Solar resource assessment and forecasting EUDP project 64015-0025: Final report

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1.1 Project details

Project title	Solar resource assessment and forecasting
Project identification (pro-gram abbrev. and file)	64015-0025
Name of the programme which has funded the project	EUDP internationale samarbejdsprojekter (90%), DTU (6.1%), DMI (3.9%)
Project managing compa-ny/institution (name and ad-dress)	Danmarks Meteorologiske Institut (DMI) Lyngbyvej 100, 2100 Kbh. Ø.
Project partners	DMI & Danmarks Tekniske Universitet (DTU)
CVR (central business register)	DMI: 18 15 91 04 DTU Byg: 30 06 09 46
Date for submission	2017-06-19

1.2 Short description of project objective and results

Measurements of directional irradiances at DTU have been expanded to include the large solar collector field at Hedehusene. DMI has led an international collaboration activity to improve the use of meteorological data for solar resource assessment. This work was done within the IEA SHC Task 46 and IEA SolarPACES Task V expert groups. An IEA report has been published as a result. A main conclusion is that yearly datasets such as Design Reference Years or Typical Meteorological Years should no longer be recommended as the primary meteorological data sets for solar energy simulations; rather, multiyear data sets should be used. DTU and DMI have in collaboration done just that and analysed the thermal performances of all Danish solar heating plants to quantify the yearly variability.

1.2.a Kort beskrivelse af projektets formål og resultater på dansk

DTU’s målinger af retningsbestemte irradianser er blevet udvidet til solfangerfeltet i Hedehusene. DMI har ledet en international samarbejde-aktivitet om bedre brug af meteorologiske data til solressource-vurderinger. Dette arbejde er gjort i IEA SHC Task 46 og IEA SolarPACES Task V ekspert-grupperne. En IEA-rapport er blevet publiceret om dette. Hovedkonklusionen i denne er, at årlige datasæt som: “Design Referenceår” eller “Typiske Meteorolgiske År” ikke længere bør bruges som de primære meteorologiske datasæt i solenergi-simuleringer. I stedet bør multiårs-datasæt bruges. DTU og DMI har I fællesskab gjort netop dette og har analyseret variationen i de årlige termale ydelser fra alle større danske solvarmeanlæg til fjernvarme.

1.3 Executive summary

With the fast increase in the utilisation of various solar energy technologies, there is an ever increasing need to better understand the distribution of the solar resource. In particularly, the short-term variability caused by clouds is being investigated these years. In this project we have addressed to main goals: 1) To quantify the importance of the directional distribution of the solar resource available *in situ* in the solar heating plant in Hedehusene; 2) To work on better guidelines for using meteorological data for feasibility and bankability studies of solar energy.

The measurements at the solar heating plant in Hedehusene are also representative for photovoltaic (PV) plants as these in most cases have a similar geometric design with flat panels in rows tilted toward south. The work on guidelines for using meteorological data is inspired by feedback for companies, who often use data sources of varying quality that are easily available online. Also the use of typical meteorological yearly data sets as the Design Reference Year is not good for comprehensive resource assessments. Better recommendations are needed.

Accounting for the directionality of the solar resource matters. On sunny days the irradiance reaching the bottom of the solar collectors is measured at to be 3% less than the irradiance reaching the top the solar collectors. This is due to shading of the circumsolar diffuse irradiances. On cloudy days the relative reduction of the solar irradiance available at the bottom of the solar collectors is even higher. In the rows behind the first row of solar collectors the overall shading reduction of diffuse irradiance is around 10%.

As a result of the collaboration in the IEA SHC Task 46 and IEA SolarPACES Task V expert groups two reports were published in 2017: The first is an extensive discussion report about the use of meteorological data set for concentrating solar power (CSP) simulations; the second is a concise road map report for how to make and use better meteorological data sets. On a more practical level, we have analysed the thermal performance of 48 Danish solar heating plants as compared with multi-year meteorological data from a 5 year period. The yearly thermal performance has a span of 84%. About half – 40% – of this variability is due to the meteorological conditions.

1.4 Project objectives

The international collaboration work on improving the guidelines for using meteorological data sets for solar energy simulations was successful as two reports were published. This was finalised with more than half a year's delay, due to an extensive review process and many internal delays and discussion among the authors of the report. In such work this is hard to avoid. Thus, the overall final report from SHC Task 46 is only due to be sent for review in June 2017. In the original plans, it should have been published in 2016.

The measurements at the DTU site have been well maintained and continue to provide a valuable data set for characterising the solar resource variability in Denmark. The *in situ* measurements at the site in Hedehusene worked as planned; it was, however, challenging logistically to do measurements at this site. For future projects it is better to do measurements as these at the DTU test site.

The multi-year analysis of solar plant performance was carried out as planned.

1.5 Project results and dissemination of results

In the following we first briefly describe published results and presentations. References are given to these for those who would like to know more. Then we make a more detailed description of the measurements in the solar heating plant in Hedehusene, since these have not yet been sent for publication.

1.5.1 Published results, presentations and other forms of dissemination

The directional irradiance measurements and the quality control of these were presented at the European Geophysical Union (EGU) meeting in April 2016 [1]. Here an analysis of the risk of major volcanic eruptions in the coming decades was also presented [2]. Here 'major volcanic eruptions' are eruptions that that reduce the solar resource significantly on a global scale.

The solar plant performance analysis results were presented at the international Solar District Heating (SDH) conference in Billund in September 2016 [3]. A paper [4] detailing these results have also been submitted for publication in the journal: "Solar Energy". An overview of these results is shown in Table 1. Here measured potentially available yearly solar energy at 48 Danish solar heating plants is compared to the measured thermal performance for the five year period 2012-2016. More results can be found the referenced publications.

Table 1: Available solar energy (columns 2-6) and thermal performances (columns 7-11) for 48 Danish solar heating plants during the 5-year period 2012-2016. In the final five columns the utilization of the potentially available solar energy is given in percent.

