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YEARLY THERMAL PERFORMANCES OF SOLAR HEATING PLANTS IN DENMARK – MEASURED AND CALCULATED

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Abstract

The thermal performance of solar collector fields depends mainly on the mean solar collector fluid temperature of the collector field and on the solar radiation. For Danish solar collector fields for district heating the measured yearly thermal performances per collector area varied in the period 2012-2016 between 313 kWh/m² and 577 kWh/m², with averages between 411 kWh/m² and 463 kWh/m². The percentage difference between the highest and lowest measured yearly thermal performance is about 84%. Calculated yearly thermal performances of typically designed large solar collector fields at six different locations in Denmark with measured weather data for the years 2002-2010 vary between 405 kWh/m² collector and 566 kWh/m² collector, if a mean solar collector fluid temperature of 60°C is assumed. This corresponds to a percentage difference between the highest and lowest calculated yearly thermal performance of about 40%. This variation is caused by different weather conditions from year to year and from location to location. Approximately half of the variations of yearly thermal performances can be related to variable weather conditions.

Keywords: Solar heating plants, yearly thermal performance, solar radiation.

Nomenclature

η collector efficiency, -
θ incidence angle, °
K_θ incidence angle modifier, -
G solar irradiance on the solar collector, W/m²
Gb direct radiation on horizontal, W/m²
Rb geometric factor, -
T_m mean solar collector fluid temperature, °C
T_a ambient temperature, °C

1. INTRODUCTION

The number of solar heating plants in Denmark for district heating has increased strongly in the last couples of years (Windeleff and Nielsen, 2014) and (Bava, Dragsted and Furbo, 2017). Denmark is today frontrunner worldwide on large solar heating plants connected to district heating systems (Weiss, Spörk-Dür and Mauthner, 2017). In 2016 about 500,000 m² solar collectors were installed in large scale solar heating plants. By the end of 2016, 110 solar heating plants with a total collector area of more than 1,300,000 m² were in operation. The solar collector fields are based on a high number of parallel connected rows of serial connected collectors mounted on the ground. In most of the solar heating plants flat plate solar collectors are used, see figure 1.

Figure 1. Solar collector field with a high number of rows with flat plate collectors.

The solar collector fluids in the solar collector loops are propylene glycol/water mixtures. Flat plate heat exchangers are used to transfer the heat produced by the solar collectors from the solar collector fluid to water in the secondary loop. In order to achieve a good cost efficiency of the solar heating plants it is important that the thermal performances of the plants are as high as expected. The heat production of all the solar collector fields is measured.

This paper summarizes measured yearly thermal performances of Danish solar heating plants for the period 2012-2016 as well as theoretically calculated yearly thermal performances of a typical solar heating plant based on measured weather data for different locations in Denmark. The locations of the plants are in the paper indicated by region numbers according to figure 2, which shows six different regions for Demark as suggested by (Wang, Scharling and Nielsen, 2012). The yearly thermal performance vary from plant to plant and for one plant from year to year. This work elucidate how much of the variation are caused by different weather conditions from location to location and from year to year.

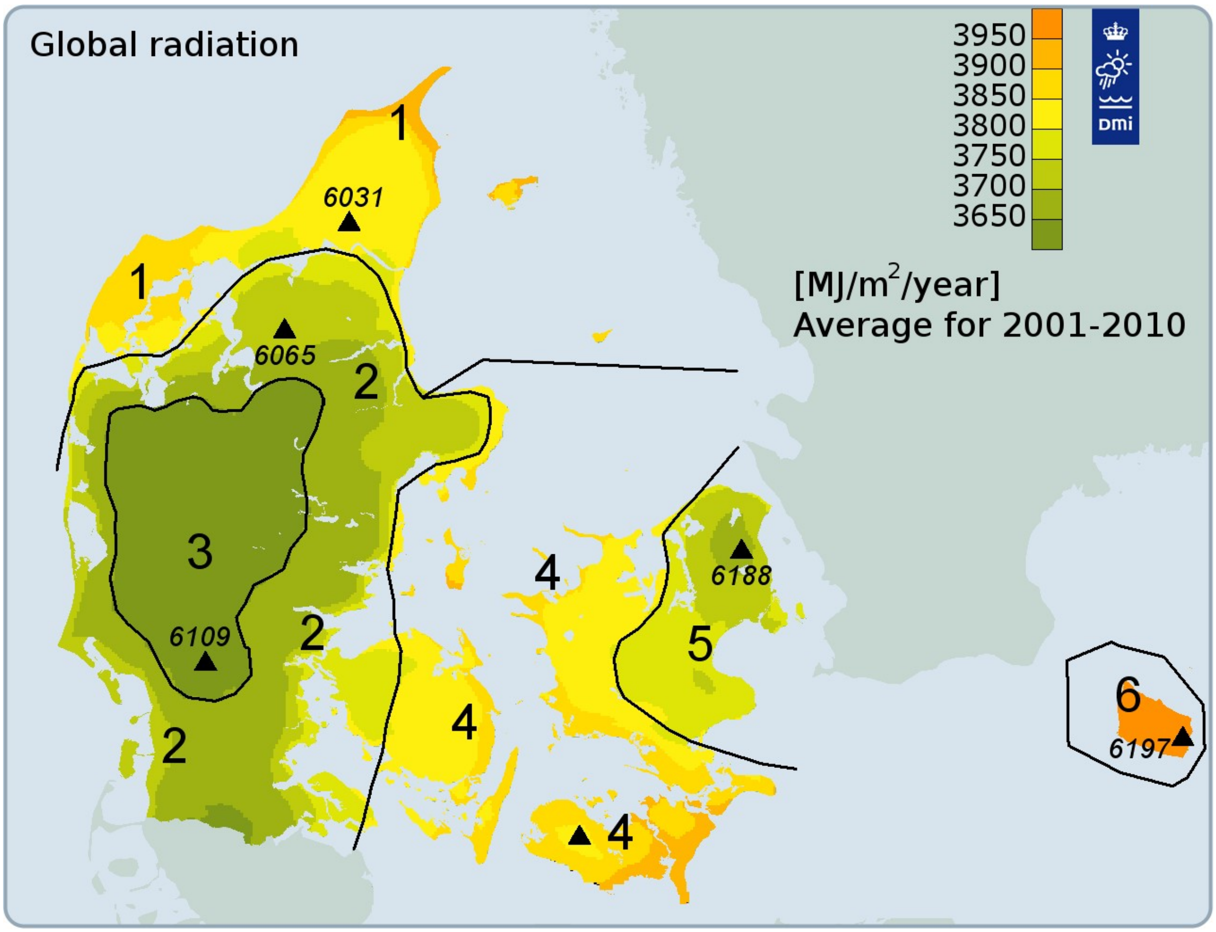

Figure 2. Six Danish regions with different solar radiation.

2. MEASURED YEARLY THERMAL PERFORMANCES OF SOLAR COLLCTOR FIELDS

The thermal performances of all Danish solar heating plants are measured. The measurements of the thermal performance are carried out with conventional energy meters in the secondary loop with water as the heat transfer fluid. The solar radiations are typically measured with inexpensive pyranometers on the top of collectors inside the collector fields. Most of the measurements are available on the website www.solvarmedata.dk (2017). Information for most of the solar heating plants, such as collector manufacturer, collector area, ground area of the collector field, collector tilt, year of installation, etc. is also available. The solar collectors in all the solar heating plants face south and the solar collector tilts vary in the interval from 30° to 45°. Most of the solar heating plants have collector tilts between 35° and 40°.

