurements made at DTU.

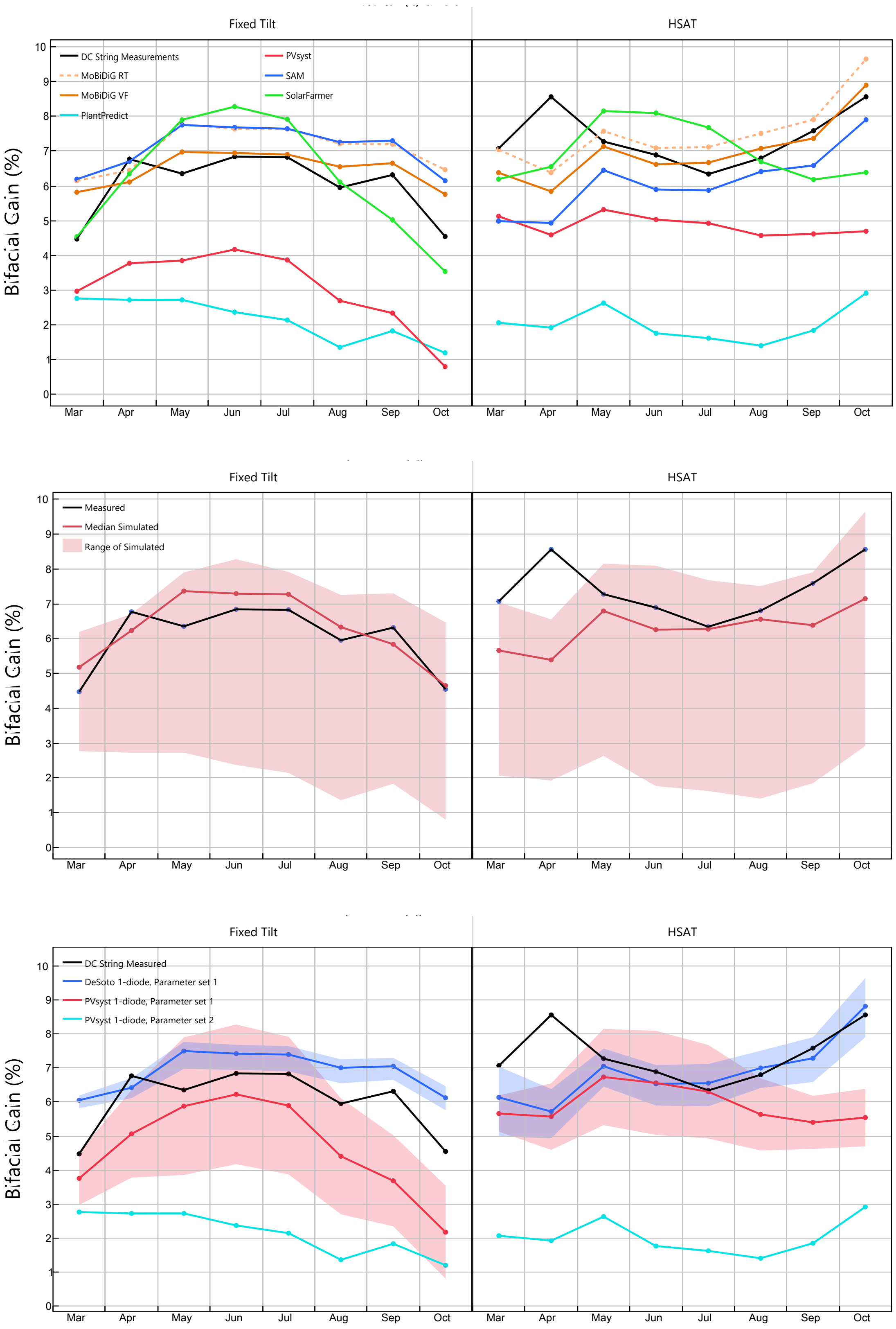


Figure 19: Monthly bifacial gain from DC power simulated by six software and from DC string measurements. The left column shows results from the fixed tilt system, and the right column shows the single axis tracker results. Each row shows the same data but grouped in different ways. The first row shows the results grouped by software (Table 1), the

second row is grouped by measurement/simulation, and the third row groups results by which 1-diode model and parameter set was used.