Solar heating plant	Measured potentially available solar energy, kWh/m²					Measured thermal performance, kWh/m²					Utilization of solar radiation, %				
	2012	2013	2014	2015	2016	2012	2013	2014	2015	2016	2012	2013	2014	2015	2016
Hundested	-	-	-	-	1250	-	-	-	-	538	-	-	-	-	43.0
Vejby	-	-	1136	1127	1134	-	-	577	517	512	-	-	50.8	45.9	45.1
Helsinge	-	1126	1114	1145	1159	-	483	493	475	446	-	42.9	44.3	41.9	38.5
Jægerspris	1267	1363	1300	1309	1251	441	493	476	464	446	34.8	36.2	36.6	35.4	35.7
Skuldelev	-	-	-	-	1227	-	-	-	-	451	-	-	-	-	36.8
Nykøbing Sjælland	-	-	-	1325	1327	-	-	-	503	466	-	-	-	38.0	35.1
Østervang	-	-	-	-	1131	-	-	-	-	447	-	-	-	-	39.5
Svebøl-Viskinge	-	-	1039	1142	1099	-	-	423	511	324	-	-	40.7	44.7	29.5
Hvidebæk	-	-	1186	1207	1186	-	-	474	457	432	-	-	40.0	37.9	36.4
Sydfalster	1087	1070	1079	1230	1126	484	491	476	508	462	44.5	45.9	44.1	41.3	41.0
Sydlangeland	-	-	1132	1051	1186	-	-	472	448	487	-	-	41.7	42.7	41.1
Marstal	1046	1055	1116	1078	-	377	419	429	412	-	36.0	39.7	38.4	38.2	-
St. Rise	-	-	-	1177	1118	-	-	-	416	376	-	-	-	35.3	33.6
Ærøskøbing	1274	1264	-	-	1210	355	389	-	-	378	27.9	30.8	-	-	31.2

Broager	1085	1075	1474	1066	1127	385	420	445	439	449	35.5	39.1	30.2	41.2	39.8
Gråsten	-	1103	1114	1099	1115	-	438	469	447	412	-	39.7	42.1	40.7	37.0
Toftlund	-	-	-	-	1148	-	-	-	-	410	-	-	-	-	35.7
Christianfeld	-	-	1103	1081	1117	-	-	506	485	481	-	-	45.9	44.9	43.1
Vojens	-	1124	1107	1039	1029	-	414	427	342	404	-	36.8	38.6	32.9	39.2
Gram	1081	1138	1397	-	-	388	419	557	-	-	35.9	36.8	39.9	-	-
Gørding	-	1118	1091	-	-	-	482	522	-	-	-	43.1	47.8	-	-
Hejnsvig	942	-	1022	965	1008	351	-	390	361	397	37.3	-	38.2	37.4	39.4
Sig	-	-	-	1044	1084	-	-	-	323	369	-	-	-	31.0	34.0
Tistrup	1005	1039	1005	1000	1070	453	473	450	409	413	45.1	45.5	44.8	40.9	38.6
Oksbøl	1106	-	1152	1104	1121	423	-	451	405	353	38.2	-	39.1	36.7	31.5
Skovlund	-	1143	1066	885	-	-	429	408	322	-	-	37.5	38.3	36.4	-
Tørring	1129	1233	1111	911	-	392	466	474	418	-	34.7	37.8	42.7	45.9	-
Brædstrup	1135	1153	1046	1097	1249	313	425	403	426	489	27.6	36.9	38.5	38.8	39.2
Ejstrupholm	1049	1095	1048	1039	975	422	485	467	494	473	40.2	44.3	44.6	47.5	48.5
Ringkøbing	1110	1139	991	1198	1383	453	492	474	510	505	40.8	43.2	47.8	42.6	36.5
Tarm	-	-	1075	1031	-	-	-	452	385	-	-	-	42.0	37.3	-
Tim	-	-	1106	1071	-	-	-	489	452	-	-	-	44.2	42.2	-
Ørnhøj-Grønbjerg	-	1095	1059	1023	1048	-	409	442	402	417	-	37.4	41.7	39.3	39.8
Vildbjerg	-	-	-	1148	1184	-	-	-	433	517	-	-	-	37.7	43.7
Feldborg	-	1072	998	876	1018	-	425	417	352	373	-	39.6	41.8	40.2	36.6
Frederiks	-	-	1033	1033	1000	-	-	414	409	390	-	-	40.1	39.6	39.0
Karup	-	-	1113	1111	1057	-	-	450	428	422	-	-	40.4	38.5	39.9
Haderup	-	-	-	-	1237	-	-	-	-	365	-	-	-	-	29.5
Grenå	-	-	-	1244	1074	-	-	-	469	451	-	-	-	37.7	42.0
Mou	-	-	1179	1268	1245	-	-	470	497	464	-	-	39.9	39.1	37.3
Ulsted	1163	1190	-	-	1188	445	450	-	-	408	38.3	37.8	-	-	34.3
Dronninglund	-	-	-	1054	1113	-	-	-	417	426	-	-	-	39.6	38.3
Aså	-	-	-	1140	1118	-	-	-	496	470	-	-	-	43.5	42.0
Jerslev	-	-	-	-	1312	-	-	-	-	463	-	-	-	-	35.3
Sæby	1030	1149	1013	1188	1131	420	488	459	461	420	40.8	42.5	45.3	38.8	37.1
Jetsmark	-	-	-	-	1188	-	-	-	-	456	-	-	-	-	38.4
Vrå	-	-	-	-	1099	-	-	-	-	399	-	-	-	-	36.3
Strandby	1123	1082	1140	1146	1444	481	458	484	518	493	42.8	42.3	42.5	45.2	34.1
Average	1102	1135	1114	1101	1153	411	450	463	439	435	37.3	39.6	41.6	39.9	37.9

In October 2016 the first report on use of meteorological data for CSP performance simulations [5] was presented at the 22nd SolarPACES conference. A short article version of the report was also published subsequently [6]. The report was published in March 2017. Later a roadmap for future development work on meteorological data sets was published in May 2017 [7]. A webinar [8] about this topic was made at the International Solar Energy Society website, and an interview [9] about it was also published at the website of the Global Solar Thermal Energy Council.

Overall the dissemination has been very successful.

1.5.2 Results from measuring in Hedehusene

This section describes the measurements collected from the 3000 m² solar heating plant in Hedehusene, Denmark. The focus is on the difference in radiation at the top of the collector compared to the bottom of the collector. Also measured is the difference in radiation between the 1st row of collectors and the 2nd row of collectors. These data will elucidate the radiation lost because of the shadows cast by the previous row of solar collectors.

The measurements collected at Hedehusene were collected over different days with different weather conditions and with different purposes, see

Table 1.5.

Table 1.5. Overview of the measurements collected at the solar heating plant in Hedehusene, Denmark.

