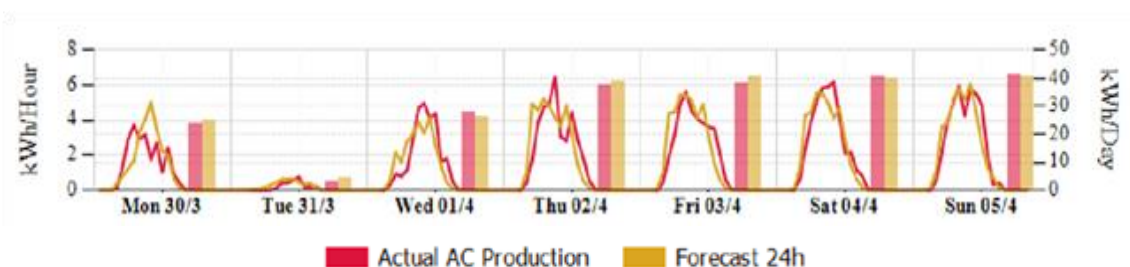


# Solar-PV-Meter

Cloud-service analyzing the efficiency of solar panel systems and delivering forecasts for AC-production



# Final report

## 1. Project details

<b>Project title</b>	Solar-PV-Meter
<b>Project identification (program abbrev. and file)</b>	64012 - 0108
<b>Name of the programme which has funded the project</b>	EUDP-2012-1
<b>Project managing company/institution (name and address)</b>	EXERGI
<b>Project partners</b>	EXERGI, DMI and Solar Unicare
<b>CVR</b> (central business register)	33501528
<b>Date for submission</b>	10.7.2012

## 2. Short description of project objective and results

### English:

The objective of the Solar-PV project was to develop:

- A weather and solar radiation forecast services - *Danish Meteorological Institute (DMI)*
- An online Web-services ("Big Data") analysing the efficiency of solar PV plants, based on AC-production and weather data, including the effect of local shadings from buildings, trees etc.- *EXERGI/Solar-PV-Meter<sup>1</sup>*
- A forecast service estimating the solar AC-production 48 hours ahead based on efficiency analysis and weather forecast services - *EXERGI/Solar-PV-Meter*
- A forecast for all plants in a geographical area, a grid or a portfolio of PV's, based on data for a sample of plants in combination with statistics – *EXERGI/Solar-PV-Meter*

These services are developed, but the last one – algorithms for region/grid forecast – has not been implemented and tested.

### Dansk sammenfatning:

Projektets formål har været at udvikle følgende services

- Geografisk specifikke vejrprognoser som indbefatter prognoser for den direkte og diffuse solstråling - *DMI*
- En online Web-services (Big Data) som analyserer den faktiske effekt af solcelleanlæg, herunder effekter af lokale skygger fra bygninger træer osv. - *EXERGI/Solar-PV-Meter*
- En prognosetjeneste der leverer timeprognoser for solcelleanlægs AC-produktion 48 timer frem i tid – *EXERGI/Solar-PV-Meter*
- En algoritme som leverer en samlet timeprognose for elproduktion for et geografisk område, el-distributionsnet eller portefølje af solcelleanlæg, baseret på DC-prognoser og nøgletal for en gruppe af solcelleanlæg – *EXERGI/Solar-PV-Meter*

Disse services er udviklede i projektet. Implementering og forsøg med prognose for samlet AC-produktion for netområde el.lign. afventer dog adgang til data for flere anlæg.

<sup>1</sup> The company 'Solar-PV-Meter' has all rights to software and developed methods.

### 3. Executive summary

Solar Photo Voltaic (PV) panels deliver a smaller - but fast growing - contribution to the total Danish and European electricity production. There are 100.000 solar plants in Denmark with a total capacity of 800 MW. Energinet.dk<sup>2</sup> expects that the capacity would grow to 2.115 MW ultimo 2025.

Private homes, local authorities, companies and utilities all invest in solar PV panels. The actual framework makes it beneficial to invest in solar PV panels *if* the primary part of the produced electricity replaces power bought from the grid.

The production cost per produced kWh, is below the consumer price for electricity. By producing electricity for your own use, you can save tariffs and taxes for electricity. Selling solar PV-power to the grid – with the actual framework - gives an income per kWh that could be as low as 20 pct. of the consumer prices (Denmark).

For a solar PV investor, it is important that the Solar PV plant use high efficiency panels and inverter, that the panels have a proper azimuth and tilt towards the sun, and a minimum of shadings from neighbour buildings, trees etc. Finally yet importantly, the solar plants power production should match the consumer profile, eventually supported by storage in batteries.

Solar PV production can give problems for local grids – as seen in Germany – when peaks of solar generated power reaches low voltage grids. A forecast service on grid-level would help the grid/DSO-responsible to be proactive in these situations.

The project consists of two parts:

First solar energy and weather forecast delivered for any location in Northern Europe 48 hours ahead, based on the newest DMI forecasts of direct and diffuse solar radiation.

Secondly, Solar-PV-Meter provides an analytic services including forecast. The electricity production is analysed and monitored on the Solar-PV-Meter Cloud services. Based on the meteorological forecasts, solar position, panel's direction relative to the direct solar beam and calculated efficiency and a new shading and reflection index, the Cloud-services presents energy efficiency analysis and a forecast for expected hour-production 48 hours ahead.

Solar-PV-Meter would launch a special offer to grid companies where a forecast is calculated for total solar PV-production in a specific geographical area, grid or for a portfolio of plants. The "upscale" function uses data for a smaller number of solar plants in combination with statistics for installed plant, total production, or net deliverers to grid etc.

#### Example: Monthly Solar Statistics

STATISTICS	April 2016	Last 12 months
Solar Hours	457 h	4,856 h
Total Solar Energy *	5,378 kWh	60,858 kWh
Projected Solar Energy **	2,846 kWh	29,067 kWh
AC Production kWh	346 kWh	3,287 kWh

\*) Total energy in solar radiation, if solar panels where perpendicular towards the sun in every hour

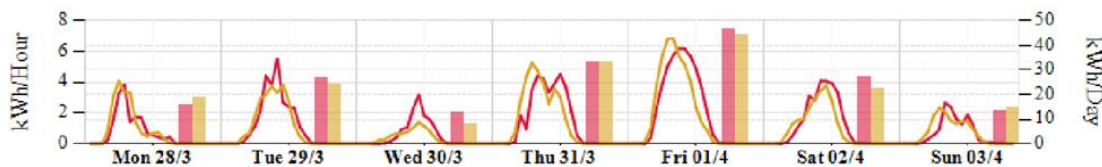
\*\*) Total energy in solar radiation that hits the panel with its fixed installation angles (azimuth and panel tilt)

<sup>2</sup> Energinet.dk <http://www.energinet.dk/DA/KLIMA-OG-MILJOE/Miljoerapportering/VE-produktion/Sider/Sol.aspx>

### Example: Monthly Efficiency analytics

	April 2016	Last 12 months
Potential DC-production based on actual calculated efficiency	715 kWh	8,356 kWh
Losses due to projection – since panels not 90° against the sun	-337 kWh	-4,374 kWh
Losses due to shadows and reflections	-22 kWh	-607 kWh
Losses due to inverter conversion	-11 kWh	-89 kWh
<i>Actual AC production kW/h</i>	<i>346 kWh</i>	<i>3,287 kWh</i>

### Example: Forecast and actual AC-production



Solar-PV-Meters data export-function makes it easy to use forecast for power production in control systems for flexible electricity use and battery storage.

Producers and deliverers of high quality PV plants could use the concept to document - or even guarantee - the *efficiency* of a plant installation (but not the solar radiation).

\*

Where traditional solar web-monitor systems typically only show the actual AC-production, the ambition with Solar-PV-Meter is to provide the owner with information regarding the actual efficiency and losses, and evaluate losses due to nearby shading trees or flagpoles. The new forecast for power production next day should help the solar panel owners to optimize the use of electricity and battery storage control.

The two new separate services from the Danish Meteorological Institute (DMI) and Solar-PV-Meter should make it easier to

- Analyse the actual efficiency of their installation based on local and valid data for weather and solar radiation in combination with advanced algorithms,
- Optimize the use of electricity and battery systems, based on forecast for AC-production
- Control low voltage grids and portfolios of solar PV plants, based on statistics and forecast for a smaller group of solar PV panels.

### The next step: Big scale test and market introduction

Based on the positive outcome of this project, the market potentials and lack of competitors, Solar-PV-Meter plans to open [www.Solar-PV-Meter.com](http://www.Solar-PV-Meter.com) for panel owners and grid companies in North Europe in summer 2017.