Table 1 lists 48 solar heating plants inclusive the region numbers of the locations with available measurements of the thermal performance for all months of 2012, 2013, 2014, 2015 and/or 2016. The solar heating plants were installed in the period 1996-2015. All the plants have flat plate collectors either from ARCON Solar A/S and/or from SUNMARK

Solutions A/S. Arcon-Sunmark A/S was established in 2015 as the fusion of the two companies. The collector aperture areas of the solar heating plants are in the interval 2970 m² - 70000 m². The average solar collector area for the 48 solar heating plants is 12756 m². The table shows the measured yearly thermal performance, the measured yearly solar radiation on the solar collectors and the yearly utilization of the solar radiation for the solar heating plants for 2012, 2013, 2014, 2015 and/or 2016. The thermal performance and the solar radiation are given per m² solar collector aperture area. The utilization of the solar radiation is the ratio between the thermal performance of the solar collector field and the solar radiation on the collectors of the solar collector field. Measurements from 16, 21, 31, 36 and 41 plants are available for 2012, 2013, 2014, 2015 and 2016.

The measured yearly thermal performances of the solar heating plants per collector area ranged from 313 kWh/m² to 577 kWh/m² with averages for all plants of 411kWh/m², 450 kWh/m², 463 kWh/m², 439 kWh/m² and 435 kWh/m² for 2012, 2013, 2014, 2015 and 2016, respectively. The measured yearly solar radiations on the solar collectors were in the interval 876 kWh/m² collector - 1474 kWh/m² collector with averages for all plants of 1102 kWh/m² collector, 1135 kWh/m² collector, 1114 kWh/m² collector, 1101 kWh/m² collector and 1153 kWh/m² collector for 2012, 2013, 2014, 2015 and 2016. The yearly utilizations of the solar radiation were in the interval 27.6% - 50.8%, with averages for all plants of 37.3%, 39.6%, 41.6%, 39.9% and 37.9% for 2012, 2013, 2014, 2015 and 2016. It is estimated that the measured thermal performances and utilizations of the solar radiation for all the plants are satisfactory high.

There are many reasons for the differences in thermal performances between the different solar heating plants. First of all, different weather conditions from location to location and from year to year will influence the yearly thermal performance. (Adsten, Perers and Wäckelgård, 2001) and (Andersen and Furbo, 2009) have for Swedish and Danish locations shown that both the yearly thermal performance of solar collectors and the yearly utilization of solar radiation of solar collectors will increase for increasing yearly solar radiation. This also appear from figure 3, which for all plants in the different regions for all years shows the yearly thermal performances as functions of the yearly solar radiation on the solar collectors. Further, there are different temperature levels in the different district heating systems. This will result in different temperature levels in the solar collector fields and therefore in different thermal performances. The lower the temperature level is, the higher the thermal performance.

Furthermore, the different solar collector types, the different designs of the solar collector fields, the different control strategies including the different flow rates and maybe the different uneven flow distributions in the solar collector fields will influence the thermal performance. For instance, (Bava and Furbo, 2016) showed that the flow rate will influence the flow distribution and efficiency of solar collectors and (Rohde and Knoll, 1976), (Dorantes, Garcia, Salazar, Oviedo, Gonzalez, Alanis, Salazar and Martin-Dominguez, 2014) and (Bava and Furbo, 2017) showed that the flow rate influence the flow distribution and thermal performance of a solar collector field.

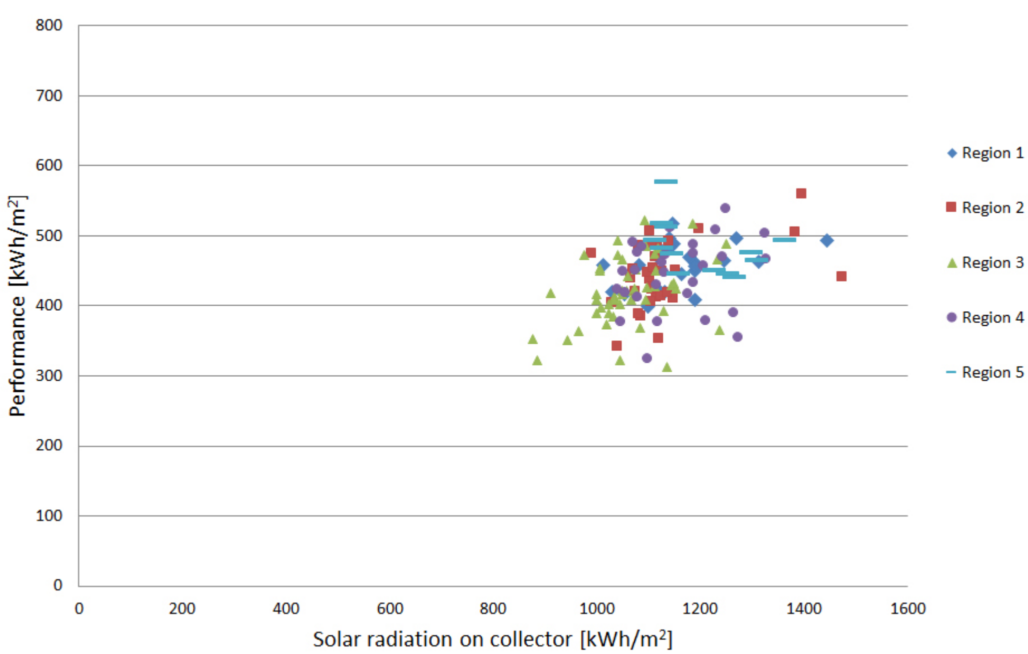

Figure 3. Yearly thermal performances as function of yearly solar radiation on solar collectors for all plants and years.

Additionally, the different heat losses from the pipes in the solar collector loops, the different collector tilts, the different shading conditions, the different moisture conditions inside the solar collectors, the different snow conditions, and the different dirt conditions on the glass covers of the solar collectors may influence the thermal performance. Finally, some plants have long term heat storages charged at high temperatures during summer resulting in a relatively lower thermal performance per m² collector.

3. CALCULATED YEARLY THERMAL PERFORMANCES OF SOLAR COLLECTOR FIELDS

Yearly thermal performances of a solar collector field have been calculated for the six different Danish locations shown in figure 2. The calculations have been done with a typical marketed solar collector from Arcon-Sunmark A/S, HTHEATstore 35/10 with the efficiency and incidence angle modifier based on the aperture area given by (Månsson and Aronsson, 2016):

$$\eta = K_\theta \cdot 0.802 - [2.226 \cdot (T_m - T_a)/G] - [0.010 \cdot (T_m - T_a)^2/G]$$

$$K_\theta = 1 - \tan^{3.1}(\theta/2)$$

The collector has a polymer foil between the absorber and the cover glass.

Calculations are carried out for each location and each year with measured weather data from the period 2002-2010. An hourly value for the global radiation on horizontal is measured for every hour of the years. The method described by (Dragsted and Furbo, 2012) is used to calculate the hourly diffuse and direct radiation on horizontal G_b. The hourly direct radiation on the collector plane is determined by $R_b \cdot G_b$. The direct radiation on the collectors is decreased by shadows from the collector row in front of the collector row in question. The reduction of direct radiation is proportional to the shaded area in relation to the total collector area of the row.