24/9-15	25/9-15	25/9-15	1/10-15
Mix day – top and bottom, 50 cm	Clear day – Sliding test, top and bottom 10 cm	Mix day - top and bottom, 50 cm	Cloudy day - top and bottom, 50 cm
16/3-16	10/5-16	6/6-16	
Cloudy day - top and bottom, 10 cm	Clear day - top and bottom, 10 cm	Clear day- 1st and 2nd row, top	

The surrounding area where the solar heating plant is placed is fields with low vegetation, se Figure 1

East:

South:

West:

Figure 1. The surrounding area of the solar collector field in Hedehusene, Denmark.

To the front of the collectors (south) the ground leans downwards, and has a small pond in the spring and summer months. The pond could influence the measurement for the 1st row, but since the ground is leaning away from the collectors this influence is assumed negligible. The measurements were collected with two portable data loggers only allowing 3 hours of measurements each because of power loss.

Pyranometers placed in front of collectors are used to measure the solar irradiance on the collector plane. The measurements with fixed positions of the pyranometers are collected with two different settings, se Figure 2.

50 cm from the top and bottom of the collector

10 cm from the top and bottom of the collector

Figure 2. Placement of the pyranometers in fixed positions.

In the left panel of Figure 3 the measurements of total radiation are shown for four different locations in the solar heating plant. It can be seen that the weather was a mixture of cloudy and clear sky conditions. The right panel in Figure 3 shows the measured data with two pyranometers fixed 50 cm from the top and bottom of the solar collectors. Also shown on the figure is the relative difference between the two measurements. The difference of the solar irradiance is 5 % in average across the collector.

September 24^{th} 2015

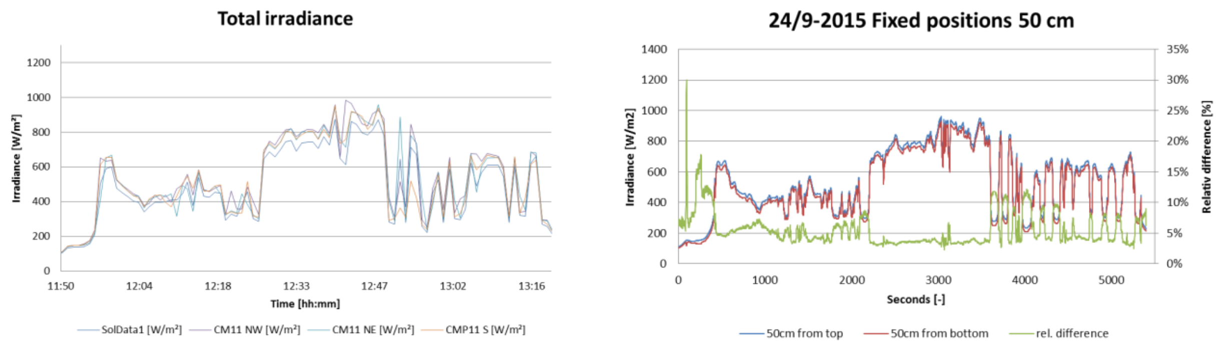

Figure 3. The measurement on September 24^{th} 2015. Left: total irradiance 4 places in the solar heating plant. Right: Fixed top and bottom measurements in the middle of the field.

The measurements shown on Figure 4 are from the 25^{th} of September 2015, where the weather started out cloudy and turned sunny at 13 o'clock. Again the total radiation from 4 locations in the field is shown to the left and the fixed measurements 50 cm from the top and bottom are shown to the right along with the relative difference. The relative difference is again around 5% when there are clouds. When there is a clear sky the relative difference drops to around 4%.

September 25th 2015

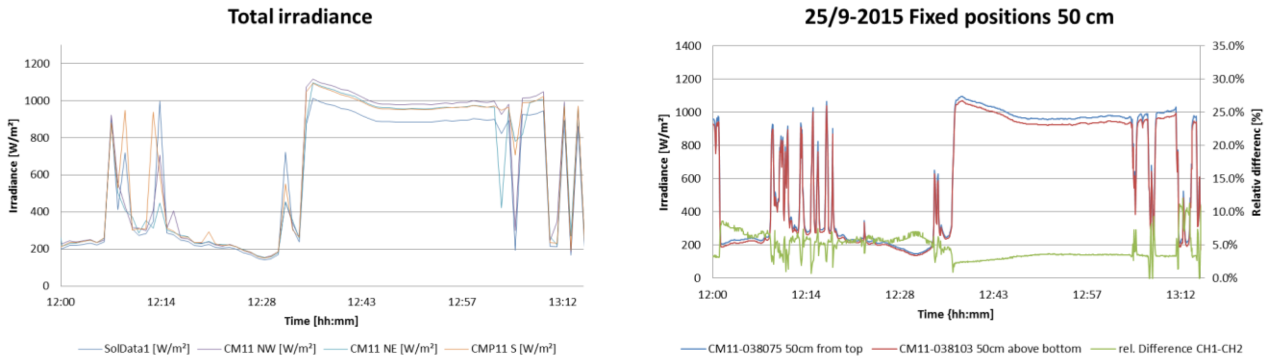

Figure 4. The measurement on September 25th 2015. Left: total irradiance 4 places in the solar heating plant. Right: Fixed top and bottom measurements in the middle of the field.

On Figure 5 data from the 1st of October 2015 are shown. The same tendency is seen as described for the previous days.

October 1st 2015

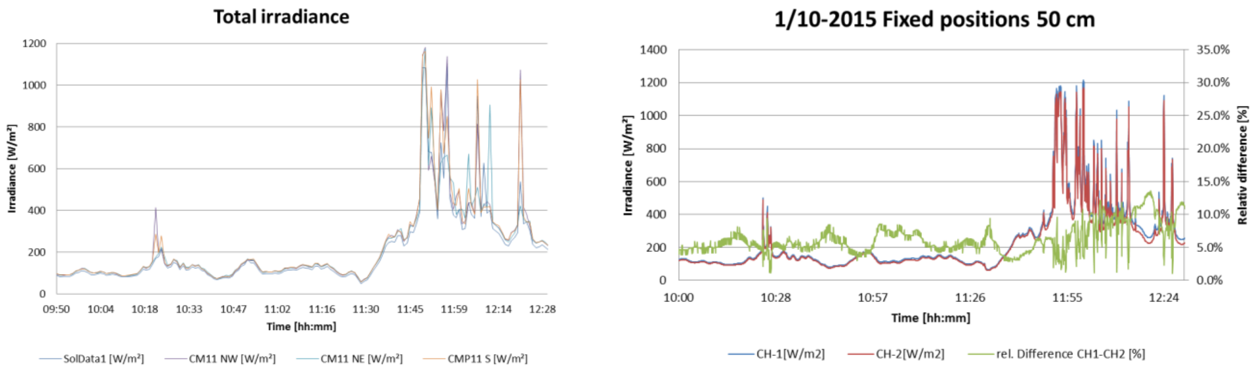

Figure 5. The measurement on October 1st 2015. Left: total irradiance 4 places in the solar heating plant. Right: Fixed top and bottom measurements in the middle of the field.