Solar-PV-Meter are looking for partners and finance to implement a big scale test including the 'upgrade' forecast for all solar PV's in a grid, and market introduction of the Cloud-services.

### 3. Project objectives

#### 3.1 Team EXERGI, DMI and Unicar Solar

The project and the agreement between the project participants defines the tasks as well as the ownership of the developed services.

*Danish Meteorological Institute (DMI)* is responsible for the weather and solar forecast services that includes several internal analytic tools, satellite monitoring's etc. This is a separate services form DMI.

*EXERGI/Solar-PV-Meter* is responsible – and owner – of the algorithms and Web services analysing the efficiency of solar plants, clearness/shadow index and produces forecasts for hour-production 48 hours ahead.

EXERGI has bought consultant assistance from DMI, and the IT-consulting companies 1508 and Rehfeld to develop and test algorithms and Web-services.

*Unicare Solar* has been responsible for the demonstration plants.

*EXERGI* has been project leader.

The work is carried out in three phases:

- 1) Services that delivers weather and solar radiation forecasts for a location
- 2) Algorithms tested on detailed data - HIRLAM ensemble model and satellite observations
- 3) Cloud services with algorithms that automates the calculation of efficiency and forecast

#### *Phase 1: Services that delivers weather- and solar radiation forecasts for a location*

Danish Meteorological Institute (DMI) establish a forecast concept based on the DMI HIRLAM ensemble model. The prognoses describe the expected direct and diffuse solar radiation for the next 48 hour, with update every 6 hours.

To special analysis in phase 2, DMI included satellite data and shorter time steps.

#### *Phase 2: Algorithms tested on detailed data - HIRLAM ensemble model and satellite obs.*

DMI and EXERGI establish a model setup to see if it was possible to develop a stable model that handles to total chain from solar ration to DC and AC power production, including solar positions, temperature, panel positions and the effect of local shadings from building, trees etc. In these analysis data for satellites and shorter time steps (15 min.) where used.

The result is a model that gives a clear relation between input and output data.

#### *Phase 3) Cloud-based services with algorithms that automates the calculation of efficiency key figures and forecasts*

The last step was to transform the test model to a Cloud-service, with full-automatic calculations of efficiency and local shadings. The Cloud services did not have access to satellite information, and forecast estimates based on hour prognoses for weather and solar radiations.

The transformations from "laboratory" calculation tests to fully automated calculations on less detailed data have been a big challenge in the project. In top of this, the Cloud services should produce qualified forecast for AC-production 48 hours ahead for each plant.

There has been used a lot of resources and test to develop different methods that gives reasonable accurate estimate of efficiencies and a 48 hour forecast services during to project. Methodical and technical challenges in phase 3 has caused a severe delay before qualified results was obtained.

### **3.2 Results**

DMI has launched a solar forecast service that includes forecasts of both the direct and scattered solar irradiances, and the position of the sun. The forecast includes ensemble irradiances averages and uncertainties.

DMI and EXERGI's cooperation delivered a set of algorithms, which gave an optimal description of measured AC-production as a function of weather and solar data, information about to solar plant etc. A calculated shading and reflection index shows its value by giving response to actual shadings from trees and buildings.

As the last step, EXERGI has standardized and simplified the analytic process in a full-automated Cloud services, including forecast calculation of expected AC-production. In top of this single panel forecast, there is a tool for "upscale" to a total forecast for a grid, geographical area or portfolio of solar plants.

The Solar-PV-Meter setup should make it possible to use the Cloud services at any position, where proper weather forecasts are available.

The cloud service utilizes data for up to 6 months to establish a stable model for efficiency calculations and forecasts.

The idea of establishing a service that could handle any solar PV panels, was ambitious and could today be classified as high-risk initiative, especially under the low budget framework. The actual resources needed to bring the concept to the current state have been much higher than expected and involved works without payment.

#### **Conclusion:**

The project delivered an analytical "tool box" and a Cloud-service concept that can deliver relevant services to Solar PV owners and grid companies World Wide. Similar services do not appear to exist in the market today.

## 4. Project results and dissemination of results

### 4.1 Results from DMI's and EXERGI's research

This chapter describes the result of the collaboration between DMI and EXERGI to develop an analytic approach for solar PV's efficiency and test it under 'experimental' conditions. Chapter 5 describes the demonstrations set up and chapter 6 the transformation into a Web services.

The experiment handles two steps. Firstly, solar energy prognoses for any location in Northern Europe for the coming 48 hours, based on the newest DMI forecasts of direct and diffuse solar radiation. Secondly, the PV electricity production is analyzed and monitored. The effects of meteorological variables, solar panel geometry relative to the direct solar beam and shadowing conditions are all analyzed.

### 4.2 PV production forecasts based on NWP model output

Given the uncertainty of cloud forecasts – and thereby solar irradiance forecasts – the DMI HIRLAM ensemble model was chosen. The ensemble model with average forecasts of solar irradiance have been shown to have up to 20% less root mean square error (RMSE) than output from a standard deterministic numerical weather prediction (NWP) model (Lundholm 2013).

The ensemble model includes 25 members (Feddersen 2009). The prognoses are delivered for the electrical power production during the next 48 hours. The prognoses are updated every 6 hours and include the following ensemble average parameters:

- Global horizontal solar irradiance (GHI);
- Scattered horizontal irradiance (SHI);
- 2-meter temperature;
- 2-meter relative humidity;
- 10-meter wind speed;
- Direction of the 10-meter wind;
- Integrated atmospheric water vapor.

Here GHI is the sum of SHI and the direct beam irradiance on a horizontal surface (DHI). DHI can thus be calculated by subtracting SHI from GHI.

Additionally, the standard deviation of the ensemble model output is given for GHI and SHI.

### 4.3 PV production performance monitoring

From the 2-meter temperature, *GHI* and *SHI* output averages from the ensemble model the final electrical power produced  $P_f$  can be estimated with the following formula:

$$P_f = P_a \gamma_{inverter} = P_r PR_{DC} \gamma_{inverter} \quad (1)$$

$$P_r = (GTI P_{nomG}) / GHI_{ref} \quad (2)$$

$$PR_{DC} = \frac{P_a GHI_{ref} k_{other}}{(DTI k_{shadow}(\theta_0, \varphi_0) k_{inc}(\Theta) + STI) P_{nomG} (1 - \beta_{ref} (T - T_{ref})) k_{wind}(\vec{u}) k_{RH}(RH)} \quad (3)$$

Here  $P_a$  is the power of produced DC electricity,  $\gamma_{inverter}$  is the DC to AC conversion efficiency of the inverter,  $P_r$  is the reference power of the PV production,  $P_{nomG}$  is the nominal power of the array at a reference  $GHI_{ref}$  of 1000 W/m<sup>2</sup> and a reference temperature of  $T_{ref}$  of 25°C,  $PR_{DC}$  is the DC performance ratio,  $DTI$  is the direct solar irradiance on the tilted plane of the PV array,  $STI$  is the scattered – or indirect – irradiance on the tilted plane of the PV array, and  $T$  is the ambient 2-meter temperature.

In Eq. 3 six coefficients ( $k_{shadow}$ ,  $k_{inc}$ ,  $k_{other}$ ,  $k_{wind}$ ,  $k_{RH}$  &  $\beta_{ref}$ ) are included that describe factors that can degrade the performance ratio from 100%. If the five  $k$ -coefficients are 1.0 and  $\beta_{ref}$



is 0.0 (or  $T = T_{ref}$ ) the produced DC power of the array  $P_a$  will be equal to the reference power  $P_r$ . Details about the coefficients:

- $\beta_{ref}$  is the temperature coefficient of the PV array. This has been studied in detail and is mostly specified by the PV module manufacturer. In the review of Skoplapki & Palyvos (2009) an average  $\beta_{ref} = 0.0045 \text{ K}^{-1}$  is found.
- $k_{shadow}(\theta_0, \phi_0)$  is the shadow index as a function of the direction of the direct solar beam as specified by the solar zenith angle  $\theta_0$  and the solar azimuth angle  $\phi_0$ . If the shadow index is 0.0 all direct solar irradiance is shaded. The shadow index, as we use it, can also be larger than 1.0 in order to include effects of reflecting objects around the PV array.
- $k_{inc}(\Theta)$  is the beam incidence index that accounts for the Fresnel reflection of the direct beam away from the PV module glass surface (Born & Wolf 1999).  $\Theta$  is the angle of the solar beam relative to the PV module normal. The glass surface is assumed to have a refractive index of 1.52 and the solar beam is assumed to be unpolarized.
- $k_{wind}$  is the wind index that depends on the strength of the wind and the direction of the wind relative to the PV module surface.
- $k_{RH}$  is the relative humidity index.
- $k_{other}$  is the effect of all other factors that can degrade the PV module performance. This includes technical problems and soiling of the surface of the module. When monitoring PV module performance determining this coefficient is the main objective.