If the normalization were instead made using the manufacturer's nameplate rating, the measured bifacial gain would be 1.5 % higher than what is shown. This difference can significantly affect the economics of project decisions that are made based on an expected bifacial energy gain.

The results in figure 19 (and figure 20) only include datapoints where sun elevation is greater than 15°. This filter is why November through February are not shown: the sun elevation in Denmark is too low during these months. During winter months, there is a significant amount of inter-row shading on the fixed tilt system and even some shading on the HSAT from surround objects. We chose to exclude periods of severe shade-loss because during such times, the simulated results become heavily affected by the shade-model and by the backtracking model used by each software. It was not this work's objective to assess the performance of the shading and backtracking models.

The measured bifacial gain on the fixed tilt system is between 4.5–7.0 %. Meanwhile, the bifacial gain on the tracker is consistently higher - between 6.3–8.5 %. This is likely due to the wider 12 m spacing between rows on the HSAT (GCR = 0.28) versus the narrower 7.6 m spacing on the fixed tilt system (GCR = 0.4), which creates more self-shading within the inner rows of the PV park.

The simulated bifacial gain values mostly follow the trends of the measurements, except for April when a small spike in bifacial gain is observed on both the fixed tilt and HSAT system. Since the measured albedo data from April 2019 were higher than any other month studied here (0.229), and since the spike in bifacial gain is observed in both systems, it could be that the measurements from the onsite albedometer were not representative of the overall site during this month. If this is true, then it could mean that a best-practice for bifacial PV monitoring systems is the implementation of redundant albedometers throughout the park – similar to the well-known best practice for frontside plane-of-array pyranometers.

One notable outcome in figure 19 is the results from SolarFarmer are frequently within 1 % of the measured bifacial gain, despite the deviations in $G_{POA,Rear}$ shown previously. This is due to the fact that the rear irradiance constitutes 8 % or less of the total irradiance for half of the timestamps studied here. Of course, the higher the albedo and/or the higher the module bifaciality factor, the larger influence modeled $G_{POA,Rear}$ is expected to contribute to the overall model accuracy.

The bottom row of figure 19 shows the simulated bifacial gains grouped into which of the two electrical models was used and – in the case of the PVsyst 1-diode model – which of two parameter sets was used. Recall that the parameters used within each electrical model were determined by a fit to measured I-V data at STC – i.e. low irradiance measurements were not considered. We found that the six parameters used in the DeSoto 1-diode model (used by MoBiDiG and SAM) more accurately predicted measured low light performance than did the five parameters used in the PVsyst 1-diode mode (used by PVsyst, PlantPredict and SolarFarmer). Therefore, we believe this is why the software that used the DeSoto 1-diode model, more accurately predicted the measured bifacial gain. The reason there are two parameter sets used among software implementing the PVsyst 1-diode model is that PlantPredict sets limits based on what its developers consider to be realistic. Specifically, series resistance of the module must be ≥ 100 mΩ. Due to this restriction, the series resistance used in the PlantPredict bifacial module file was ten times higher than the 10 mΩ extracted from fitting the I-V data, and used in the PVsyst and SolarFarmer models. Therefore, the modeled voltages of bifacial systems in PlantPredict were lower than in PVsyst and SolarFarmer, which resulted in the lowest simulated bifacial gain of all software.

Figure 20 shows the simulated bifacial gain according to the $G_{POA,Rear}$ to $G_{POA,Front}$ ratio. The modeled results show better agreement with each other when the bifacial gain is calculated using the optical gain, as opposed to using the simulated energy.

