VARIATIONS OF YEARLY THERMAL PERFORMANCE OF DANISH SOLAR HEATING PLANTS – MEASURED AND CALCULATED

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Abstract – The thermal performance of solar collector fields depends mainly of the mean solar collector fluid temperature of the collector field and of the solar radiation. Measured yearly thermal performances of Danish large solar collector fields vary in the period 2012-2015 between 313 kWh/m² collector and 577 kWh/m² collector with averages for all plants of 411 kWh/m² collector, 450 kWh/m² collector, 463 kWh/m² collector and 439 kWh/m² collector for 2012, 2013, 2014 and 2015. The collector area is the aperture area of the collector. 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 360 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 57%. This variation is caused by different weather conditions from year to year and from location to location.

1. INTRODUCTION

The number of large Danish solar heating plants has increased strongly in the last couples of years. 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. It is possible to follow the operation and thermal performance of a high part of the plants on the homepage (www.solvarmedata.dk, 2016).

The thermal performance of a solar collector field is influenced by a high number of parameters resulting in differences in thermal performances between different solar heating plants. First of all, there are different temperature levels in different district heating plants resulting 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 will be. Further, different weather conditions from location to location and from year to year will influence the yearly thermal performance. The higher the yearly solar radiation is, the higher the thermal performance will be.

Calculations with measured weather data for different locations in Denmark are carried out in order to elucidate how much different weather conditions influence the thermal performance of Danish solar collector fields.

2. MEASURED YEARLY THERMAL PERFORMANCES OF SOLAR COLLCTOR FIELDS

The thermal performances of all Danish solar heating plants are measured. Most of the measurements are available on the homepage (www.solvarmedata.dk, 2016). Information for most of the solar heating plants, such as on solar collector manufacturer, solar collector area, ground area of collector field, collector tilt, year of installation etc. is also available on the homepage. The solar collectors are in all the solar heating plants facing south and the solar collector tilts are situated in the interval from 30° to 45°. Most of the solar heating plants have collector tilts between 35° and 40°.

Table 1 shows the most important data for 40 solar heating plants with available measurements of the thermal performance for all months of 2012, 2013, 2014 and/or 2015. If the solar collector area has been increased after the start of the operation of a plant, more years are mentioned as year of installation. 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 a fusion of the companies ARCON Solar A/S and SUNMARK Solutions A/S. The collector aperture areas of the solar heating plants are situated in the interval from 2970 m² to 70000 m². The average solar collector area for the 40 solar heating plants is 13174 m².

Table 2 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 and/or 2015. 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 and 36 plants are available for 2012, 2013, 2014 and 2015.

The measured yearly thermal performances of the solar heating plants are placed in the interval from 313 kWh/m² collector to 577 kWh/m² collector with averages for all plants of 411kWh/m² collector, 450 kWh/m² collector, 463 kWh/m² collector and 439 kWh/m² collector for

Location	Collector area, m² 2015	Collec-tor tilt, °	Installed
Vejby	8000	38	2012
Helsinge	19588	40	2012, 2014
Jægerspris	13405	40	2010
Nykøbing Sjælland	20084	38	2014
Svebøl-Viskinge	10000	38	2011, 2014
Hvidebæk	12038	38	2013
Sydfalster	12094	38	2011
Sydlangeland	12500	38	2013
Marstal	33365	40	1996, 2001, 2012
St. Rise	3600	45	2002
Ærøskøbing	7050	38	1998, 2010
Broager	9988	40	2009, 2010
Gråsten	19024	38	2012
Christianfeld	9545	38	2013
Vojens	70000	38	2012, 2015
Gram	10073	38	2009
Gørding	7424	38	2012
Hejnsvig	5767	40	2011, 2013
Sig	3479	38	2014
Tistrup	5409	40	2010
Oksbøl	14745	40	2010, 2013
Skovlund	2970	40	2011
Tørring	7284	45	2009
Brædstrup	18612	33	2007, 2012
Ejstrupholm	6243	45	2011
Ringkøbing	30000	30	2010, 2014
Tarm	18585	30	2013
Tim	4235	38	2013
Ørnhøj-Grønbjerg	5083	40	2012
Vildbjerg	21234	38	2014
Feldborg	4000	38	2012
Frederiks	8438	35	2013
Karup	8063	35	2013
Grenå	12096	38	2013/2014
Mou	4775	38	2013
Ulsted	5012	33	2006
Dronninglund	37573	35	2014
Aså	5695	35	2014
Sæby	11866	30	2011
Strandby	8019	35	2008

Table 1. Data for solar heating plants.