At the beginning of this project, the following questions relating to Eq. 3 were unanswered:

- Are the temperature coefficients specified by the PV module manufacturers correct?
- Does the relative humidity affect PV performance?
- Does the synoptic wind strength and direction affect PV performance?
- How significant is the effect of shadowing, and can this effect be quantified?
- Can beam incidence reflection be accounted for with the Fresnel reflectance equations?

#### 4.4 The PV array data

The PV array data was obtained from customers of Unicare Solar, the Danish importer of the *SolarLog* data loggers (<http://home.solarlog-web.eu/>). The SolarLog data loggers provide both DC and AC output power in five minute intervals.

PV ID	Spring 2012	Autumn 2012	Spring 2013	Autumn 2013	Spring 2014
BH01			May-June	X	X
EM01				Nov.-Dec.	X
FS01				X	X
JH01	X	X	X	X	X
LL01	X	X	X	X	X
LK01				X	X
PH01	April-June	X	X	X	X
PJ01	April-June	X	X	X	X
S701	April-June	X	X	X	X

*Table 1: The seasons from which PV output data was monitored. The first column gives the PV array ID's. Seasons from which a full data set has been obtained are marked with X. Spring is here defined as the first six months of the year, and autumn as the last six months of the year. When data has been obtained only from some months in a season these are specified.*

In table 1 the half-year seasons from which data were obtained are specified. All in all data were obtained from 29 half-year seasons. Besides the power output data, meta-data were

obtained for each of the PV arrays. These include the coordinate, the tilt, the direction, the nominal output power ( $P_{\text{nomG}}$ ), the number of inverters, and the number of monitored strings. Note that the number of monitored strings is not necessarily equal to the number of inverters on a given PV array. The strings may cover parts of a PV array pointing in different directions, and which are shaded differently by surrounding objects. Therefore, the analysis is made on a string by string basis.

All of the analyzed PV arrays are mounted on the roofs of private homes. Thus, it is expected that the sensitivity to meteorological conditions (temperature, relative humidity and wind) are different from standard testing conditions of free-standing PV arrays. Also, with limited possibilities of optimally placing the PV arrays, shading is expected to play a significant role.

#### 4.5 Satellite data for estimating the solar irradiances

The best way of monitoring the performance ratio of a PV array is with the aid of *in situ* measurements of the solar horizontal irradiances (GHI, DHI and SHI) or the solar irradiances in the tilted plane of the PV array (GTI, DTI, STI). Additionally, the PV cell temperature can be monitored directly. Such measurements are, however, costly and in particular, the solar irradiance measurements require frequent calibrations and maintenance making them ill-suited for a regular home owner.

One alternative to *in situ* monitoring of the solar irradiances is to interpolate these from global radiation measurements performed in the national weather station grid of DMI. These global radiation stations, however, may be as much as 50 km away from a given location. We have chosen a second alternative.

It has been shown that the potentially available solar irradiances can be reasonably well assessed from satellite data (Nielsen 2011). Such data have the advantage that they can be derived for any location seen by a geo-stationary satellite, i.e. the whole world except the polar regions. DMI routinely maps the satellite derived solar irradiances with 15 minute time resolution, corresponding to the time resolution of the Meteosat SEVERI images (Nielsen 2011).

#### 4.6 PV performance compared the meteorological data

As mentioned, we work from the hypothesis that the temperature, relative humidity and wind affect the performance of the PV arrays. The dependency on temperature is well established (e.g. Skoplakpi & Palyvos 2009). In agreement with what has previously been found, we also find that there is a negative linear relationship of the PV performance with temperature, however, we find the magnitude of the temperature coefficient not to be representative of the typical value of  $\beta_{ref} = 0.0045 \text{ K}^{-1}$ .

From optimization analyses we find  $\beta_{ref}$  values in the range of  $0.0072 \text{ K}^{-1}$  to  $0.0090 \text{ K}^{-1}$  with an average of  $\beta_{ref} = \underline{0.0080} \text{ K}^{-1}$  for the PV arrays analyzed. There may be two reasons for this discrepancy: Firstly, PV arrays mounted on roofs can only cool through emission of longwave radiation in the hemisphere away from the roof, while free-standing PV arrays can cool also by emitting longwave radiation in the opposite hemisphere; secondly, the relative humidity is covariant with the temperature. Thus, colder air has a higher relative humidity, which again means that the air has a higher heat capacity to transport heat away from the PV array.

In our investigation of the PV performance compared to relative humidity, we did not see any clear correlation between these two variables. Again, this could be due to the covariance of temperature and relative humidity. In the early morning, the relative humidity will often reach 100% and dew will form on the PV array. The latent cooling due to evaporation of this dew is also implicitly included in the observed temperature changes. Thus, we conclude that relative humidity either does not significantly affect the PV performance or, that if it does, its effect is implicitly included in the temperature coefficient  $\beta_{ref}$ . Therefore,  $k_{RH}$  in Eq. 3 can be assumed to be 1.0.

Similarly, we found no correlation between either the wind speed or the wind direction and the PV performance. An extra study was made, where the data was split into three groups with no to little wind (< 2 m/s), moderate winds (>= 2 m/s and < 10 m/s) and strong winds (>= 10 m/s). When comparing these three groups of data, no differences were found for either of the analyzed PV arrays.

The fact that the PV performance is not affected by the general winds in case of no to little wind, can be explained by the PV array creating its own winds through convection when it is relatively warmer than its surroundings. Therefore,  $k_{wind}$  in Eq. 3 can be assumed to be 1.0.

#### 4.7 PV performance compared with the incidence angle

The solar beam incidence angle relative the PV array plane is found to have a significant impact on the PV performance ratio. In Fig. 1 data from the entire year of 2012 are plotted as a function of the incidence angle. In particular, in the data categorized as 'Blue input' the dependence of the performance ratio on the incidence angle is clear to see. We find that using the Fresnel expressions of reflectance of direct solar irradiance to estimate  $k_{inc}$  in Eq. 3 adequately can account for this dependence for the PV arrays included in this study.

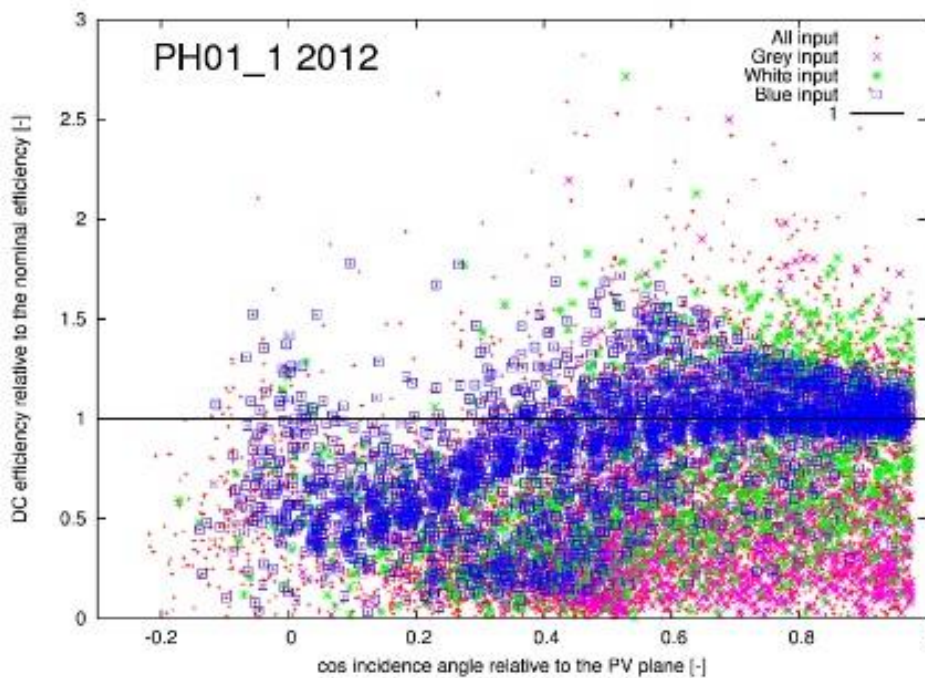


Figure 1: The DC performance ratio as a function of the solar incidence angle relative to the PV array plane for the four data categories: 'All', 'Grey', 'White' and 'Blue'.