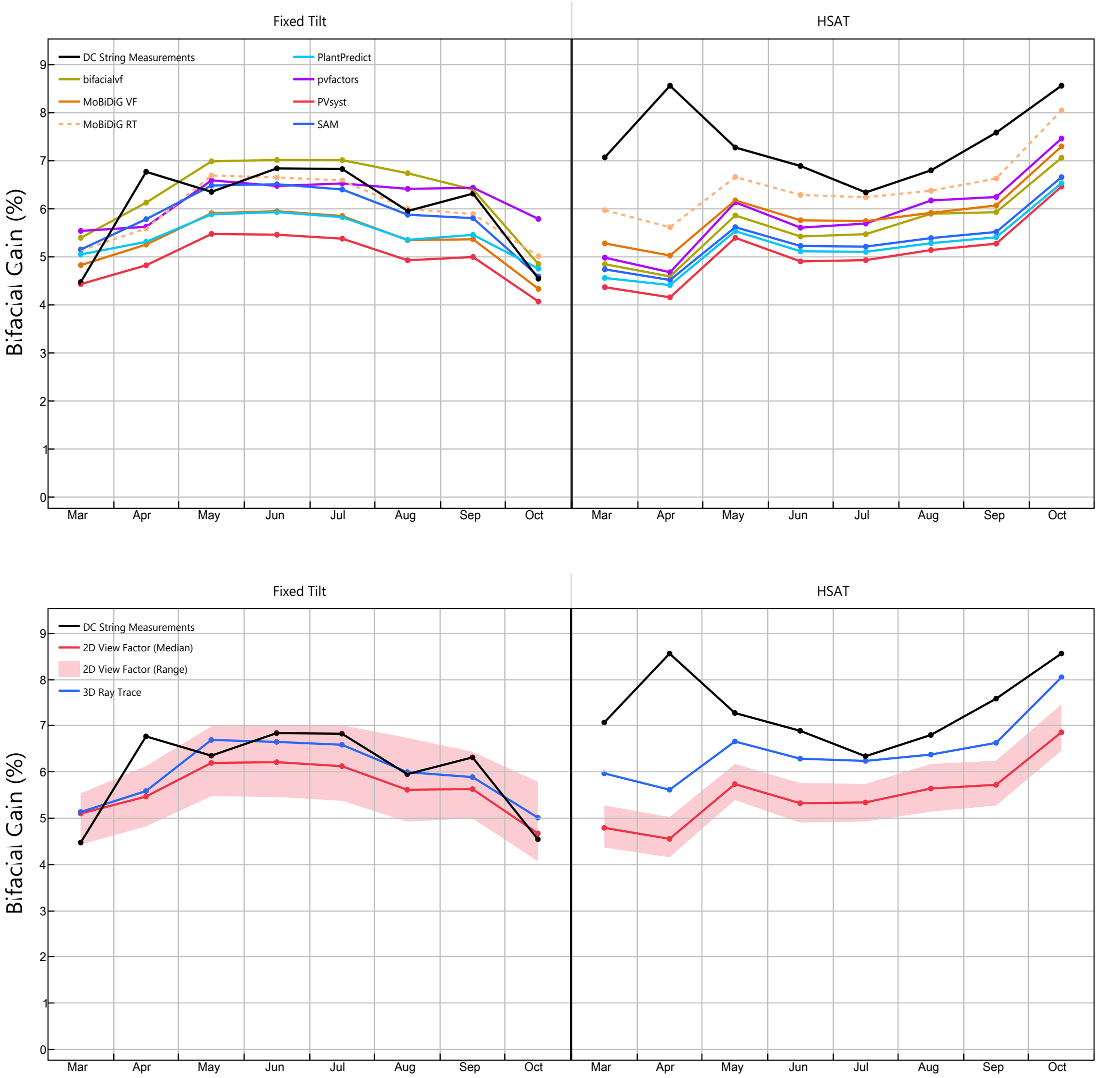


Figure 20 - Monthly bifacial gain from modeled rear to front side irradiance ratios from seven software and from DC string measurements. The left column shows results from the fixed tilt system, and the right column shows the single axis tracker results. Both rows show the same data but grouped in different ways. The first row shows the results grouped by software (Table 1), the second row is grouped by whether a 2D view factor or 3D ray trace approach was used to calculate back side irradiance.