The diffuse radiation on horizontal is converted to tilted diffuse radiation using a classical isotropic model, and both diffuse radiation from the sky and from the ground are taken into account. Inside the collector field the diffuse radiation is reduced due to the shading from the collector row in front using view angles from the collector to the sky and to the ground from the middle height of the collector row. Solar angles in the middle of the hour in question are used in the calculations. The diffuse and direct radiation determined as described above as well as the incidence angle for direct radiation are used together with the collector efficiency to determine the hourly thermal performance of the solar collector field. It is estimated that the method will give reasonably accurate results.

A solar collector field with 20 collector rows with 35° tilted collectors facing south is assumed. The row distance is 5.5 m and shadows from one row to the next are considered.

Figures 4 and 5 show the results for the nine years period 2002-2010. These include the measured yearly global radiation on horizontal, the calculated total yearly radiation on the collectors and the calculated yearly thermal performance of the collector field as a function of the mean solar collector fluid temperature which is assumed constant during all operation periods for region 1, see figure 2. Further, the values for the design reference year for the region (Wang, Scharling and Nielsen, 2012) are included in the figures. The performance ratio included in figure 5 is defined as the ratio between the thermal performance of the solar collector field for the year in question and the thermal performance of the solar collector field for the reference year for the region.

Quantities similar to the quantities shown for region 1 are shown for region 2, 3, 4, 5 and 6 in figures 6-15. It should be mentioned that solar radiation measurements for 2004 for region 5 are not available and therefore omitted.

Solar heating plant/region number	Solar radiation, kWh/m²					Thermal performance, kWh/m²					Utilization of solar radiation, %				
	2012	2013	2014	2015	2016	2012	2013	2014	2015	2016	2012	2013	2014	2015	2016
Mou/1	-	-	1179	1268	1245	-	-	470	497	464	-	-	39.9	39.1	37.3
Ulsted/1	1163	1190	-	-	1188	445	450	-	-	408	38.3	37.8	-	-	34.3
Dronninglund/1	-	-	-	1054	1113	-	-	-	417	426	-	-	-	39.6	38.3
Aså/1	-	-	-	1140	1118	-	-	-	496	470	-	-	-	43.5	42.0
Jerslev/1	-	-	-	-	1312	-	-	-	-	463	-	-	-	-	35.3
Sæby/1	1030	1149	1013	1188	1131	420	488	459	461	420	40.8	42.5	45.3	38.8	37.1
Jetsmark/1	-	-	-	-	1188	-	-	-	-	456	-	-	-	-	38.4
Vrå/1	-	-	-	-	1099	-	-	-	-	399	-	-	-	-	36.3
Strandby/1	1123	1082	1140	1146	1444	481	458	484	518	493	42.8	42.3	42.5	45.2	34.1
Broager/2	1085	1075	1474	1066	1127	385	420	445	439	449	35.5	39.1	30.2	41.2	39.8
Gråsten/2	-	1103	1114	1099	1115	-	438	469	447	412	-	39.7	42.1	40.7	37.0
Toftlund/2	-	-	-	-	1148	-	-	-	-	410	-	-	-	-	35.7
Christianfeld/2	-	-	1103	1081	1117	-	-	506	485	481	-	-	45.9	44.9	43.1
Vojens/2	-	1124	1107	1039	1029	-	414	427	342	404	-	36.8	38.6	32.9	39.2
Gram/2	1081	1138	1397	-	-	388	419	557	-	-	35.9	36.8	39.9	-	-
Oksbøl/2	1106	-	1152	1104	1121	423	-	451	405	353	38.2	-	39.1	36.7	31.5
Ringkøbing/2	1110	1139	991	1198	1383	453	492	474	510	505	40.8	43.2	47.8	42.6	36.5
Tim/2	-	-	1106	1071	-	-	-	489	452	-	-	-	44.2	42.2	-
Gørding/3	-	1118	1091	-	-	-	482	522	-	-	-	43.1	47.8	-	-
Hejnsvig/3	942	-	1022	965	1008	351	-	390	361	397	37.3	-	38.2	37.4	39.4
Sig/3	-	-	-	1044	1084	-	-	-	323	369	-	-	-	31.0	34.0
Tistrup/3	1005	1039	1005	1000	1070	453	473	450	409	413	45.1	45.5	44.8	40.9	38.6
Skovlund/3	-	1143	1066	885	-	-	429	408	322	-	-	37.5	38.3	36.4	-
Tørring/3	1129	1233	1111	911	-	392	466	474	418	-	34.7	37.8	42.7	45.9	-
Brædstrup/3	1135	1153	1046	1097	1249	313	425	403	426	489	27.6	36.9	38.5	38.8	39.2
Ejstrupholm/3	1049	1095	1048	1039	975	422	485	467	494	473	40.2	44.3	44.6	47.5	48.5
Tarm/3	-	-	1075	1031	-	-	-	452	385	-	-	-	42.0	37.3	-
Ørnhøj-Grønbjerg/3	-	1095	1059	1023	1048	-	409	442	402	417	-	37.4	41.7	39.3	39.8
Vildbjerg/3	-	-	-	1148	1184	-	-	-	433	517	-	-	-	37.7	43.7
Feldborg/3	-	1072	998	876	1018	-	425	417	352	373	-	39.6	41.8	40.2	36.6
Frederiks/3	-	-	1033	1033	1000	-	-	414	409	390	-	-	40.1	39.6	39.0
Karup/3	-	-	1113	1111	1057	-	-	450	428	422	-	-	40.4	38.5	39.9
Haderup/3	-	-	-	-	1237	-	-	-	-	365	-	-	-	-	29.5
Hundested/4	-	-	-	-	1250	-	-	-	-	538	-	-	-	-	43.0
Nykøbing Sjælland/4	-	-	-	1325	1327	-	-	-	503	466	-	-	-	38.0	35.1
Østervang/4	-	-	-	-	1131	-	-	-	-	447	-	-	-	-	39.5
Svebøl-Viskinge/4	-	-	1039	1142	1099	-	-	423	511	324	-	-	40.7	44.7	29.5
Hvidebæk/4	-	-	1186	1207	1186	-	-	474	457	432	-	-	40.0	37.9	36.4
Sydfalster/4	1087	1070	1079	1230	1126	484	491	476	508	462	44.5	45.9	44.1	41.3	41.0
Sydlangeland/4	-	-	1132	1051	1186	-	-	472	448	487	-	-	41.7	42.7	41.1
Marstal/4	1046	1055	1116	1078	-	377	419	429	412	-	36.0	39.7	38.4	38.2	-
St. Rise/4	-	-	-	1177	1118	-	-	-	416	376	-	-	-	35.3	33.6
Ærøskøbing/4	1274	1264	-	-	1210	355	389	-	-	378	27.9	30.8	-	-	31.2
Grenå/4	-	-	-	1244	1074	-	-	-	469	451	-	-	-	37.7	42.0
Vejby/5	-	-	1136	1127	1134	-	-	577	517	512	-	-	50.8	45.9	45.1
Helsinge/5	-	1126	1114	1145	1159	-	483	493	475	446	-	42.9	44.3	41.9	38.5
Jægerspris/5	1267	1363	1300	1309	1251	441	493	476	464	446	34.8	36.2	36.6	35.4	35.7
Skuldelev/5	-	-	-	-	1227	-	-	-	-	451	-	-	-	-	36.8
Average	1102	1135	1114	1101	1153	411	450	463	439	435	37.3	39.6	41.6	39.9	37.9

Table 1: Measured thermal performance for solar heating plants.