#### 4.8 PV performance compared with the shading index

From Eq. 3 the shadow index  $k_{shadow}$  can be solved, when the other coefficients are known,  $k_{other}$  and  $PR_{DC}$  are assumed to be 1.0, and measurements of reasonable estimates of DTI and STI are available. We used satellite data to assess DTI and STI. The results were at first unclear.

It was realized that the satellite in some cases give assessments of the clouds – and thereby the irradiances – that are not representative of the actual conditions. The problem arises since the SEVIRI satellite pixels have spatial resolutions of 6-7 km on each side. Typical cumulus clouds have spatial scales of 0.1 to 1 km and cannot be resolved in the satellite images.

In the satellite images these are seen as a thin cloud cover evenly spread out over the pixels. In reality, the cumulus clouds cause strong intermittent shading interceded by clear sky conditions. This challenge can, however, be solved by using only data from days with either clear sky conditions or with a homogeneous cloud cover.

The satellite data were sorted into 4 categories: 'Blue', 'White', 'Grey' and 'Non-smooth'. The first three of these categories are all cases of 'smooth data', which are defined by *the variability index* (Skartveit et al. 1998) being less than 0.025. The sub-division of the 'smooth data' is based on *the clear-sky index* (Skartveit et al. 1998) being > 0.85 for 'Blue' data, > 0.7 and <= 0.85 for 'White' data and <= 0.7 for 'Grey' data.

In Fig. 2 the four data categories are plotted for the PV array 'LL01\_1' during the month of July 2012. Strong shading is clearly seen in the 'Blue' data at solar azimuth angles < 1.9 radians (109°) and > 4.5 radians (258°). In the other data categories, the shading is less pronounced. Therefore, the 'Blue' data were used to determine the shadow index.

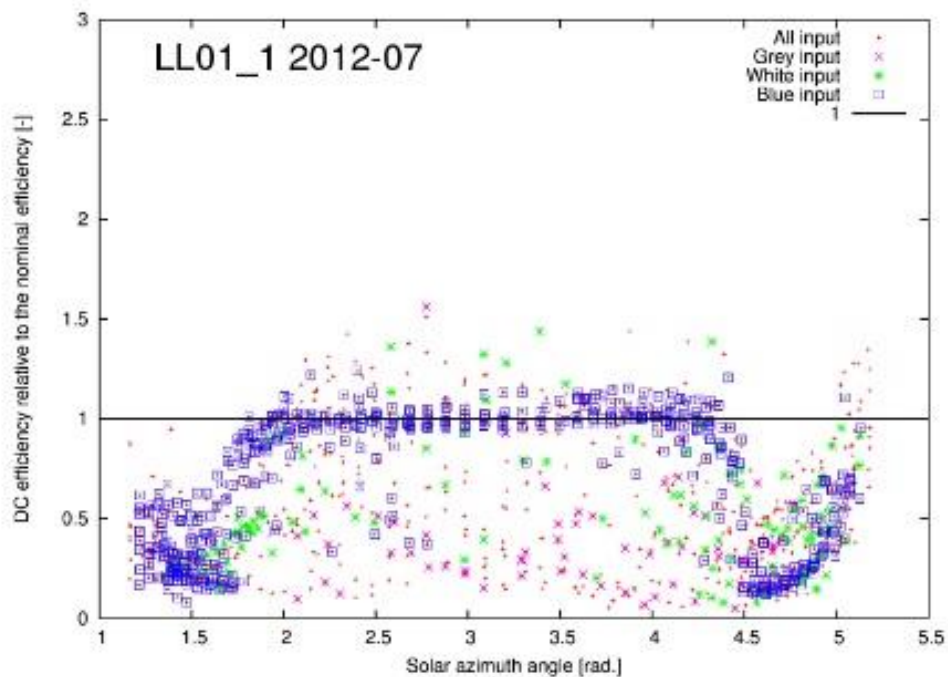


Figure 2: The DC performance ratio as a function of solar azimuth angle in radians for the four data categories: 'All', 'Grey', 'White' and 'Blue'.

The shading index is derived independently for pixels of with sizes of 5° x 5° on a half-yearly basis. The reason for calculating the shading index on a half-yearly basis is illustrated in Fig. 3, where the shading index is shown for each month in 2012; over the course of a half year from winter solstice to summer solstice – or roughly from January to June – all possible positions of the Sun in the sky are scanned.

In cases where the shading is due to buildings or other firm structures the shading will be symmetrical between the first and second half of the year. In cases where the shading is due to trees, which is Denmark mostly are deciduous, the shading can vary strongly from the first to the second half of the year.

In Fig. 4 an example of this is shown. In the azimuth direction 0° - to the South – a clear difference is seen in the pattern of the shadow index.

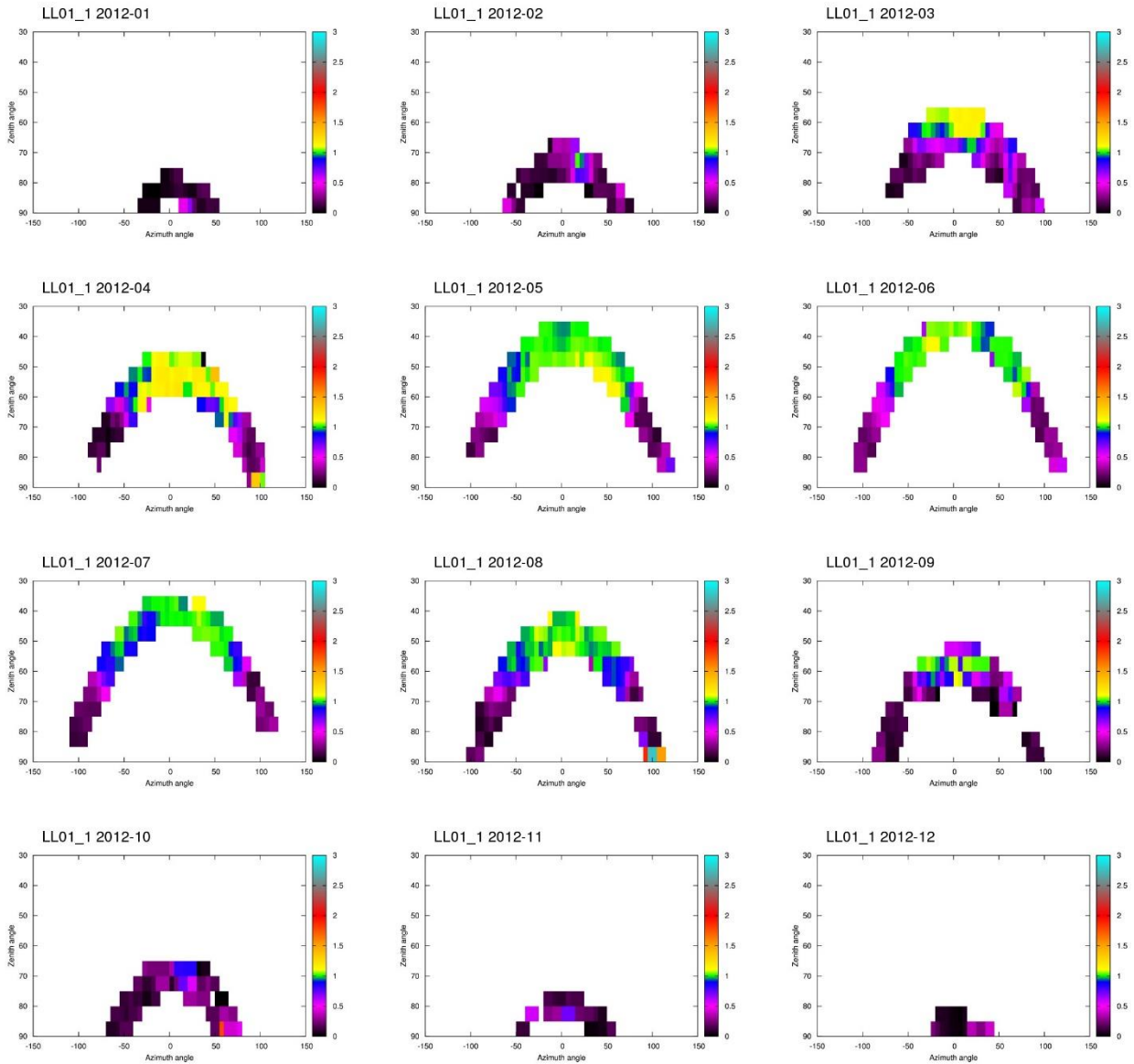


Figure 3: The derived shadow index for the 12 individual months of 2012 for the PV array LL01\_1. The blue, magenta and black colors indicate various levels of shading. The green color indicates that there is no shading. The yellowish to reddish colors indicate enhancement of the solar irradiance due to reflections.