2012, 2013, 2014 and 2015. The measured yearly solar radiation on the solar collectors are placed in the interval from 876 kWh/m² collector to1474 kWh/m² collector with averages for all plants of 1102 kWh/m² collector, 1135 kWh/m² collector, 1114 kWh/m² collector and 1101 kWh/m² collector for 2012, 2013, 2014 and 2015, respectively. The yearly utilizations of the solar radiation are placed in the interval from 27.6% to 50.8% with averages for all plants of 37.3%, 39.6%, 41.6% and 39.9% for 2012, 2013, 2014 and 2015. 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, 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 will be. Further, the different solar collector types, the different designs of the solar collector fields, the different weather conditions, the different operation strategies inclusive the different flow rates and maybe the different uneven flow distributions in the solar collector fields, the different heat losses from the pipes in the solar collector loops, the different collector tilts, the different shadow conditions and the different moisture conditions inside the solar collectors, the different snow conditions and dirt conditions on the glass covers of the solar collectors will influence the thermal performance. Furthermore, some plants have long term heat storages charged at high temperatures during summer resulting in a relative low 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 six different locations as suggested by (Wang, Scharling and Nielsen, 2012), see figure 1. 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):

$$\eta = K_\theta * 0.802 - 2.226 * \frac{T_m - T_a}{G} - 0.010 * \frac{(T_m - T_a)^2}{G}$$

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

η is the collector efficiency, -

K_θ is the incidence angle modifier, -

T_m is the mean solar collector fluid temperature, °C

T_a is the ambient temperature, °C

G is the solar irradiance on the solar collector, W/m²

The collector has a polymer foil between the absorber and the cover glass. The calculations of the yearly thermal performances of solar collector fields are based on the method developed by (Dragsted and Furbo, 2012). Calculations are done for each location and each year with measured weather data for the period 2002-2010. 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.