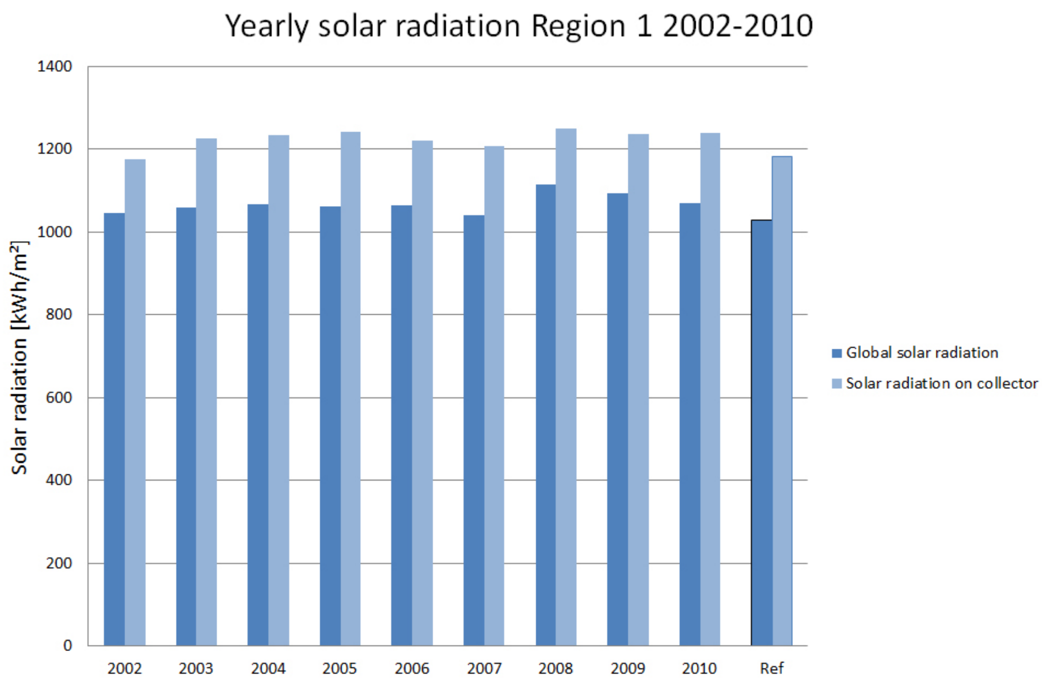

Figure 4. Measured yearly global radiation and calculated yearly solar radiation on collectors for region 1.

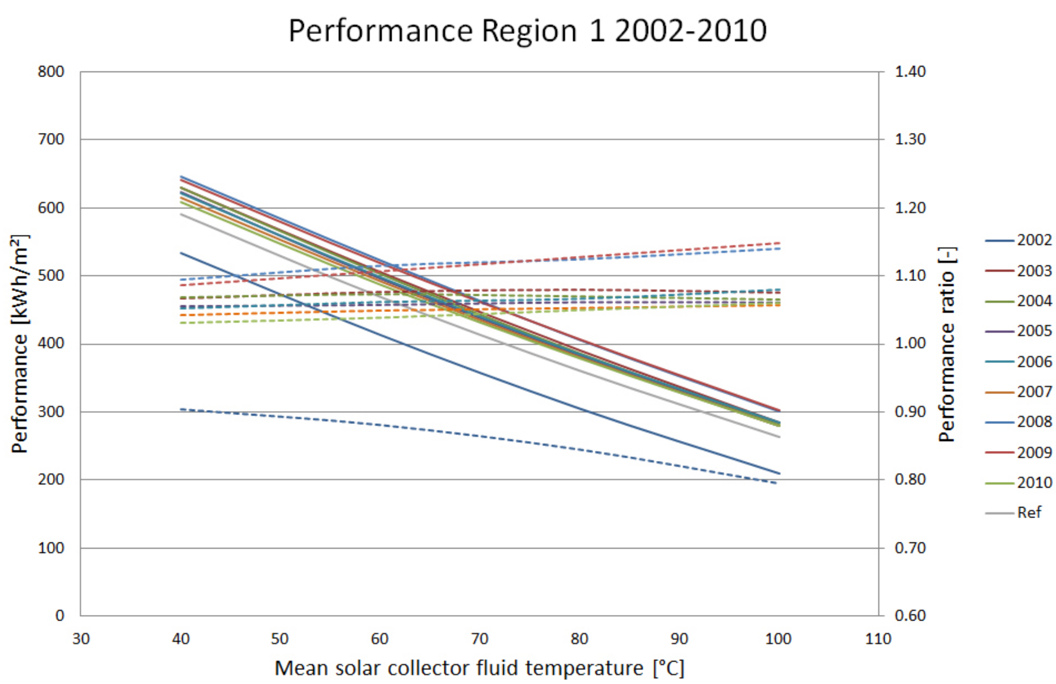

Figure 5. Calculated yearly thermal performance of a collector field for region 1.

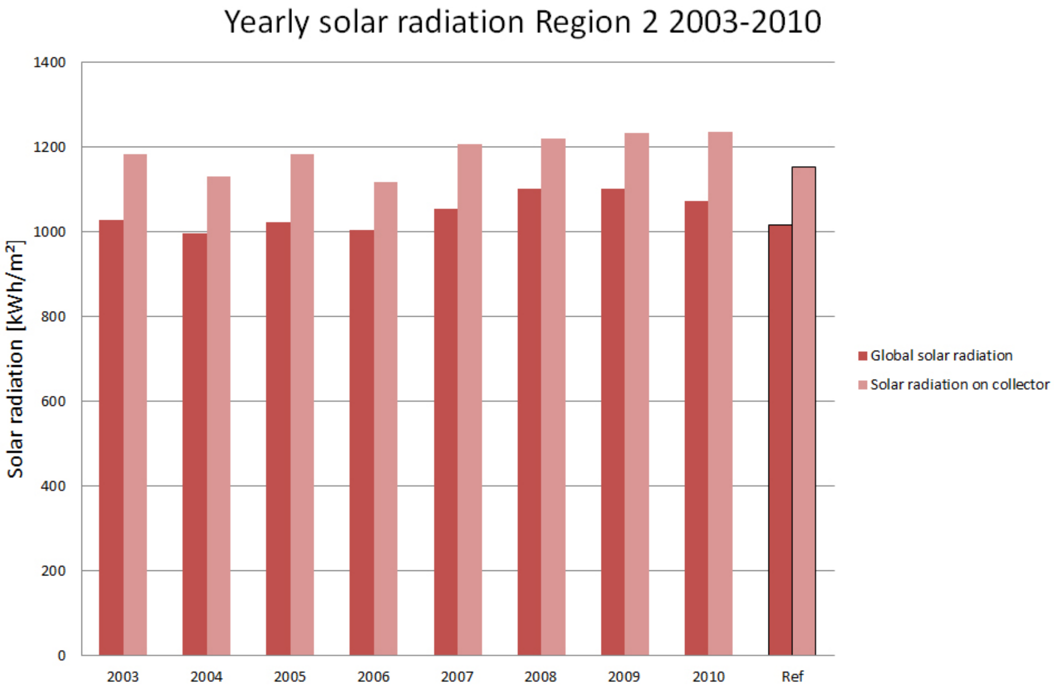

Figure 6. Measured yearly global radiation and calculated yearly solar radiation on collectors for region 2.