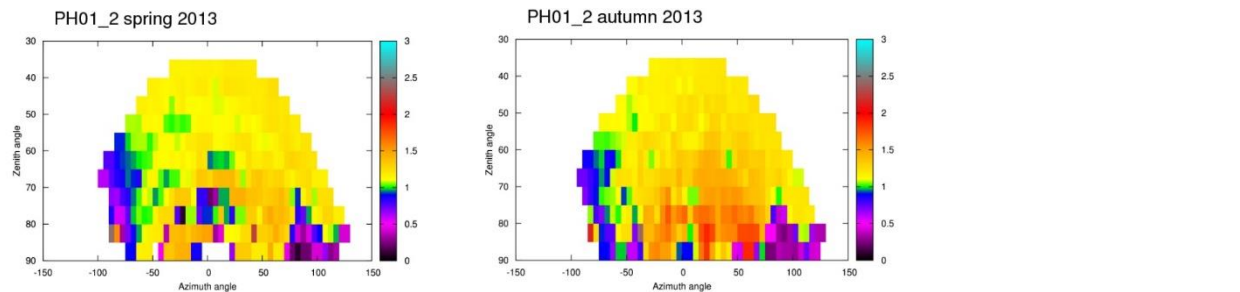


Figure 4: The derived shadow index for the spring and the autumn halves of 2013 for the PV array PH01\_2. The colors are explained in the caption of Fig. 3.

#### 4.9. Conclusions

- The temperature coefficient of the PV array performance is found to be  $0.0080 \text{ K}^{-1}$  in average for the roof mounted PV arrays analyzed, which is almost twice the typical value of  $0.0045 \text{ K}^{-1}$ .
- The relative humidity is not found to have a significant effect on the PV array performance. At least not an effect that is independent from the temperature.
- The wind strength and direction is not found to have a significant effect on the PV performance.
- The direct solar beam reflectance as a function of the incidence angle has been found to be adequately described by the Fresnel reflectance equations.
- A new method for determining the effect of PV performance on shading has been developed. This is based on satellite data and can thus be used without *in situ* measurements of solar irradiance.
- Satellite derived irradiances are not representative for the actual irradiances in case of inhomogeneous cloud cover at a scale smaller than the satellite pixels. This means that PV array production data can provide information on the clouds that is not available otherwise. Such data can be used for verification of weather and climate models and for assimilation into weather models.

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## **5. Production data from solar PV's and demonstration plants**

### **5.1 Production data from solar PV's**

The idea of analyzing the efficiency of Solar PV's is access to DC- or AC-production data with a short time step – preferable every 5. Minute but up to 1 hour is acceptable.

Automatic upload from solar PV's has been practice in the last 5 – 10 years, and is today a standard feature. When this project started in 2012, the plant owners have to buy extra equipment to extract data from inverter and upload the information to Web-services.

The following is a general description of the development over time.

#### *Phase 1*

Originally, inverters were not equipped with other surveillance options than an indication of whether the inverter was active and connected to the grid. Measurements of production, personal consumption and the supply of power to the grid were associated with considerable uncertainty.

#### *Phase 2*

Later, many inverters became equipped with a small data display, which could show the status of the inverter and current and historical power production in different ways.

Inverters were prepared for data collection and provided either with a data interface, which could be build-in or by acquisition of a circuit board for retrofitting. In most cases, more advanced data collection was an extra option.

#### *Phase 3*

The next step was to provide the inverters with a network connection. Solar PV could either be monitored on the owner's own PC/home network or connected to a portal on the Internet, to which the inverter delivered data with different time intervals.

Data connection between the inverter and network/data logger could be established by means of cables, Bluetooth or WiFi.

For the solar PV plant owners it is more appropriate to monitor and store solar PV production data on a portal on the internet, rather than on a home PC. It is a complex IT task to develop and maintain a portal solution.

Today, the monitoring function is largely fully integrated in the inverter, and most major suppliers of inverters also can store and present data from the single solar PV installation at portals on the Internet, which is made available to the plant owner.

### **5.2 Demonstration plants**

It was originally planned to get data from 50 installations where the owners had invest in data logger to upload production data continually.

An information letter was drafted and sent to a number of stakeholders with an invitation to participate in the project or pass the invitation to customers. This included installers, organizations, utilities and other stakeholders. The invitation was also posted on the project participants' websites.

It proved harder than expected to get a commitment for making data available from owners of solar plants. Only 9 plant owners responded positively. Out of the 9 plants 2 smaller installations soon dropped out, due to various reasons (one due to change in local network and no further interest in the project, and one due to conversion of the building).

7 installations delivered data to DMI from 2013 and until today. One of the installations dropped out due to a technical reason (hit by lightning).

Data from the plants to an FTP file server or the Solar-Logs own internet portal, where thousands of PV systems all over the world are publicly available.

Data have been collected from a variety of different types of PV systems, but all using a data monitor from the German company Solar-Log. The company was early to market with a monitoring solution, but has later received strong competition from other companies with similar solutions. Today producers of inverters, integrates web-based monitoring of solar PV inverters.

Solar-Log is universally applicable, as the solution has been expanded to read data protocols from all common inverters and can be connected to both the plant owner's own homenet-work and to portals on the Internet. In the project, data from the solar PV plant was send to an FTP server, placed at DMI.

Several reasons for the low response have been discussed:

- The marked for PV installations where on it's way down 2013
- Data logger was I 2013 an extra and expensive device ,
- The owners of existing data logger find it hard to change the settings for data upload.



## 6. Web service Solar-PV-Meter.com

### 6.1 Set up for Solar-PV-Meter

Solar-PV-Meter is the new online service. The Web-service imports data from the single power plant and from weather services providers (DMI). Production data should describe the DC- or AC-production for minimum every hour and preferable for every 5<sup>th</sup> Minute. Weather and solar radiation forecast describes the values for every single hour 48 hours ahead.

Production data should be uploaded from the plants inverter or meter to the Web-services. If production data are collected by a data provider or grid company, the production information can be transferred to Solar-PV-Meters cloud services by 'push' or 'grab' techniques.

In the setup, the plant owner should give some basic information regarding the solar plant, geographical position, panel type, area and capacity, azimuth and panel tilt and inverter type and capacity.

### 6.2 Model for the single plant

The Cloud-services automatically establish a model for every single panel/inverter combination. For a building with panels in direct direction works Solar-PV-Meter with separate models for each section.

The input-output model uses several matrices that describe the conditions in different segments ('pixels') and under different weather and production conditions. The weather and production data is 'transformed' to shorter time steps that reflects the actual solar position.

In figure X the basic angles are defined – azimuth and tilt of the panel, solar altitude etc.

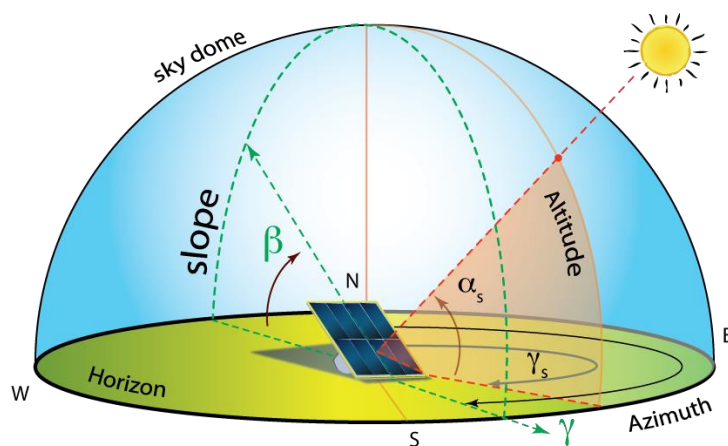


Figure 1: Solar panel and solar position. Definition of basic angles.