Solar heating plant	Solar radiation, kWh/m²				Thermal performance, kWh/m²				Utilization of solar radiation, %			
	2012	2013	2014	2015	2012	2013	2014	2015	2012	2013	2014	2015
Vejby	-	-	1136	1127	-	-	577	517	-	-	50.8	45.9
Helsinge	-	1126	1114	1145	-	483	493	475	-	42.9	44.3	41.9
Jægerspris	1267	1363	1300	1309	441	493	476	464	34.8	36.2	36.6	35.4
Nykøbing Sjælland	-	-	-	1325	-	-	-	503	-	-	-	38.0
Svebøl-Viskinge	-	-	1039	1142	-	-	423	511	-	-	40.7	44.7
Hvidebæk	-	-	1186	1207	-	-	474	457	-	-	40.0	37.9
Sydfalster	1087	1070	1079	1230	484	491	476	508	44.5	45.9	44.1	41.3
Sydlangeland	-	-	1132	1051	-	-	472	448	-	-	41.7	42.7
Marstal	1046	1055	1116	1078	377	419	429	412	36.0	39.7	38.4	38.2
St. Rise	-	-	-	1177	-	-	-	416	-	-	-	35.3
Ærøskøbing	1274	1264	-	-	355	389	-	-	27.9	30.8	-	-
Broager	1085	1075	1474	1066	385	420	445	439	35.5	39.1	30.2	41.2
Gråsten	-	1103	1114	1099	-	438	469	447	-	39.7	42.1	40.7
Christianfeld	-	-	1103	1081	-	-	506	485	-	-	45.9	44.9
Vojens	-	1124	1107	1039	-	414	427	342	-	36.8	38.6	32.9
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	351	-	390	361	37.3	-	38.2	37.4
Sig	-	-	-	1044	-	-	-	323	-	-	-	31.0
Tistrup	1005	1039	1005	1000	453	473	450	409	45.1	45.5	44.8	40.9
Oksbøl	1106	-	1152	1104	423	-	451	405	38.2	-	39.1	36.7
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	313	425	403	426	27.6	36.9	38.5	38.8
Ejstrupholm	1049	1095	1048	1039	422	485	467	494	40.2	44.3	44.6	47.5
Ringkøbing	1110	1139	991	1198	453	492	474	510	40.8	43.2	47.8	42.6
Tarm	-	-	1075	1031	-	-	452	385	-	-	42.0	37.3
Tim	-	-	1106	1071	-	-	489	452	-	-	44.2	42.2
Ørnhøj-Grønbjerg	-	1095	1059	1023	-	409	442	402	-	37.4	41.7	39.3
Vildbjerg	-	-	-	1148	-	-	-	433	-	-	-	37.7
Feldborg	-	1072	998	876	-	425	417	352	-	39.6	41.8	40.2
Frederiks	-	-	1033	1033	-	-	414	409	- .	-	40.1	39.6
Karup	-	-	1113	1111	-	-	450	428	-	-	40.4	38.5
Grenå	-	-	-	1244	-	-	-	469	-	-	-	37.7
Mou	-	-	1179	1268	-	-	470	497	-	-	39.9	39.1
Ulsted	1163	1190	-	-	445	450	-	-	38.3	37.8	-	-
Dronninglund	-	-	-	1054	-	-	-	417	-	-	-	39.6
Aså	-	-	-	1140	-	-	-	496	-	-	-	43.5
Sæby	1030	1149	1013	1188	420	488	459	461	40.8	42.5	45.3	38.8
Strandby	1123	1082	1140	1146	481	458	484	518	42.8	42.3	42.5	45.2
Average	1102	1135	1114	1101	411	450	463	439	37.3	39.6	41.6	39.9

Table 2: Measured thermal performance for solar heating plants.

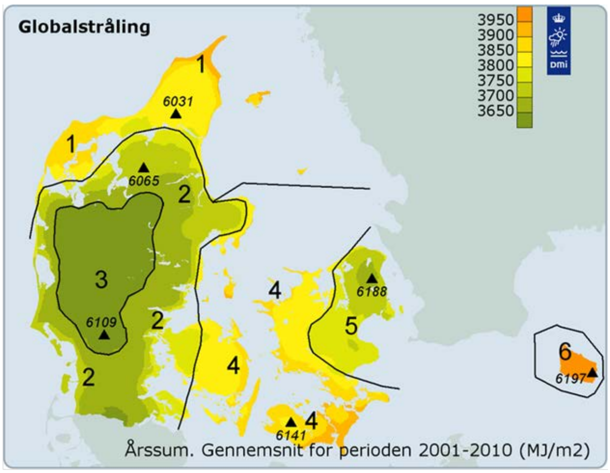

Figure 1. Six Danish regions with different solar radiation.

Figures 2, 3 and 4 show for nine years in the period 2002-2010 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 maintained constant during all operation periods for region 1, see figure 1. 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 4 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 5-19.

Figure 20 shows the highest and lowest yearly thermal performances for all six regions as a function of the mean solar collector fluid temperature.

Figure 2. Measured yearly global radiation for region 1.

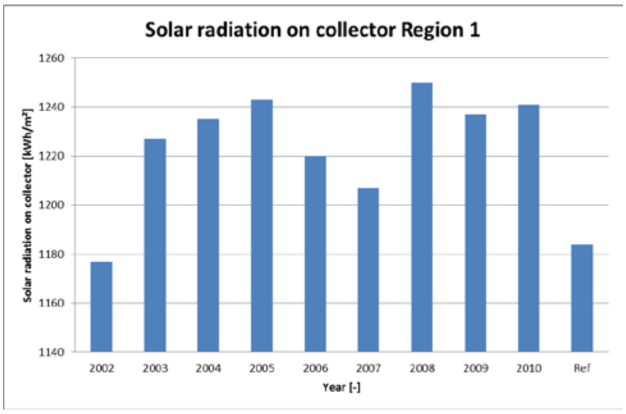

Figure 3. Calculated yearly solar radiation on collectors for region 1.