The agreement among software shown in figure 20 is within 2 % or better for both system types. The bottom row of figure 20 shows the results grouped by whether $G_{POA,Rear}$ is calculated using a 2D VF or 3D RT approach. When visualized in this manner, it becomes clear that the 3D RT approach follows the measured bifacial gain most closely for the HSAT simulation - within 0.5 % of measurement for most months. The 3D RT model also matches well – typically within 0.5 % – to bifacial gain measurements on the fixed tilt system. However, 2D VF models such the one integrated in SAM compared equally well to field measurements. Indeed, the measured bifacial gain shown in figure 20 are influenced by the value of $Bifi_{loss.}$ The static $Bifi_{loss}$ values used here, in actuality change dynamically over the day with the prevailing conditions. However, all the software tested here have the capability to use only a single value. This simplification offers room to improve the accuracy of the bifacial PV performance software used in industry today.

We have assessed eight bifacial PV performance tools to $G_{POA,Rear}$ and to DC P_{MP} measurements made at the test site at Risø. Our results show that state-of-the-art bifacial performance models add **~0.5% uncertainty** to the PV modeling chain. This finding was demonstrated using $G_{POA,Rear}$ measurements, but in a future more detailed report, we will show how the modeled and measured DC P_{MP} substantiate this finding.

Our results further show that – for the site investigated – 2D view factor fixed tilt simulations are within ±1 % of measured monthly bifacial gain. Simulations of single axis tracker systems are less accurate with 2D view factor simulations within approximately 2% and 3D ray tracing within approximately 1% of measured bifacial gain, respectively. These results are published with the motivation that similar studies from other parts of the globe are published, and a comprehensive review of those studies be made in the near future.

5.6 Commercial outcome

Based on the positive and conclusive outcome of this project, it's been possible for European Energy to commercialize the key findings while converting two utility scale PV projects installed during 2020 into tracker projects with bifacial modules. The realization of these two Danish projects have been possible a.o. due to the confidence into the simulated energy yield of the trackers and bifacial modules, as no other PV projects of similar characteristics have ever been built in northern Europe.

After the initial first-mover introduction of bifacial trackers in Denmark, and after release of commercial validated simulation tools, it's now open to any project developer active in Denmark or similar markets, to establish projects based on similar technology, based on the general technology de-risking actions taken by European Energy.

Thanks to this project Startak have designed, produced and tested a few versions of the control system and data acquisition system, that allowed Startak to make the first sales. This sales allowed Startak to produce profit and receive additional funding for 2021 which together allowed to open a position for a new hire in 2021 (software developer).

The control system prototype developed by Startak during the EUDP project has been used to control the movements of a horizontal single axis tracker developed by European Energy and installed at Risø in June 2020. The tracker has been working for about 6 months so far, and the measurement database shows it has been working reliably.

The graph below shows the position of the solar tracker using Startak's controller in blue, and the Soltec controller in red and green. Besides the different maximum slope and different backtracking strategy, the important information of this chart is that there is a perfect agreement between the calculated reference tracker position in black, and the measured tracker position in blue (Startak controller on European Energy tracker), red and green Soltec tracker and controller.