During 3 to 6 months the model calculates several matrices that describe the single step in the chain from solar radiation that hits the plants (if no local shadings), to the measured DC/AC (with the actual temperature). Based on this information the web-services provides efficiency analytics and forecasts.

### 6.3 Shading- and Reflection Index

Local shadings from buildings, trees and even flagpoles reduce the power positions, and for some panels the reduction could be considerable.

The index should give a value of the reduction of the DC/AC-production compared to solar positions without shadings. The index handles also situations where local reflections enforce the solar radiation and power production. Different methods for automatic calculation of a *shading- and reflection index* are tested.

In an early version, the panel owners should take a picture or the view seen from the panels, to fasten the calculation of the shading- and reflection index. The final solution was an algorithm that divides the pixels in different groups after their local performance, with periodic regrouping and recalculations. One of the challenges was short data intervals, where noise can be considerable.

#### **6.4 Forecast for AC-production**

The forecast services with estimates for actual hour AC-production 48 hour ahead, uses the efficiency results, the shadings- and reflection index and weather- and solar radiation forecast from DMI.

The forecast is recalculated automatically when the weather services pushes new data, typically every 6. hour.

#### **6.5 Policy for data protection and 'spam' on Solar-PV-Meter**

Basic principles for the web-services

- Solar PV data belongs to the panel owner, secured with login functions and password
- The company Solar-PV-Meter has only access to use your data to produce statistics - not to view or share single plant data with others
- Panel owners can choose to 'publish' data on the Web-sites '*Demo Gallery*' so they get visible for other users - Please do so!
- 'No spam' – Solar-PV-Meter do not distribute commercial information's to the its users

#### **6.6 Feedback to users**

User of Solar-PV-Meter can access their data in three ways,

- Automatic broadcast of a monthly report(.pdf) that describes production and efficiency
- Online monitor on APP/Web
- Export-function for forecast for automatic control of electric devices and batteries.

#### **6.7 Monthly report .pdf**

The monthly report that is the primary services to solar, consists of four sections

- System identification and Solar Statistics
- Daily production and forecast – including statistics for forecast accuracy
- Efficiency key figures, and
- Shading- and Reflection Index

##### *6.7.1 System identification and Solar Statistics*

See complete monthly pdf-report mailed to the plat owner every month in Appendix.

Example of system data and solar statistics.

### **Panel Module #1**

*Solar Panel*

Max.Capacity 6,400 W \*)

Area 42.0 m<sup>2</sup>

Panel direction: Azimuth: 20° Panel tilt: 35°

*Inverter*

Max.Capacity 6,000 W \*)

*\*) Max. panel capacity is higher than inverter max. capacity – results in 'Peak cutting'.*

Statistic for solar radiations in last months and for last 12 months.

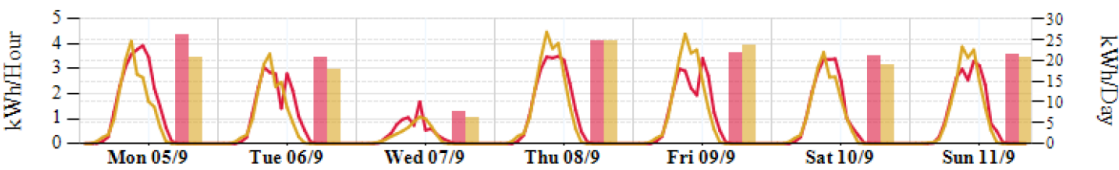
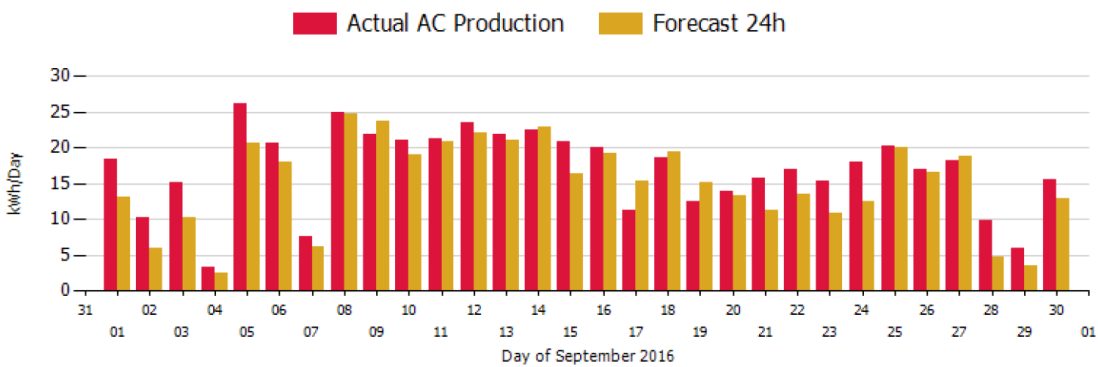
STATISTICS	September 2016	Last 12 months
Solar Hours	411 h	4,454 h
Total Solar Energy *	10,824 kWh	104,403 kWh
Projected Solar Energy **	6,383 kWh	56,777 kWh
AC Production kWh	507 kWh	4,294 kWh

\*) Total energy in solar radiation, if solar panels were perpendicular towards the sun in every hour

\*\*) Total energy in solar radiation that hits the panel with its fixed installation angles (azimuth and panel tilt)

### 6.7.2 Daily production and forecast

Example of production statistics and forecast.



### 6.7.3 Efficiency key figures

Example of step down calculations from potential to actual AC-production, step by step.

	September 2016	Last 12 months
Potential DC-production based on actual calculated efficiency	1,450 kWh	13,844 kWh
Losses due to projection – since panels not 90° against the sun	-595 kWh	-6,326 kWh
Losses due to shadows and reflections	-315 kWh	-2,929 kWh
Losses due to inverter conversion	-32 kWh	-295 kWh
Actual AC production kWh	507 kWh	4,294 kWh

The first lines indicate the potential DC-production, if the panels are directed towards the sun at all times, and if there were no losses from local shadings and in the inverter.

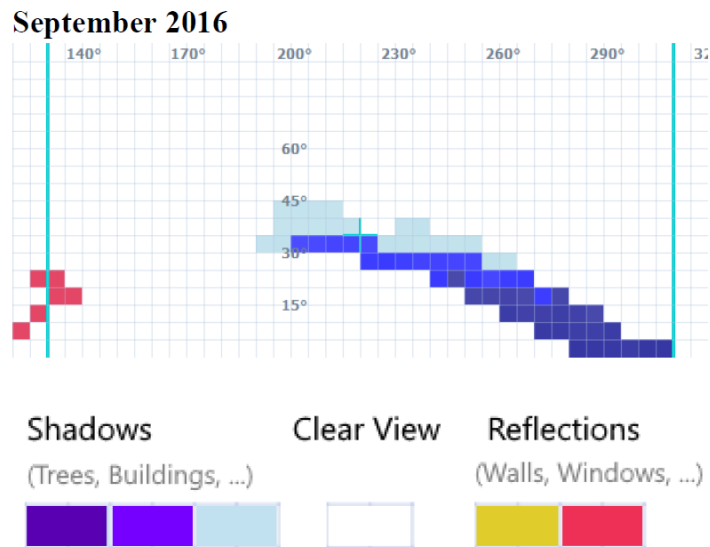
The losses due to projection reflects the fact that a fixed installed solar panel does not follow the path of the sun, so that the solar radiation hits the panels with an angle that differs from 90°.

Shadings. In this example the reduction of the potential power production caused by shadings from buildings and trees are small - 56 kWh/month and 620 kWh/12 months.

Losses in the inverters are quite small - 295 kWh a year or 6%.