In Figure 6 the measured data from the portable data loggers is shown for March 16th 2016, which was a cloudy day. Here the position of the pyranometers is changed to 10 cm from the top and bottom. Also the global radiation is measured, which allows the measurement from the top and bottom to be compared with calculations of the total radiation in the same positions.

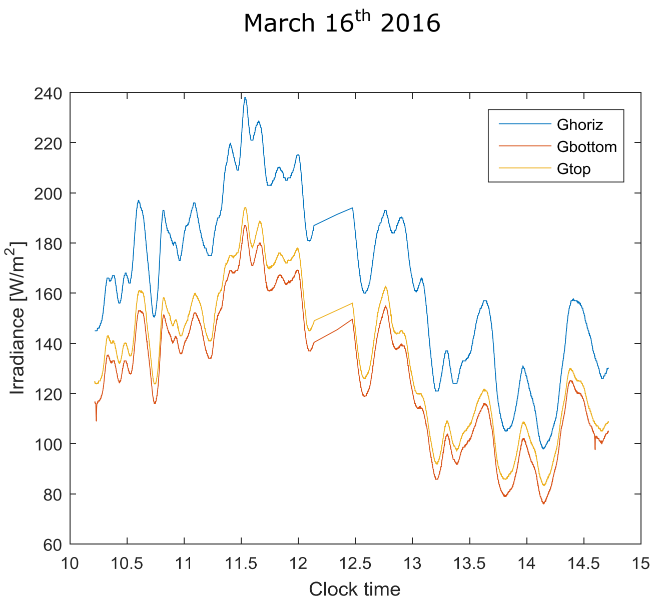

Figure 6. The measurement on March 16th 2016 from fixed positions 10 cm from the top and bottom.

The measured data for May 10th 2016 is shown on Figure 7, here it can be seen that it was a clear day.

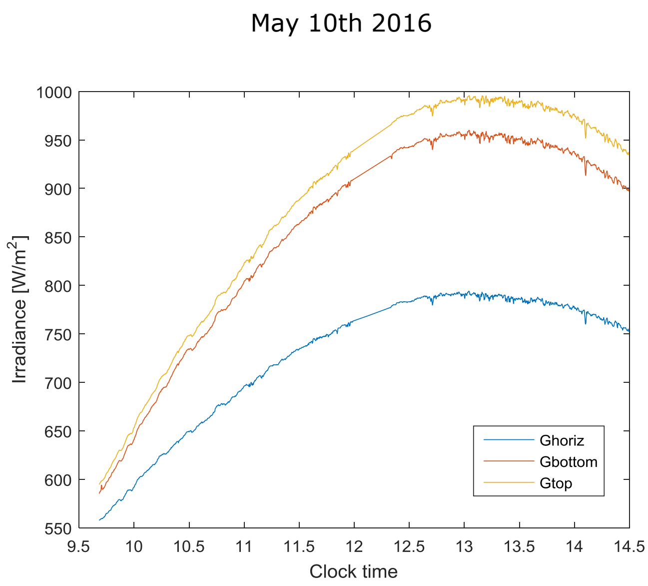

Figure 7. The measurement on May 10th 2016 from the fixed positions 10 cm from the top and bottom. in the middle of the field.

The sliding test was performed with one pyranometer fixed at the bottom of the collector and one pyranometer sliding from the top to the bottom on September 24th 2015 and from the bottom to the top on September 12th 2016.

The data collected on September 24th 2015 is shown in Figure 8. On left is shown the total radiation from 4 different locations in the solar heating plant. On the right the measurement from the fixed pyranometer at the bottom is shown (red curve) along with the sliding measurements (blue curve). The absolute and relative differences are also shown. The peak seen in the measurement and more clearly shown on the relative difference is caused by pyranometer tilting on the surface of the glass when it is moved from one position to the next. The duration of the slide test across the collector was on the September 24th 2015 approximately 1 minute and 20 seconds. The pyranometer stayed 10 seconds in each position. The slide was performed when there were no clouds in front of the sun.

September 24th 2015

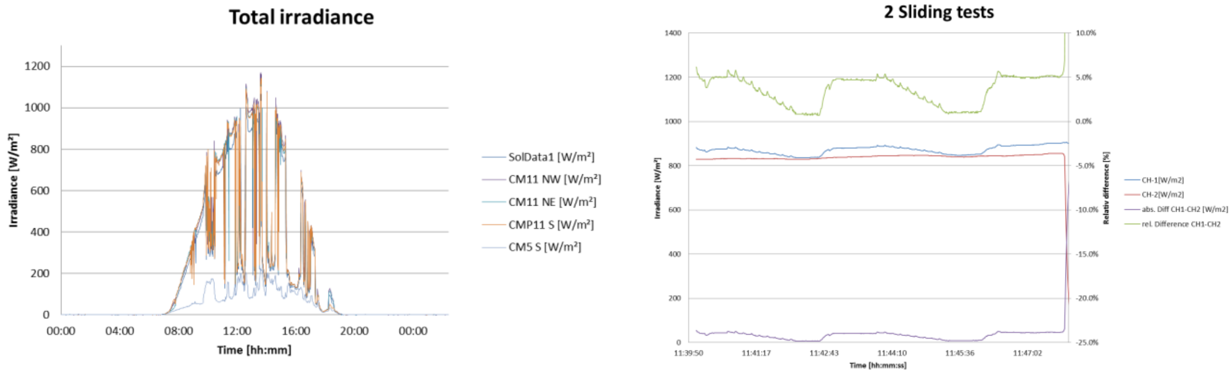

Figure 8. The measurement on September 24th 2015. Left: total irradiance 4 places in the solar heating plant. Right: Sliding test measurements in the middle of the field.

On September 12th 2016 4 additional slide tests were performed, see Figure 9. Here the sliding was from the bottom to the top, avoiding the tilting on the surface of the glass when the pyranometer was moved from one position to the next. The pyranometer was here placed in each position for 30 seconds.