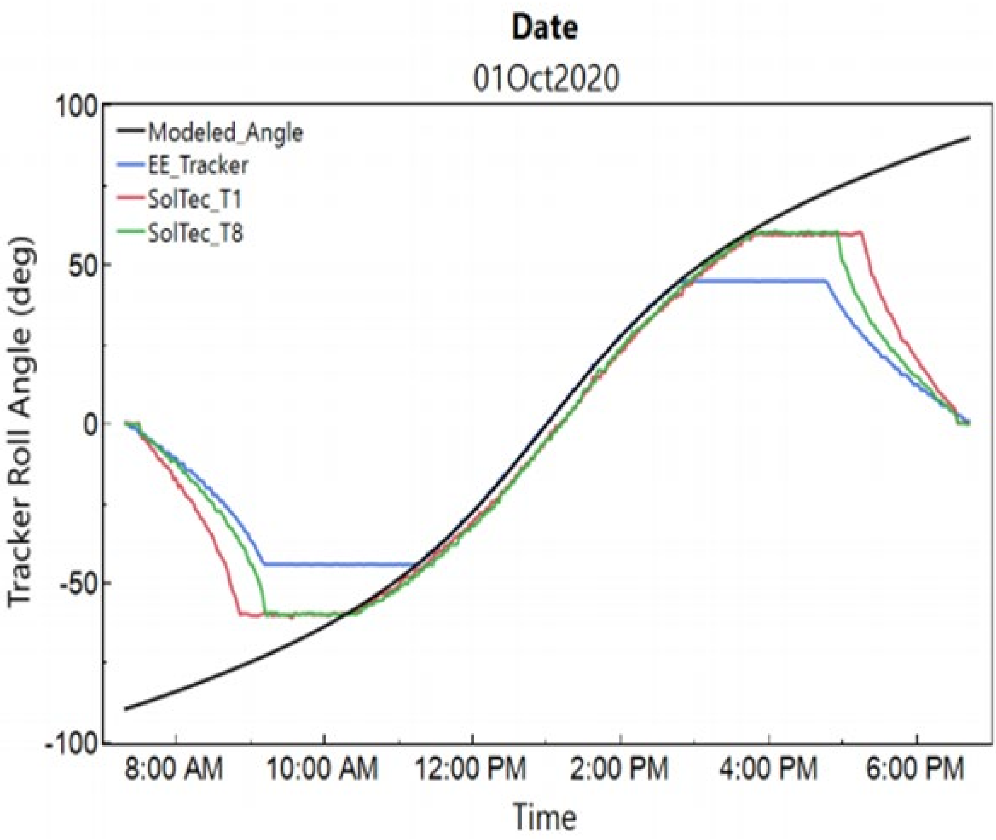


Figure 21 - Position of the solar tracker using Startak's controller in blue, and the Soltec controller in red and green

In November 2020 European Energy made and installed four additional solar trackers of their design in a commercial solar power plant in Harre, using the control system from Startak for HSAT.

It is the intention of European Energy to continue the development of the HSAT, and to employ Startak controller. It is intention of Startak to keep improving the solar tracking control system and produce it for solar tracker manufacturers.

5.7 Dissemination

The overall general outcome of this project has been published in a number of web-news sites, since the inauguration of the Risø test-site were done under supervision of the Danish Energy Minister and headmaster of DTU in October 2018.

The latest news is from January 2021, where a series of articles dedicated this EUDP project will be published on www.Energywatch.dk.

As for the scientific publications a list can be seen below:

1. Riedel, N, Berrian, D, Alvarez Mira, D, Aguilar Protti, ACD, Thorsteinsson, S, Poulsen, PB, Libal, J & Vedde, J 2020, Large-Scale Bifacial PV Test Field Performance Compared to Simulations Using Commercially Available Software, Research-Based and Open Source Tools. in *Proceedings of 37th European Photovoltaic Solar Energy Conference and Exhibition.* pp. 1324-1329, 37th European Photovoltaic Solar Energy Conference and Exhibition, 07/09/2020. https://doi.org/10.4229/EUPVSEC20202020-5CO.10.4

2. Riedel-Lyngskær, N, Berrian, D, Mira, DA, Aguilar Protti, ACD, Poulsen, PB, Libal, J & Vedde, J 2020, 'Validation of Bifacial Photovoltaic Simulation Software against Monitoring Data from Large-Scale Single-Axis Trackers and Fixed Tilt Systems in Denmark', Applied Sciences, vol. 10, no. 23, 8487. https://doi.org/10.3390/app10238487

3. Riedel, N, Aguilar Protti, ACD, Jakobsen, ML, Pedersen, HC, Thorsteinsson, S, Poulsen, PB, Santamaria Lancia, AA, Benatto, GADR, Demurtas, G, Arrighi, F, Berrian, D, Libal, J, Barnard, D & Vedde, J 2019, 'The Outdoor Bifacial PV Testing Facility and Technical University of Denmark', 2019 12th PV Performance Modeling and Monitoring Workshop, Albuquerque, United States, 22/10/2019 - 23/10/2019.