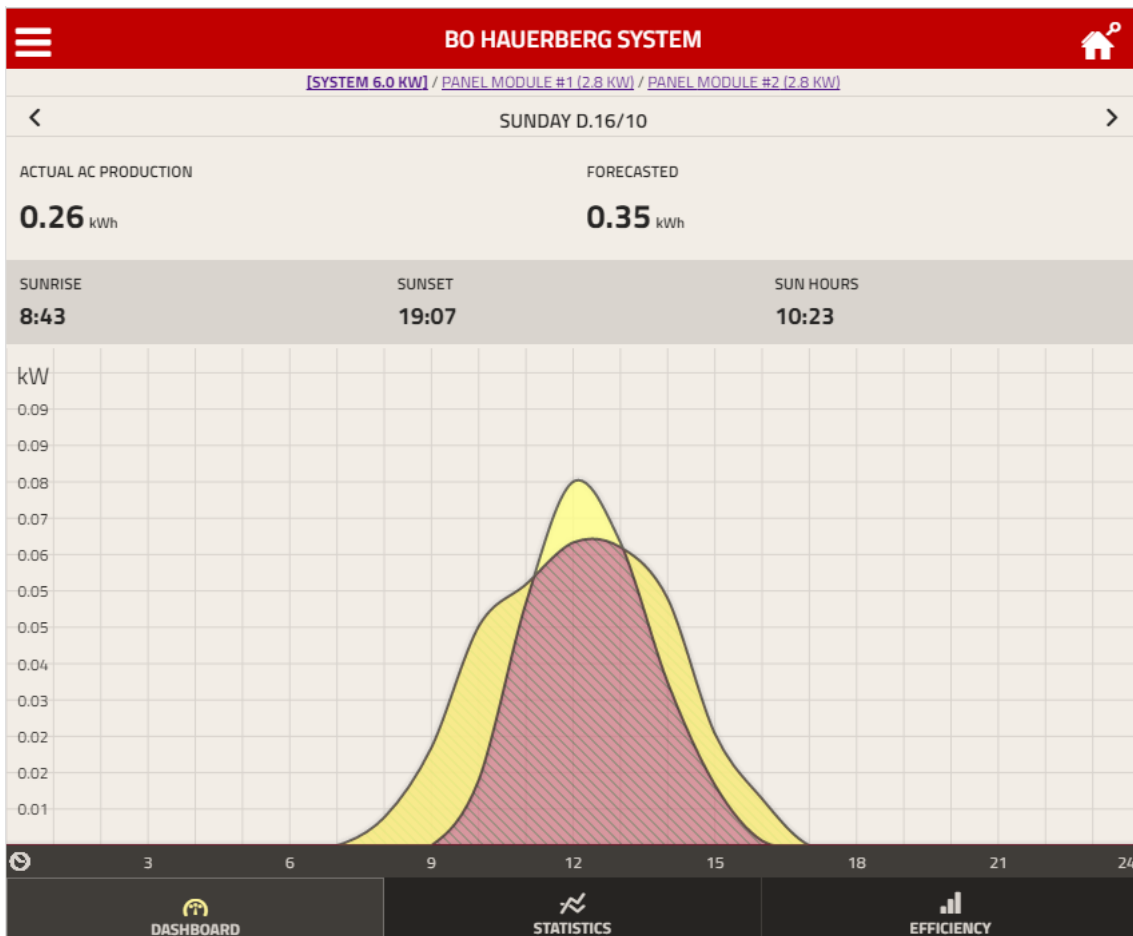
### 6.7.4 Shading- and Reflection Index

In this example of 'pixel'-view dark blue indicates strong shadings near the horizon, light blue weak shadings. Red pixels have reflections effect, where the AC-production is enforced.



### 6.8. Web services

A combined APP and Web-services give access to online data, as well as all the results shown in the monthly report. The Website exist only in a test version, but here some examples. Basically it's the same kind of information as in the monthly report.





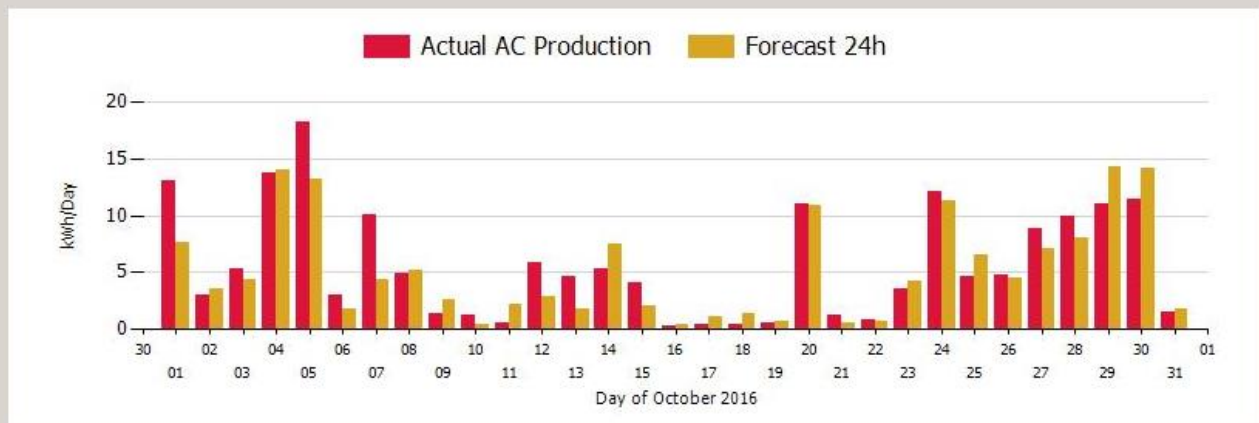
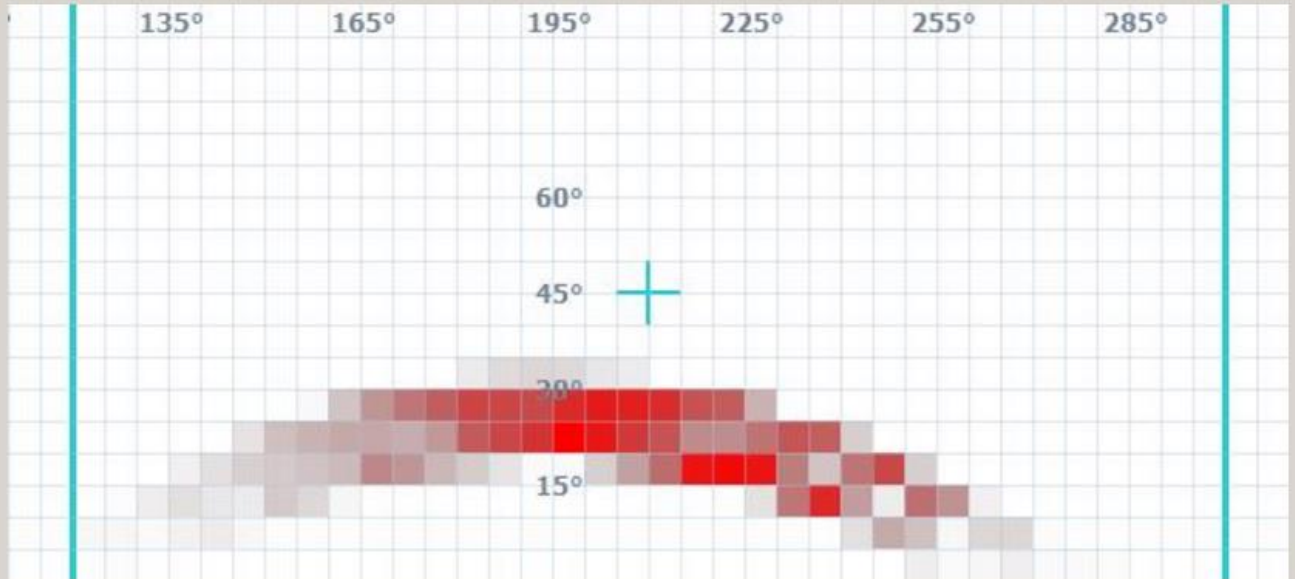
[SYSTEM 6.0 KW] / [PANEL MODULE #1 (2.8 KW)] / [PANEL MODULE #2 (2.8 KW)]

October 2016

SOLAR HOURS	<b>350 h</b>	<b>11.7 h/Day</b>
TOTAL SOLAR ENERGY * (38.8 M2)	<b>5,646 kWh</b>	kWh/Day
PROJECTED SOLAR ENERGY ** (38.8 M2)	<b>3,728 kWh</b>	kWh/Day
AC PRODUCTION KW/H	<b>177 kWh</b>	<b>5.9 kWh/Day</b>

\*) TOTAL ENERGY IN SOLAR RADIATION, IF SOLAR PANELS WERE PERPENDICULAR TOWARDS THE SUN IN EVERY HOUR

\*\*) TOTAL ENERGY IN SOLAR RADIATION THAT HITS THE PANEL WITH ITS FIXED INSTALLATION ANGLES (AZIMUTH AND PANEL TILT)