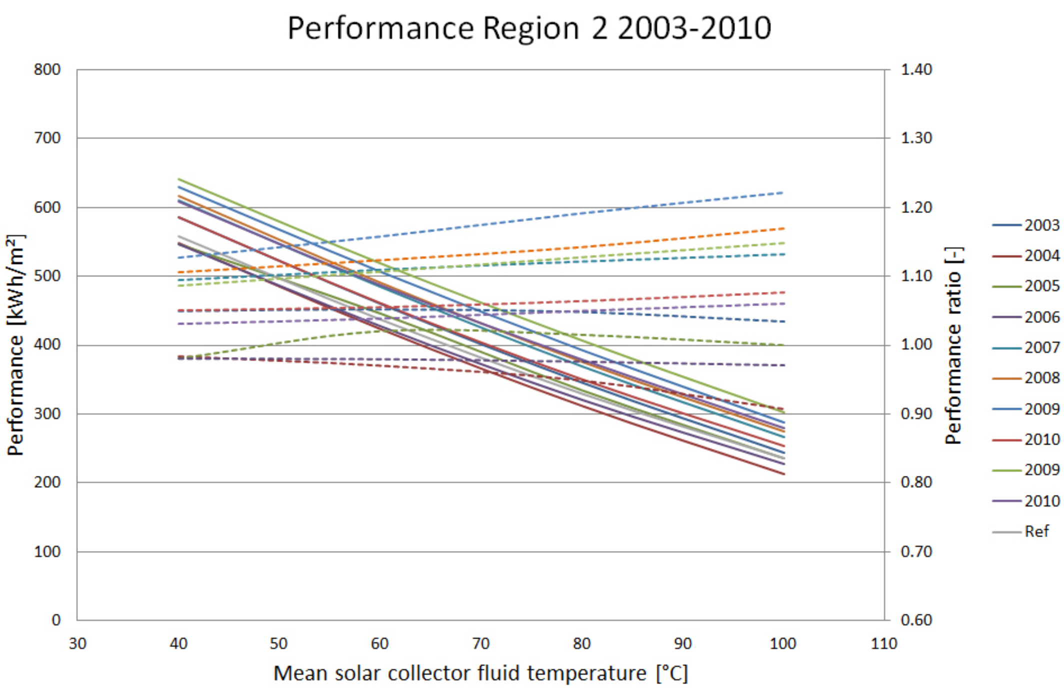

Figure 7. Calculated yearly thermal performance of a collector field for region 2.

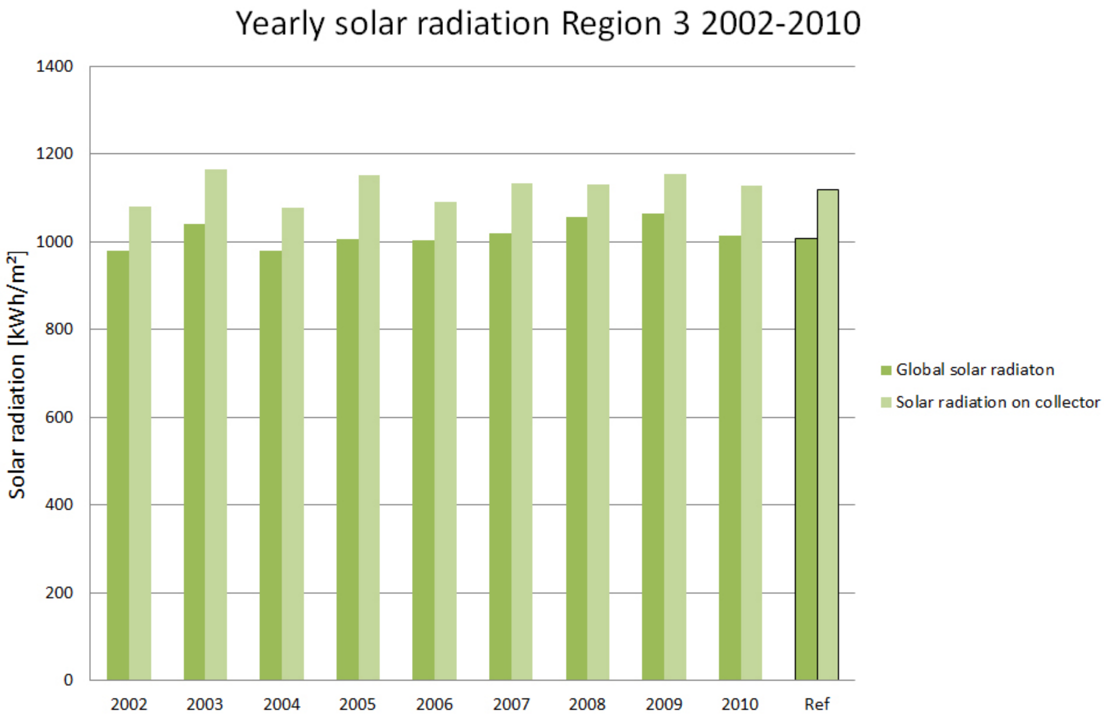

Figure 8. Measured yearly global radiation and calculated yearly solar radiation on collectors for region 3.

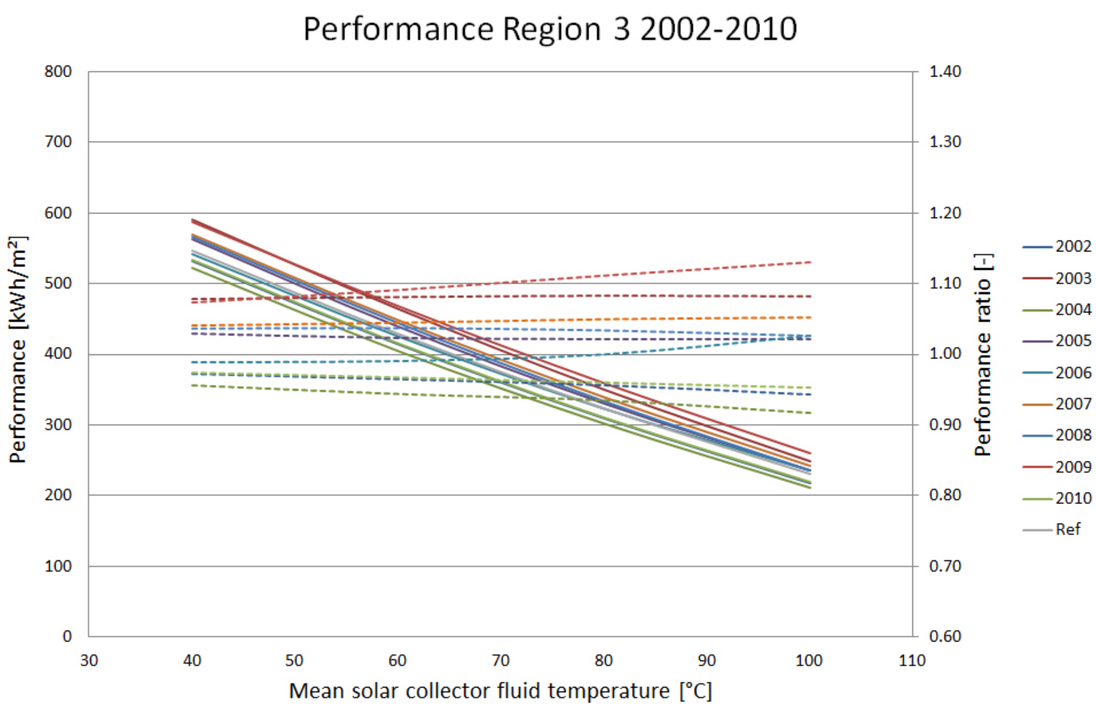

Figure 9. Calculated yearly thermal performance of a collector field for region 3.