4. Riedel, N, Aguilar Protti, ACD, Jakobsen, ML, Pedersen, HC, Thorsteinsson, S, Poulsen, PB, Santamaria Lancia, AA, Benatto, GADR, Demurtas, G, Arrighi, F, Berrian, D, Libal, J, Barnard, D & Vedde, J 2019, 'The Outdoor Bifacial Test Facility at Technical University of Denmark', Bifacial PV Workshop, Amsterdam, Netherlands, 16/09/2019 - 17/09/2019.

5. N. Riedel-Lyngskær, D. Berrian, A.A. Protti, D. Alvarez Mira, P.B. Poulsen, J. Libal, J. Vedde, Comparing Different Software Models for Estimating Bifacial Energy Gain. PEARL PV (CA16235), Webinar 01-12-2020, Pearl PV Webinar: Modelling of PV Systems – Challenges and Comparisons.

6. N. Riedel, Reducing Bifacial PV Project Risk Through Accurate Simulation, International summer school on organic, perovskite and building integrated photovoltaics, August 24-28, 2020.

7. Riedel-Lyngskær, N.; Petit, M.; Berrian, D.; Poulsen, P.; Libal, J.; Jakobsen, M. A spatial irradiance map measured on the rear side of a utility-scale horizontal single axis tracker with validation using open source tools. In Proceedings of the IEEE 47th Photovoltaic Specialists Conference (PVSC), Calgary, AB, Canada, 15 June–21 August 2020

8. Riedel-Lyngskær, N.; Nørgaard, P.; Vedde, J.; Poulsen, P.; Jakobsen, M. A, 'The value of PV on horizontal east-west trackers compared to fixed tilt structures in Denmark' has successfully been accepted for publication in IET Renewable Power Generation in 2021.

6. Utilisation of project results

As described above, commercialisation of project results has already been achieved and results are now considered generally assessable and useful for any PV project developer active in Denmark.

At least for European Energy the clear project outcome has resulted in a strategic change where all future PV projects will be based on bifacial PV modules. This result, in connection with general attractive market conditions, underlines the focus on European Energy on a strong growth of PV project in Denmark and abroad, also resulting in a steady increase of professionals engaged in development, engineering, design and construction of PV projects with more than 15 employees in 2020 alone.

The competition in these markets is strong as the number of large and serious competitors is increasing once the activities of European Energy develop and expand into more markets. Still it’s considered that European Energy do possess a strong in-house engineering capability as well as useful IP, which should ensure a successful double-digit growth for the coming years.

7. Project conclusion and perspective

The overall conclusion of the project is very positive. European Energy and project partners have successfully completed the EUDP BiSun Boost project according to the original plans and ambitions. A strong, close, and well-functioning collaboration between research institutions, dedicated sensor and controller manufacturer and a PV project developer, have been instrumental in reaching these goals. The test-site at Risø and close collaboration with competent, engaged, and flexible scientific professionals, at both DTU as well as ISC Konstanz and Startak, have demonstrated to be a very fruitful team and provided important scientific results already taken into commercialisation.

PV technology development is moving fast. Today bifacial modules are no long something special, but considered mainstream and will dominate the utility scale marketplace already within a few years. Other elements of the technology development are already moving ahead. PV module sizes have increased significantly. In 2018 when the test site at Risø were constructed, the typical size of a PV panel for utility scale project were 1.6 m^2 and the power 300 W. This year European Energy plan to install more than 1 million PV panels, each more than 3 m^2 in size and a power close to 600 Wp. Such significant changes introduce additional changes to the standard engineering design for both mechanical substructures and electrical component as current and voltage in the electrical strings will operate under different regimes. Also new cell technologies are being introduced and soon it’s also required to consider solar cells with a tandem-configuration, where two layers must be matched such that energy can be harvested form two different peak wavelengths within the solar spectrum on the same device.

In order to stay aligned with this development, it’s considered very likely that the consortium might engage in other energy technology development or demonstrations projects together.