September 12th 2016

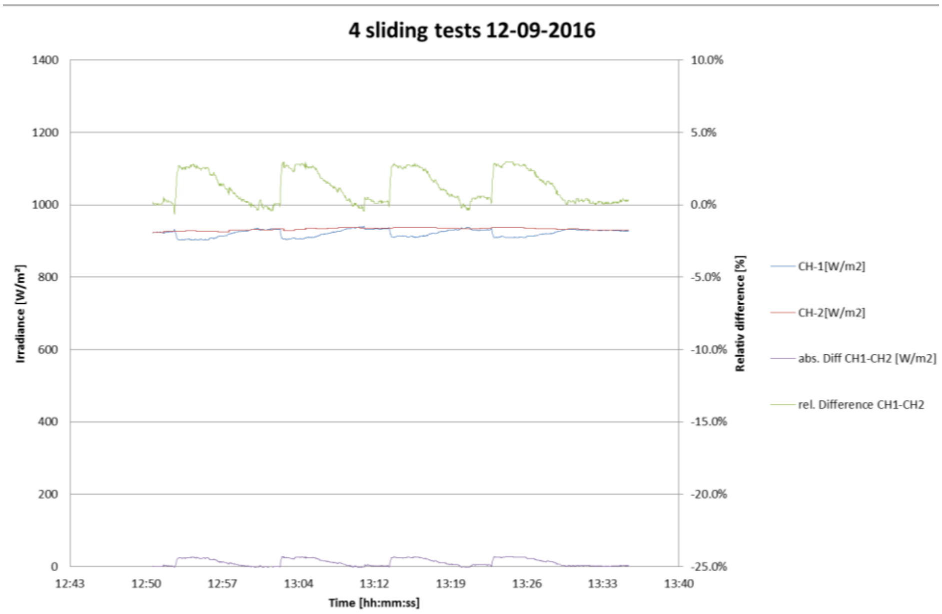

Figure 9. The measurement on September 12th 2016 from 4 sliding tests.

In order to elucidate how much a collector row influence the following collector row in terms of shadows and drop in solar radiation, measurements on the top of collectors were collected from the 1st and 2nd row at the solar heating plant in Hedehusene. On Figure 10 pictures are shown of the placement of the pyranometers.

1st row   2nd row

Figure 10. Placement of the pyranometers on the 1st row and the 2nd row.

The measurements collected are shown on Figure 11, where it can be seen that it was a clear day. As can be seen the measurements consists of total radiation on the two collectors along with the diffuse radiation measured on the 2nd row.

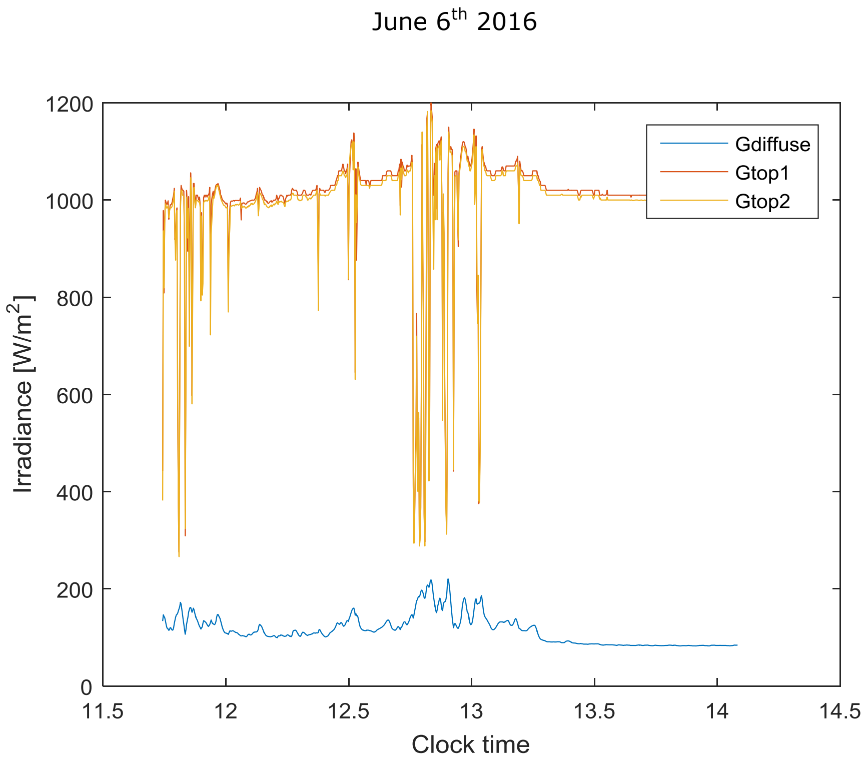

Figure 11. The measurement on June 6th 2016 from the 1st and 2nd row.

The measurements from the fixed positions are shown for the 16th of March 2016 and 10th of May 2016, see Figure 12 and Figure 13. The figures show that there is a difference from the bottom to the top of the collector of around 3% of the radiation received on the top. The difference is a function of the irradiance. On cloudy days the differences are higher but also more fluctuating.

March 16th 2016

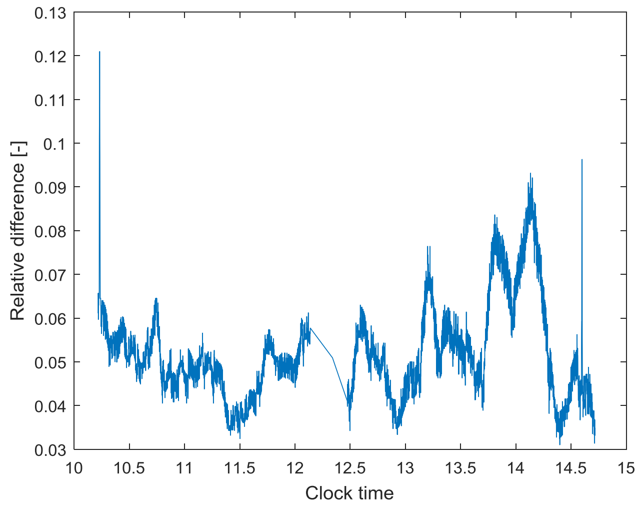

Figure 12. The relative difference between the top and bottom positions in the middle of the solar heating plant on a cloudy day.