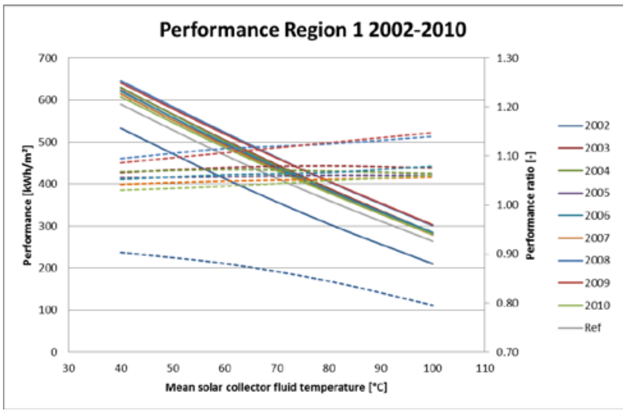

Figure 4. Calculated yearly thermal performance of collector field as a function of mean solar collector fluid for region 1.

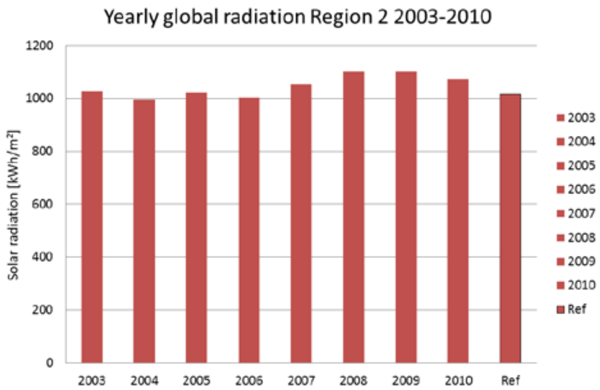

Figure 5. Measured yearly global radiation for region 2.

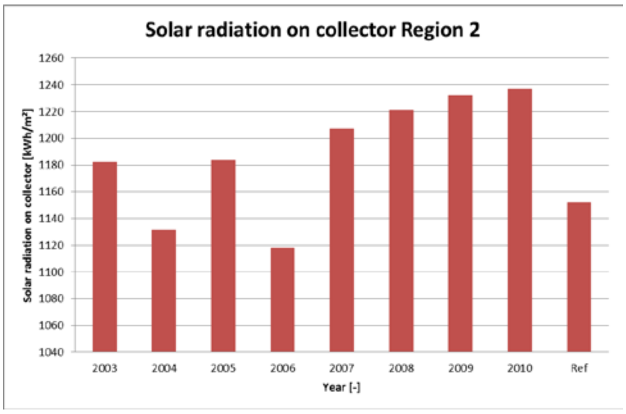

Figure 6. Calculated yearly solar radiation on collectors for region 2.

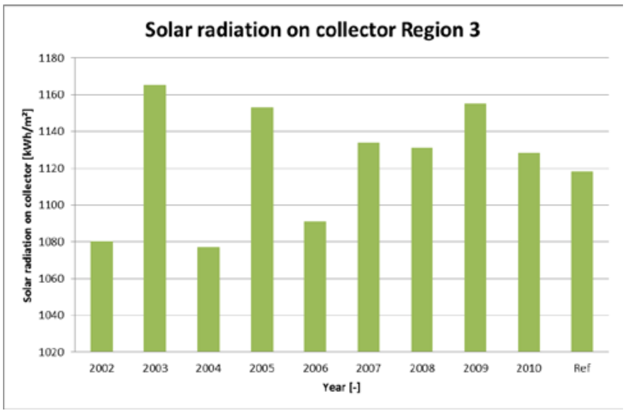

Figure 9. Calculated yearly solar radiation on collectors for region 3.