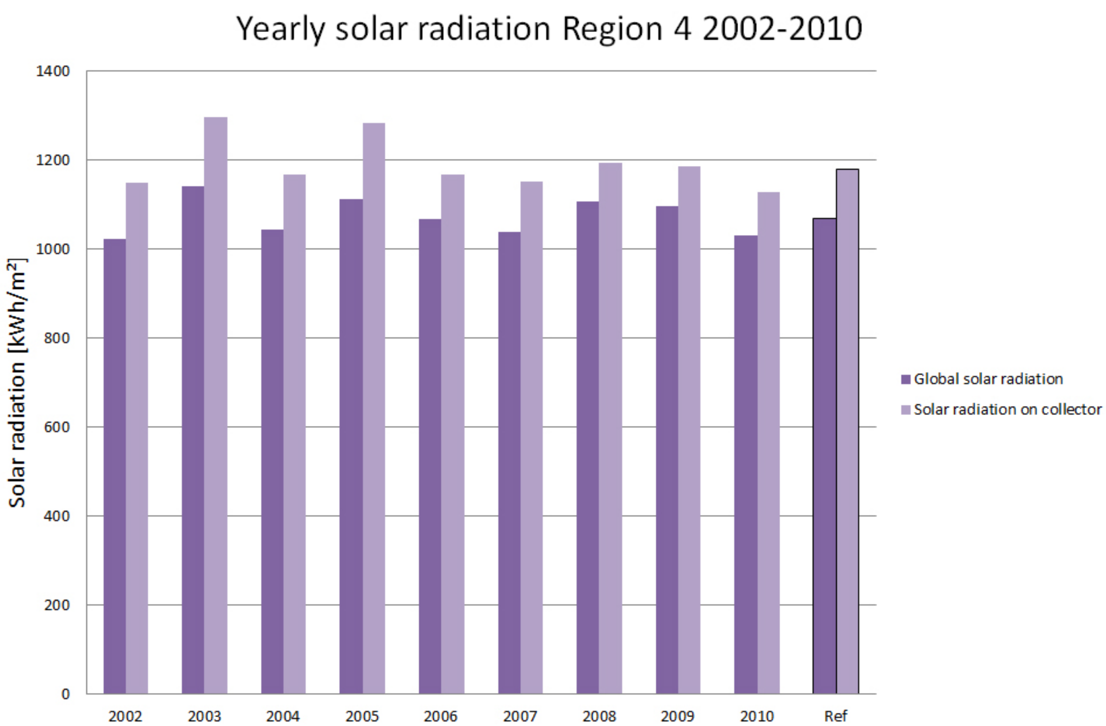

Figure 10. Measured yearly global radiation and calculated yearly solar radiation on collectors for region 4.

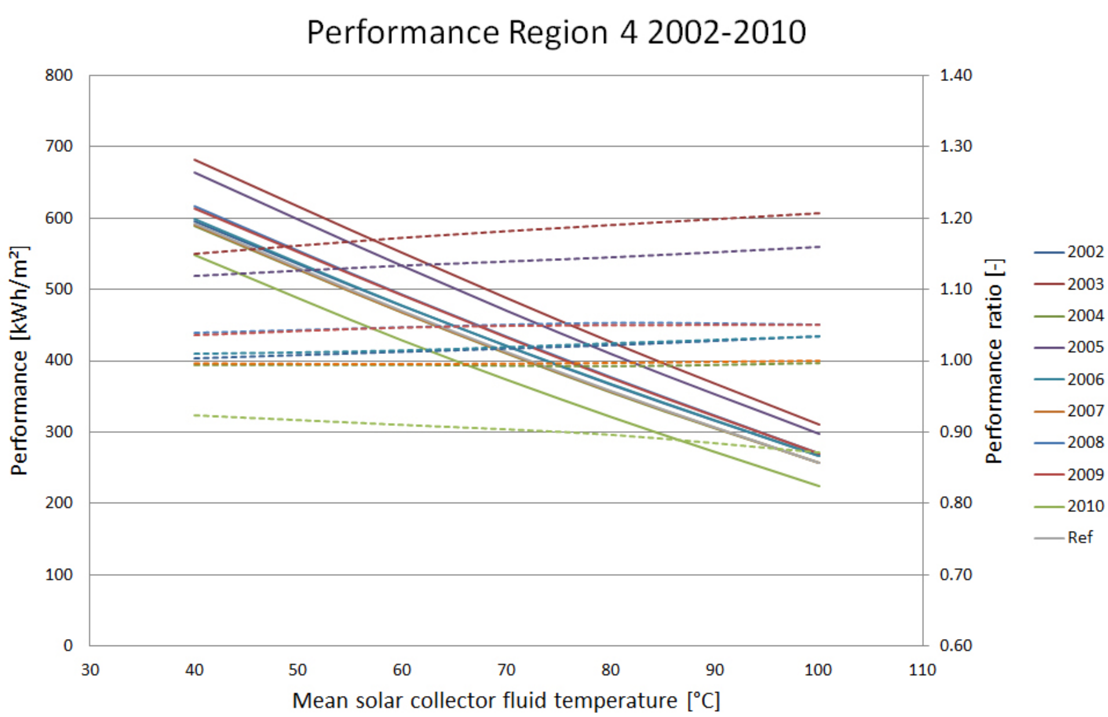

Figure 11. Calculated yearly thermal performance of a collector field for region 4.

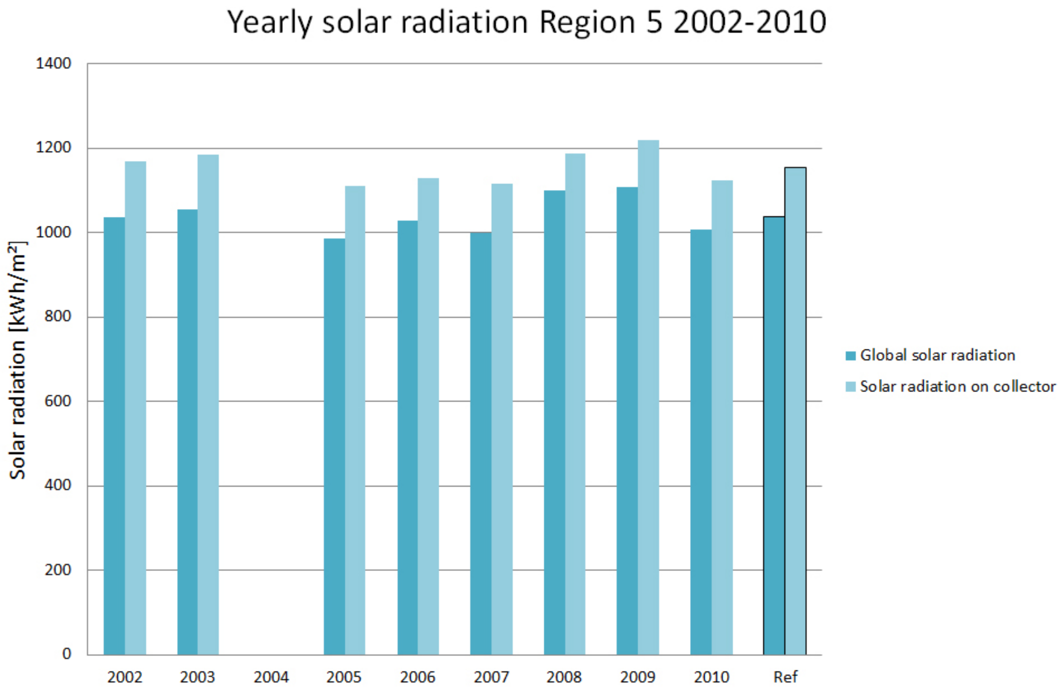

Figure 12. Measured yearly global radiation and calculated yearly solar radiation on collectors for region 5.