May 10th 2016

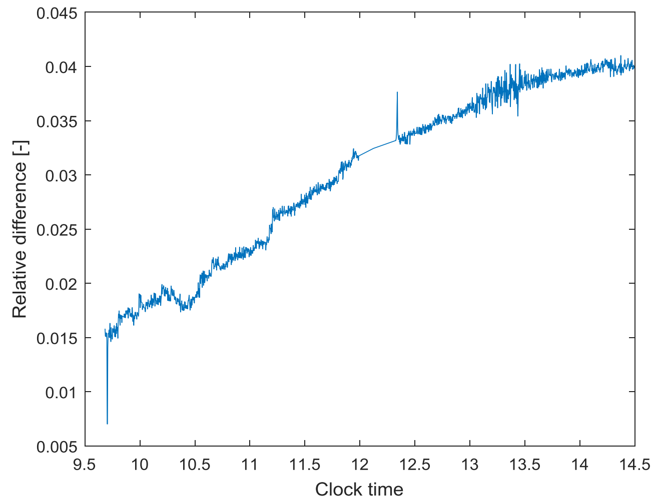

Figure 13. The relative difference between the top and bottom positions in the middle of the solar heating plant on a clear day.

The total radiations at the top and bottom of the collectors are calculated using the theory developed by Skartveit and Olseth for the diffuse radiation and an isotropic sky assumption for the total radiation. The reflection coefficient for the ground is assumed to be 0.1. The viewfactor between the collector and the sky is as an approximation assumed to be the ratio between the two angles from which the collectors can see the sky, see Figure 14.

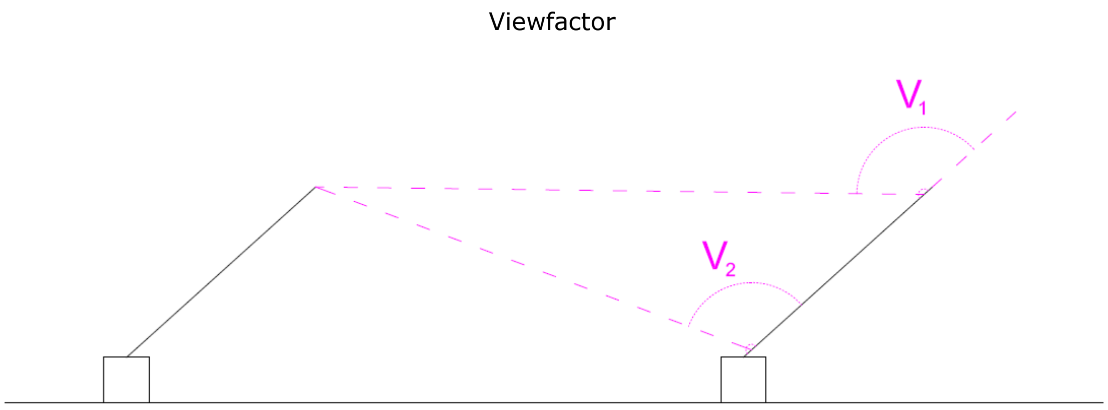

Figure 14. Sketch of the collector rows.

The result from the calculations can be seen in Figure 15 and Figure 16. On a cloudy day the calculations of the solar irradiance on the top of the collector is over estimating the total radiation with 9%, where the calculations of the bottom total radiation is underestimated with 3 %.

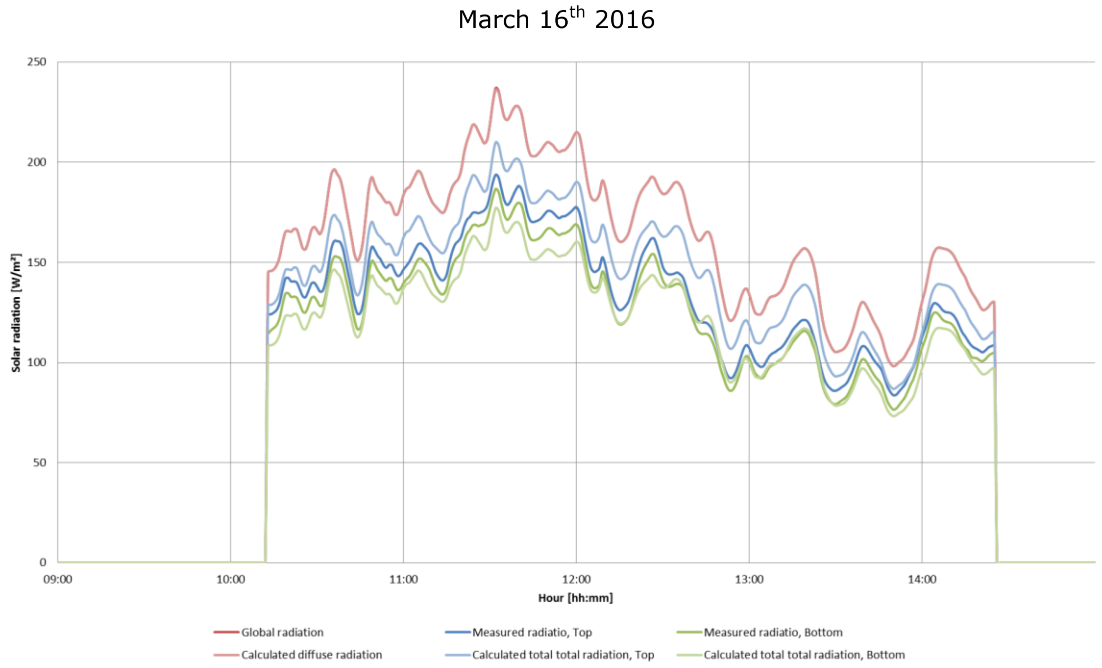

Figure 15. Measured and calculated result from the 16th of March 2016.

On a clear day the calculation of the total radiation on the top pyranometer is only slightly different from the measured results. For the bottom calculation the figures shows that the radiation is over estimated with approximately 2 %.