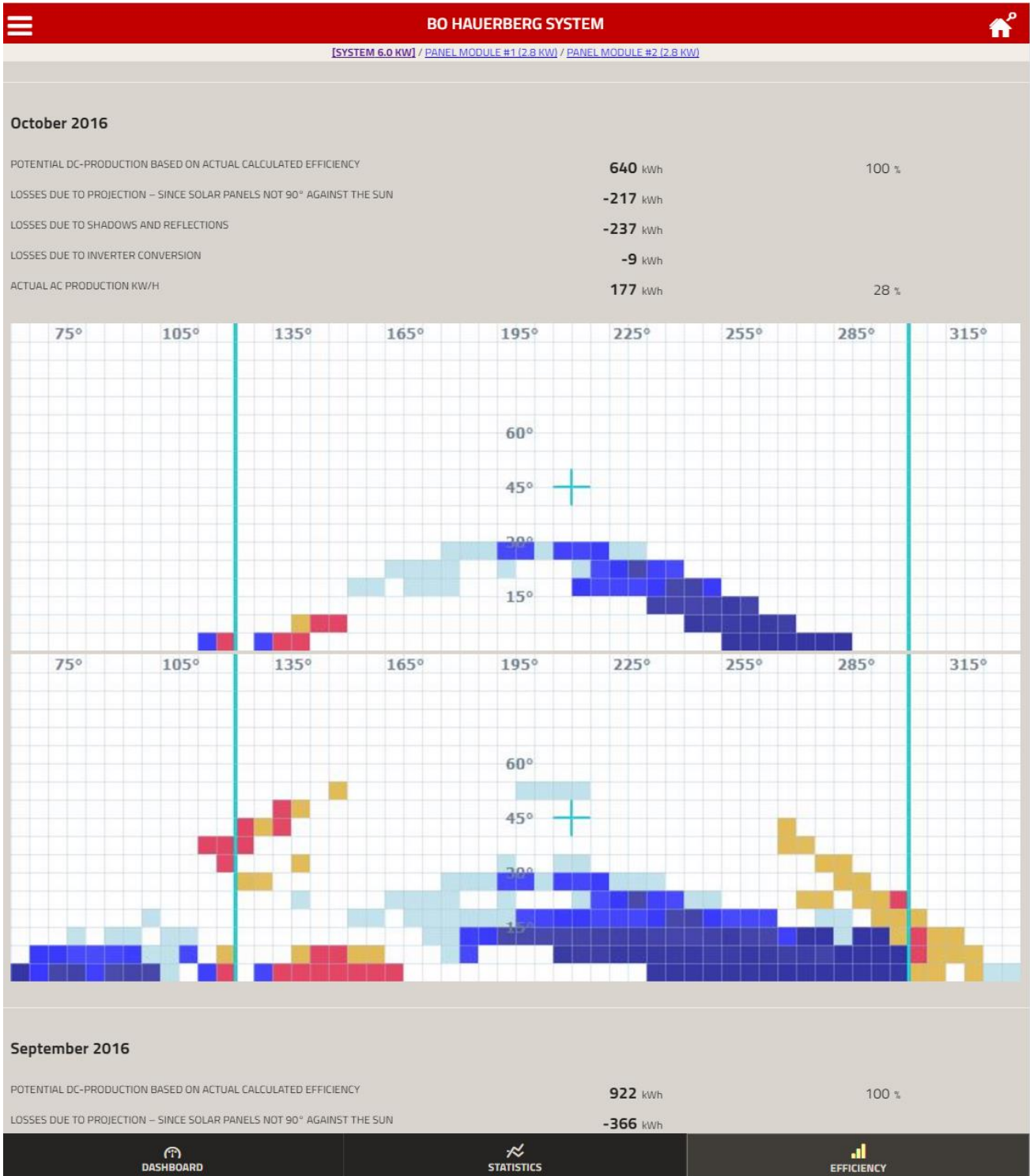


September 2016

SOLAR HOURS	<b>407 h</b>	<b>14.0 h/Day</b>
TOTAL SOLAR ENERGY * (38.8 M2)	<b>10,019 kWh</b>	kWh/Day
PROJECTED SOLAR ENERGY ** (38.8 M2)	<b>6,040 kWh</b>	kWh/Day
AC PRODUCTION KW/H	<b>428 kWh</b>	<b>14.8 kWh/Day</b>

\*) TOTAL ENERGY IN SOLAR RADIATION, IF SOLAR PANELS WERE PERPENDICULAR TOWARDS THE SUN IN EVERY HOUR

\*\*) TOTAL ENERGY IN SOLAR RADIATION THAT HITS THE PANEL WITH ITS FIXED INSTALLATION ANGLES (AZIMUTH AND PANEL TILT)



## 6.9 Export services

An export function, would give the user access to export forecast data to control functions etc. The services would include an Open API for automatic export of forecast information to control of systems for flexible electric use or loading of batteries.

## 7. Forecast for a grid, geographical area or portfolio of plants

An extra result of the project is a method to use forecasts for a sample of plants to estimate the total power production for a grid, geographical area or portfolio of solar plants.

There are two different situations that for instance a grid company needs information about

- The total AC-production from solar panels per hour in area or portfolio of plants
- The total AC-production is *not* known, but the grid operator knows the installed solar capacity and/or net import/export of AC for every hour (=users consumption minus solar PV production).

To the *first case*, there is described – but not tested – an algorithm that transforms forecast for the single forecast in the samples to the known gross AC-production. This ‘upscaling’ function uses information from single plant (efficiency and shadings- and reflection index) to establish the best model for total forecast based on historical data.

In the *second situation*, the solar PV-production is unknown, so the model has to include the general pattern of the user’s electric consumption, including estimates of flexible use and batteries.

Solar-PV-Meter will seek funding to analyze and test both cases on a larger scale.

## **8. Utilization of project results**

DMI and EXERGI published the result and had a presentation of the analytic result on EU PVSEC 2013<sup>3</sup>. The response was good. During the development of the Cloud services, there have been no information activities, since we have been waiting until the market introduction of Solar-PV-Meter.

We will publish articles and information material regarding the project results, and the company Solar-PV-Meter plans to spend resources on advertising.

The marked focus at first is companies that deliver big volumes of quality solar plants and inverters producers. The business model is that these companies pay for the Solar-PV-Meter Web-services, and include them as an extra service and quality tool in a total solar plant offer to end-users. The Solar-PV-Meter Cloud services would naturally replace the traditional Web-services – showing only actual AC-production – that typically is a part of these packages.

The second marked is the Grid/DSO companies that are looking for forecast for the total AC-production. A marked model here is that the grid company pays for the aggregated analysis and forecast, while solar panel owners get the Cloud services almost free.

<sup>3</sup> [http://www.exergi.dk/SiteAssets/Sider/Exergi/Nielsen\\_et\\_Wilke\\_EU\\_PVSEC\\_2013.pdf](http://www.exergi.dk/SiteAssets/Sider/Exergi/Nielsen_et_Wilke_EU_PVSEC_2013.pdf)



## 9. Project conclusion and perspective

The research and demonstration project has shown that it is possible to let smart algorithms in a Cloud services ('Big Data') *analyze*

- the actual efficiency of a Solar PV plant, and
- the effect of local shadings- and reflections,

and produce *forecasts* for AC-production for every hour in the next 48 hours,

- for any solar PV plant, and
- for a region, grid og portfolio of plants, based on a sample of plants analysed with Solar-PV-Meters in combination with statistics for total solar power production

There exist several web-services that visualizes the actual AC-production from solar plant, without any form efficiency analytics or forecast functions. Solar-PV-Meter introduces a new type of analytic tool. Solar-PV-Meter is a potential worldwide service that can analyse a Solar PV plants any place on earth.

While solar plants typically are tested under standardized conditions, the Solar-PV-Meter Cloud services makes it possible to get a documentation for the actual efficiency under reallife conditions, with the actual position, local shadings etc. Thereby the Solar-PV-Meter can be the knowledge platform for research projects, product lists, quality labelling etc.

The concept would help owners and buyers of solar PV plants, to check the actual quality of plant and installation. For companies that delivers high quality packages, the Cloud-services could be a part in services and guarantee agreement, ensuring the owner that the plant and installation works as expected.

In a grid perspective, the Solar-PV-Meter concept has a double value, since both the grid and the single plant owners has direct benefits of the services. A possible business model could be that the grid introduces the Solar-PV-Meter as free services for the owners of solar plants, *if* the company can use their data in the aggregation and 'upscale' forecast model.

The concept follows an actual market trend, where Cloud services with information collection and 'Big Data'-tools, makes it possible to deliver qualified analytics regarding a building, device or process by distance and without human interaction.

Next step for Solar-PV-Meter is launch the online web-services and contact companies that delivers solar PV systems and grid companies.

**Appendix: Example of a monthly pdf-report.**