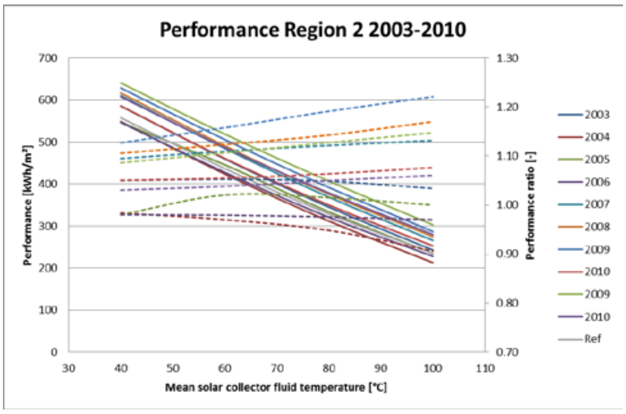

Figure 7. Calculated yearly thermal performance of collector field as a function of mean solar collector fluid for region 2.

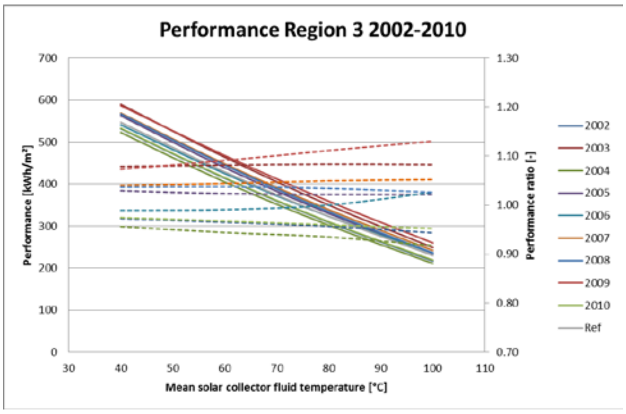

Figure 10. Calculated yearly thermal performance of collector field as a function of mean solar collector fluid for region 3.

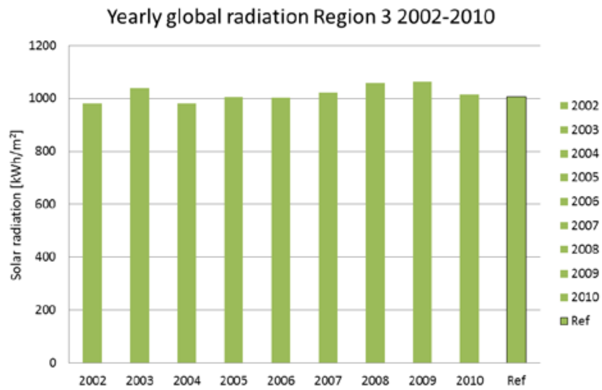

Figure 8. Measured yearly global radiation for region 3.

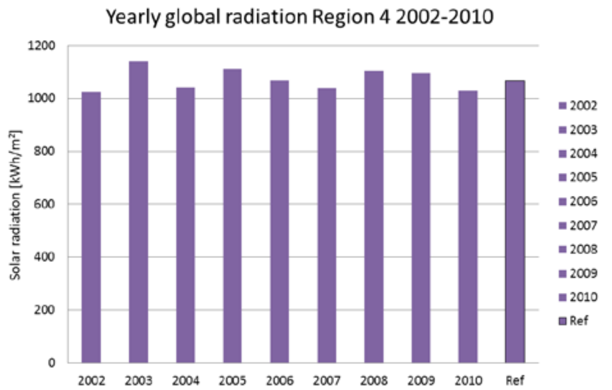

Figure 11. Measured yearly global radiation for region 4.

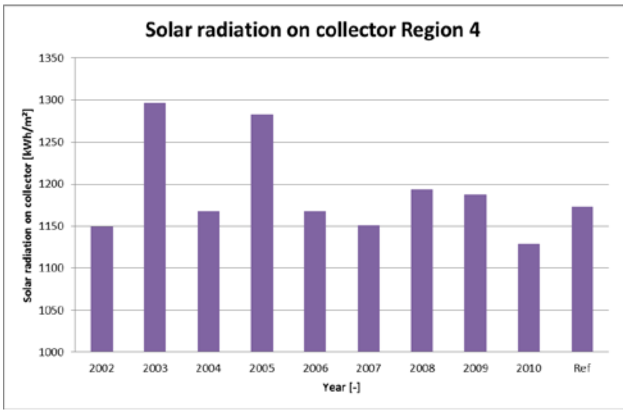

Figure 12. Calculated yearly solar radiation on collectors for region 4.