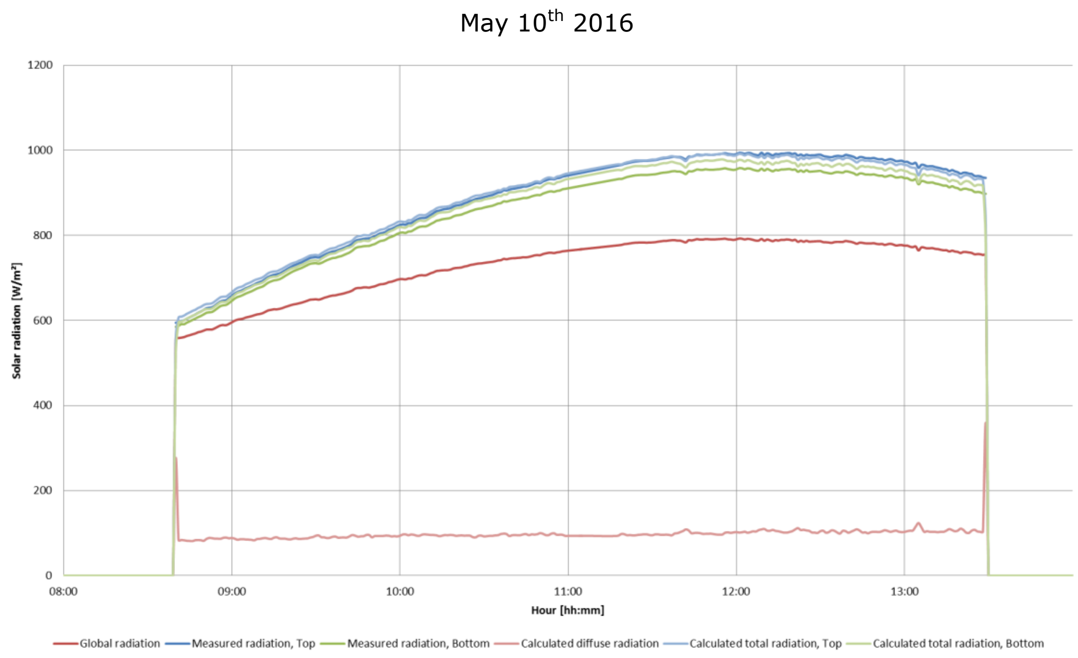

Figure 16. Measured and calculated result from the 10th of May 2016.

1.5.3 Sliding test

The results from the sliding tests support the results from the fixed measurements. Again the difference across the collector is approximately 3 % of the total radiation received at the top of the collector, see Figure 12 and Figure 13.

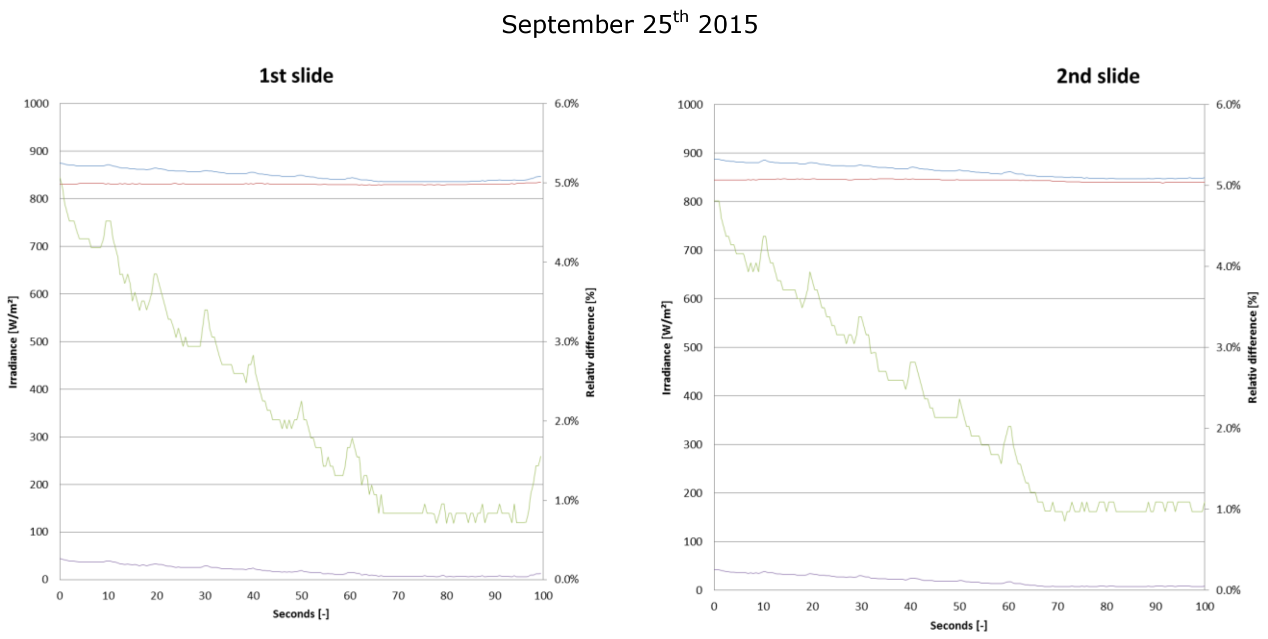

Figure 17. The absolute and relative difference between the fixed pyranometer at the bottom compared with the sliding pyranometer from September 25th 2015.