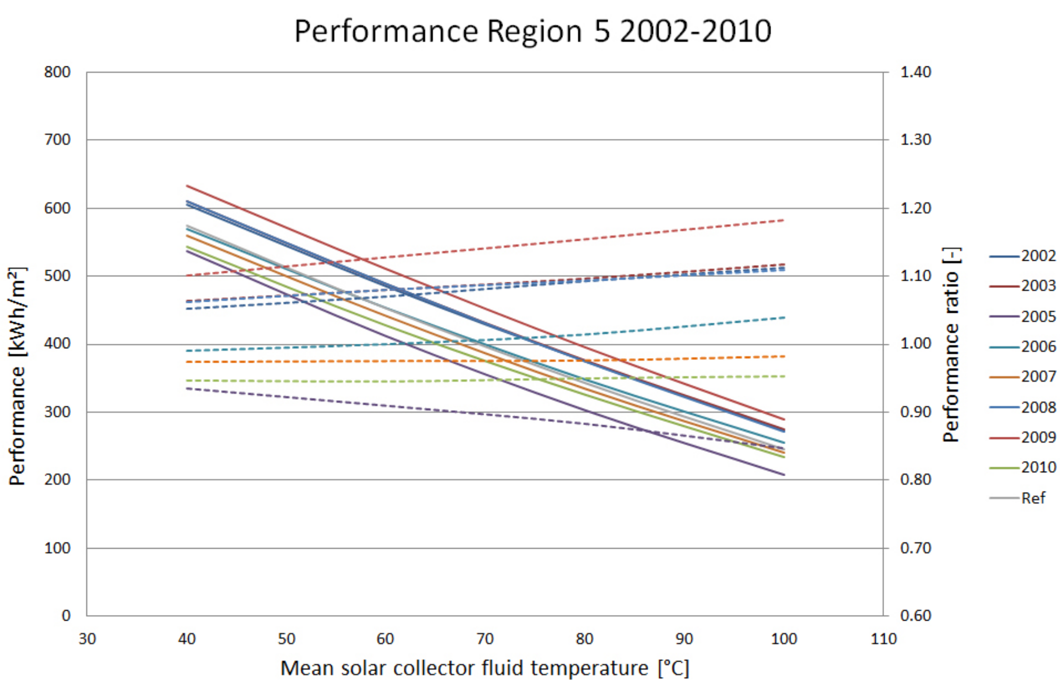

Figure 13. Calculated yearly thermal performance of a collector field for region 5.

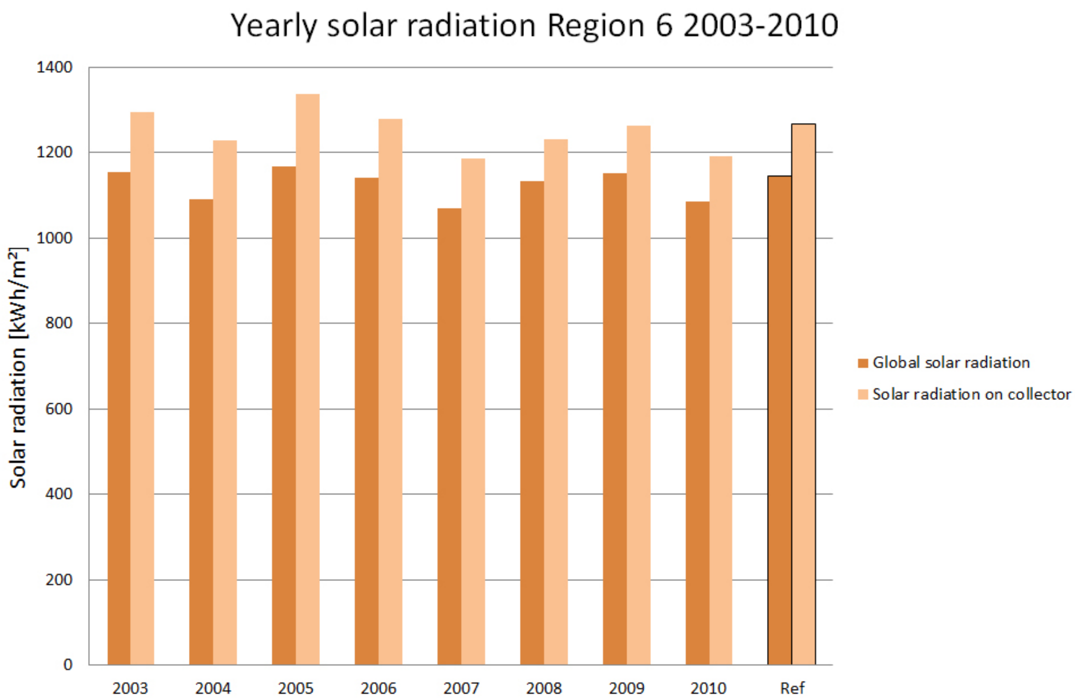

Figure 14. Measured yearly global radiation and calculated yearly solar radiation on collectors for region 6.

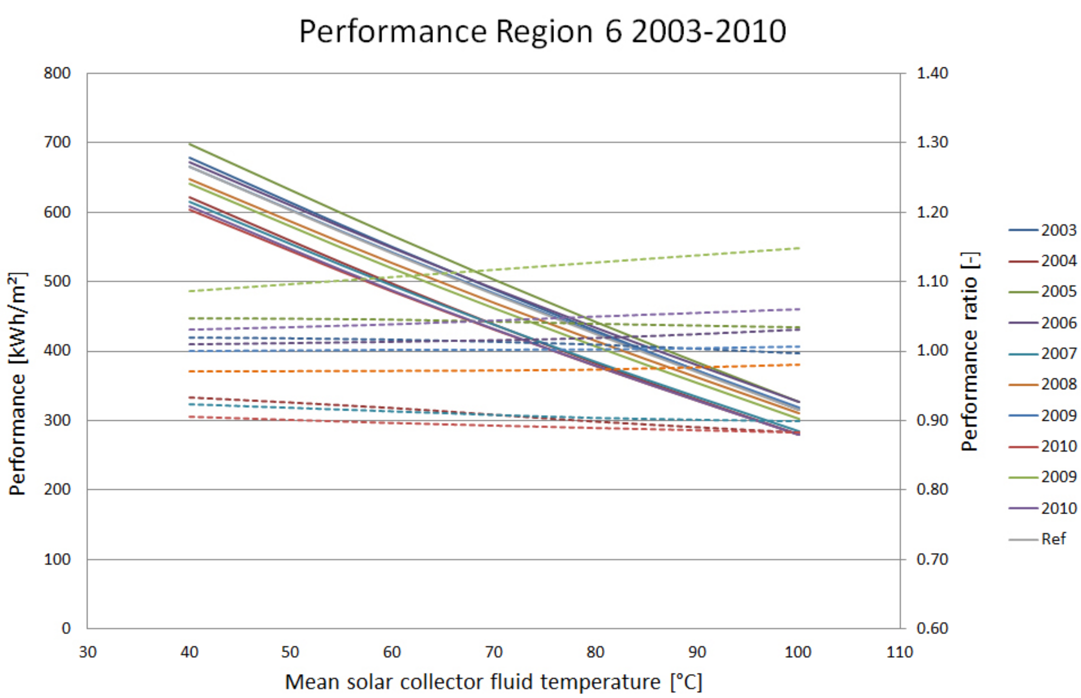

Figure 15. Calculated yearly thermal performance of a collector field for region 6.