September 12th 2016

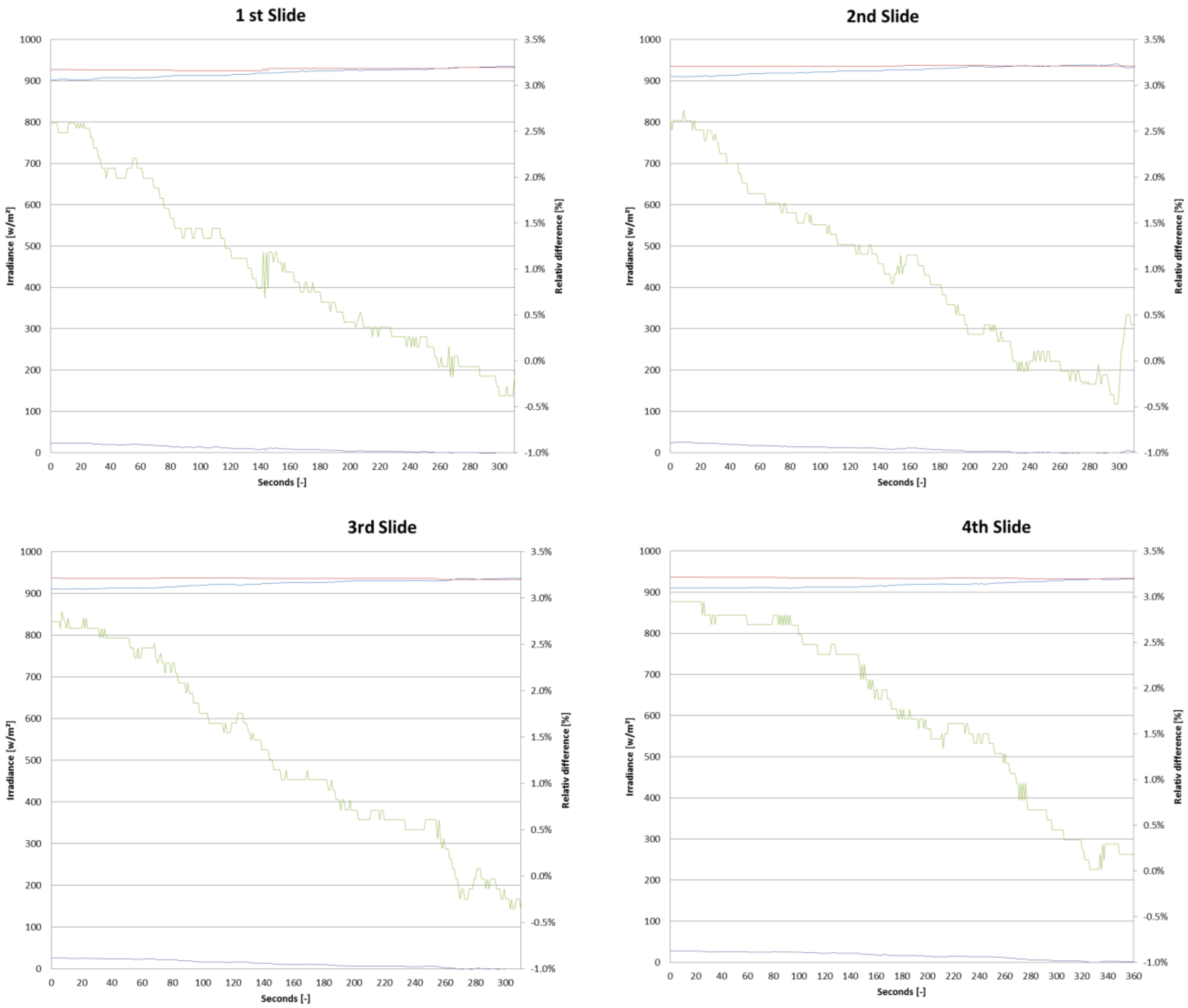

Figure 18. The absolute and relative difference between the fixed pyranometer at the bottom compared with the sliding pyranometer from September 12th 2016.

The results from the 1st and 2nd row are shown on Figure 19. The difference is here approximately 10 %, which means that there is a 10 % reduction in the diffuse radiation received by the second row of collectors due to shadows from the first row.

June 6th 2016

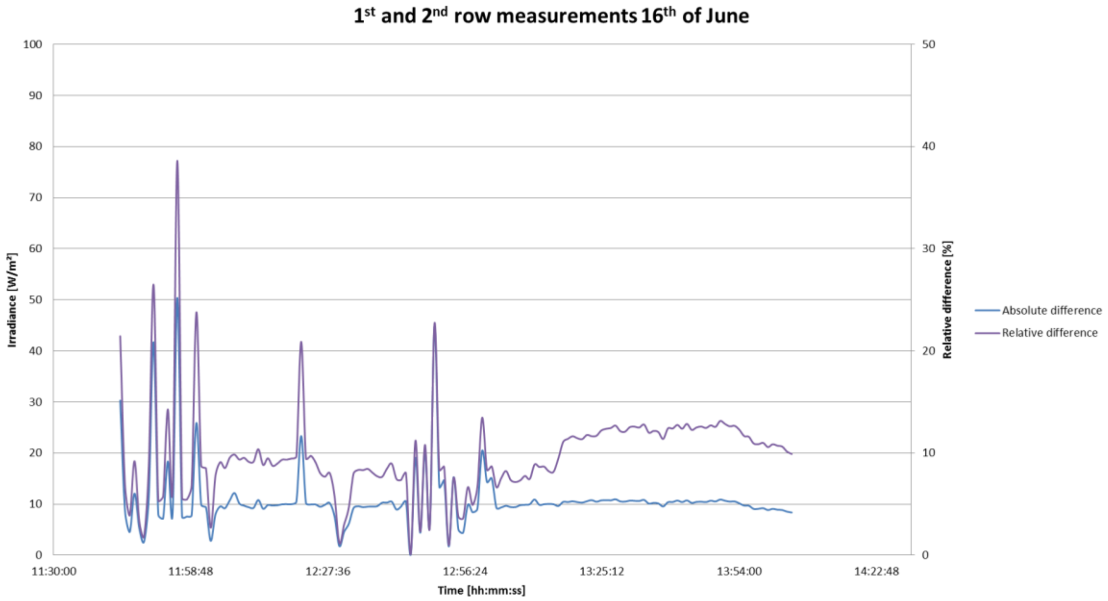

Figure 19. The results on June 6th 2016 from the 1st and 2nd row.

To conclude, our *in situ* investigations of the solar heating plant in Hedehusene show:

- The measured reduction in diffuse radiation from 1st to 2nd row in a collector field is about 10%.
- The measured reduction in solar radiation across collectors in a collector field from top to bottom is about 3% on sunny days.
- Measured reduction in solar radiation across collectors in a collector field from top to bottom is higher than 3% on cloudy days, and also more fluctuating.
- The calculated solar radiation is overestimating the solar radiation in the top of the collectors on cloudy days.
- The calculated solar radiation is underestimating the solar radiation in the bottom of the collectors on cloudy days.
- The calculated solar radiation is overestimating the solar radiation in the bottom of the collectors on clear days.

Moving on, there is a need for further investigations of reduction in solar radiation in solar heating plants due to shadows. This investigation should be carried out with additional focus on the existing calculation models for total solar radiation and their fit with the conditions in a solar heating plant. The investigations should be carried out with different collector tilts and row distances. Optimally, this should be done at a designated test site, as the site at DTU Byg.

1.6 Utilization of project results

By quantifying the solar resource available in Denmark and its temporal variability to a higher level of detail, our project provides the potential for better utilizing solar energy in Denmark and thereby contributes to the overall goal of making Denmark independent of fossil fuels.

As this is an international collaboration project some of our work is at a low technology readiness level. The discussion report of the utilisation of meteorological data set is thus quite far ahead of anything that would be used in an ISO or IEC standard. Nevertheless, this work pushes international work at the R&D level closer toward general usage by solar energy consultants and ultimately toward standardisation.

1.7 Project conclusion and perspective

Our work on monitoring the directional solar resource has been well maintained. We have temporarily extended this to include *in situ* measurement in a solar heating plant. In the future we plan to rather do such measurement at the DTU Byg measurement site

The leadership in SHC Task 46 Activity B.5 was extended to SolarPACES Task V and has completed successfully. After SHC Task 46 has finished, it has been approved that the international group can continue under the auspices of IEA PVPS, more specifically in the task 16: "Solar resource for high penetration and large scale applications" (2017-2020). Although this a task in the PVPS programme, it will be coordinated closely with the IEA SHC and SolarPACES programmes. Both DMI and DTU Byg plan to contribute to this new task.

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