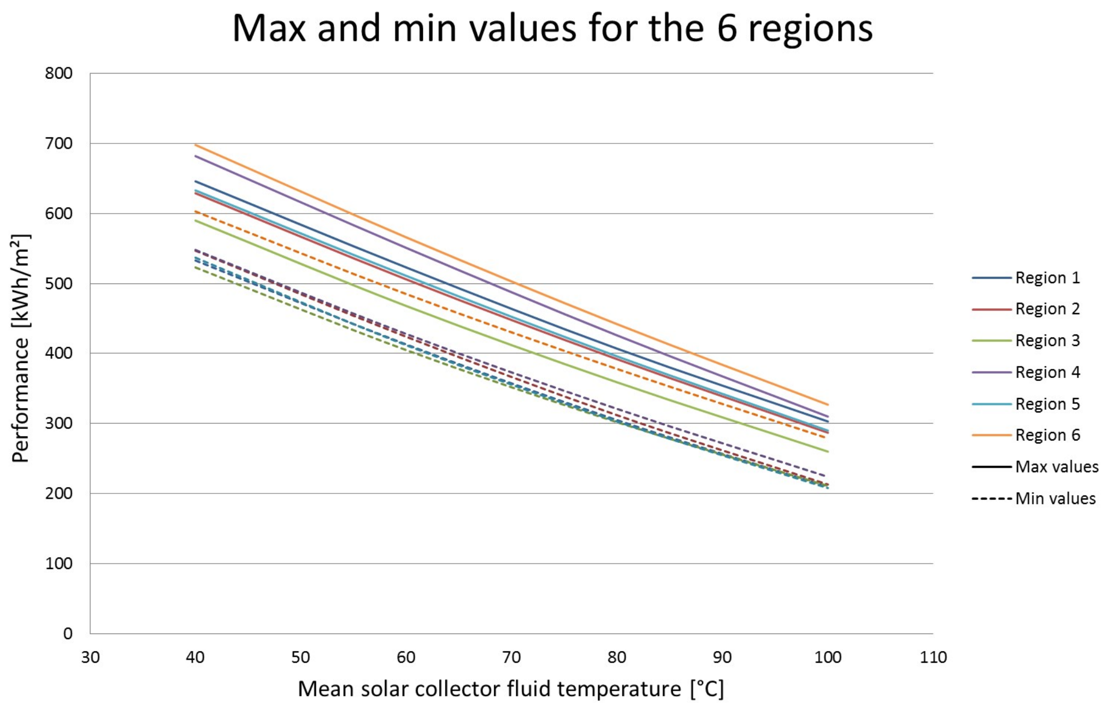

Figure 16. Calculated highest and lowest yearly thermal performance for the Danish regions as a function of the mean solar collector fluid temperature.

Figure 16 shows the highest and lowest yearly thermal performances for all six regions as a function of the mean solar collector fluid temperature.
The measured yearly global radiations on horizontal are in the interval 980 kWh/m² - 1150 kWh/m². The highest yearly global radiation is 17% higher than the lowest yearly global radiation. The highest yearly global radiation is measured in region 6, Bornholm for 2005. The lowest yearly global radiation is measured in region 3, the inner parts of Jutland for 2004.
Based on the hourly global radiation measurements, the hourly solar radiations on the collectors are calculated. Shadows from the row placed in front of the collectors are considered. The calculated yearly solar radiations on the collectors are in the interval 1077 kWh/m² - 1337 kWh/m². The highest yearly solar radiation on the collectors is 24% higher than the lowest yearly solar radiation on the collectors. Again, the highest yearly solar radiation on the collectors is for region 6, Bornholm for 2005 and the lowest yearly solar radiation on the collectors is for region 3, the inner parts of Jutland for 2004.
The yearly thermal performance is strongly influenced by the mean solar collector fluid temperature. For decreasing temperature, the yearly thermal performance is increasing and the percentage differences between the yearly thermal performances from year to year are decreasing.
It is seen that the yearly thermal performances of the solar collectors typically are highest in region 6, Bornholm followed by regions 1 and 4, the northern part of Jutland and Funen & the western part of Zealand, region 5, the eastern part of Zealand, region 2, parts of Jutland close to the coastline and last region 3, the inner parts of Jutland.
The highest and lowest yearly thermal performances for the solar collector field with a mean solar collector fluid temperature of 60°C are listed in table 2 for the six regions.

Region	Highest thermal performance, kWh/m² collector	Lowest thermal performance, kWh/m² collector	Ratio between highest and lowest yearly thermal performance, -
1	523	413	1.27
2	506	424	1.19
3	468	405	1.16
4	551	428	1.29
5	511	412	1.24
6	566	485	1.17

Table 2. Calculated highest and lowest yearly thermal performances of solar collector field for the period 2002-2010 for six regions with a mean solar collector fluid temperature of 60°C.

For a mean solar collector fluid temperature of 60°C the yearly thermal performance is in the interval 405 kWh/m² collector - 566 kWh/m² collector. The lowest thermal performance is calculated for 2004 for region 3, the inner parts of Jutland. The highest calculated thermal performance is for 2005 for region 6, Bornholm. The highest yearly thermal performance is 40% higher than the lowest yearly thermal performance.

The percentage differences between the highest and lowest yearly thermal performance of the collectors are lowest in region 3, the inner parts of Jutland, followed by region 6, Bornholm, region 2, parts of Jutland close to the coastline, region 5, the eastern part of Zealand, region 1, the northern part of Jutland, and last region 4, Funen & the western part of Zealand.

4. CONCLUSIONS

The thermal performance of solar collector fields per collector area depends mainly on the mean solar collector fluid temperature of the collector field and on the solar radiation. Measured yearly thermal performances per collector area of Danish large solar collector fields varied in the period 2012-2016 between 313 kWh/m² and 577 kWh/m² with averages for all plants of 411 kWh/m², 450 kWh/m², 463 kWh/m², 439 kWh/m² and 435 kWh/m² for 2012, 2013, 2014, 2015 and 2016, respectively.

The percentage difference between the highest and lowest measured yearly thermal performance is about 84%.

Calculated yearly thermal performances per collector area of typically designed large solar collector fields at six different locations in Denmark with measured weather data for the years 2002-2010 vary between 405 kWh/m² and 566 kWh/m², if a mean solar collector fluid temperature of 60°C is assumed. This corresponds to a percentage difference between the highest and lowest calculated yearly thermal performance of about 40%. This variation is caused by different weather conditions from year to year and from location to location. Half of the variations of yearly thermal performances of the plants can be related to variable weather conditions.

5. Acknowledgements

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