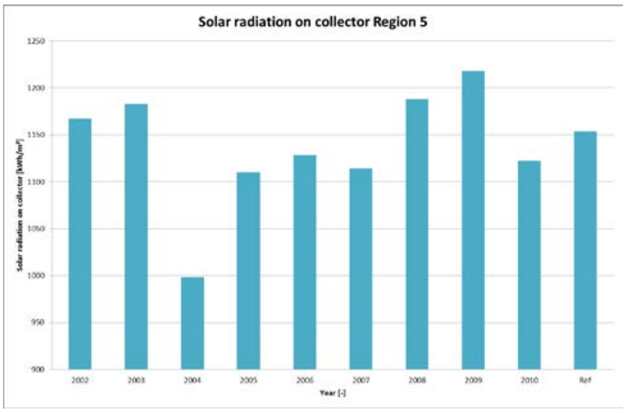

Figure 15. Calculated yearly solar radiation on collectors for region 5.

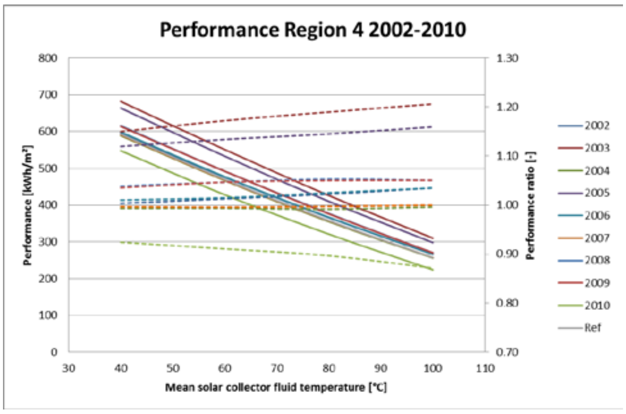

Figure 13. Calculated yearly thermal performance of collector field as a function of mean solar collector fluid for region 4.

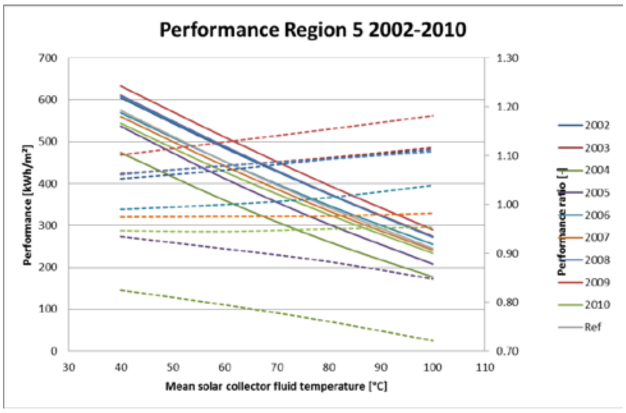

Figure 16. Calculated yearly thermal performance of collector field as a function of mean solar collector fluid for region 5.

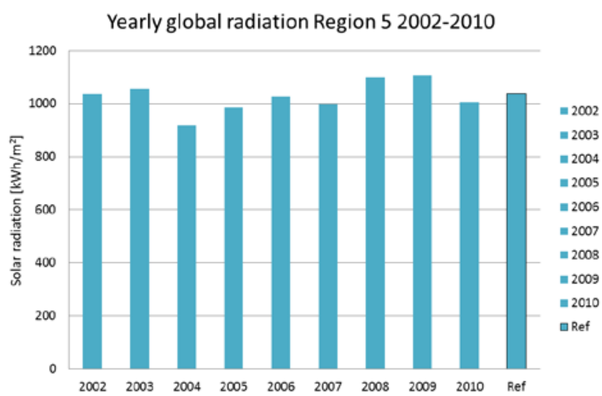

Figure 14. Measured yearly global radiation for region 5.

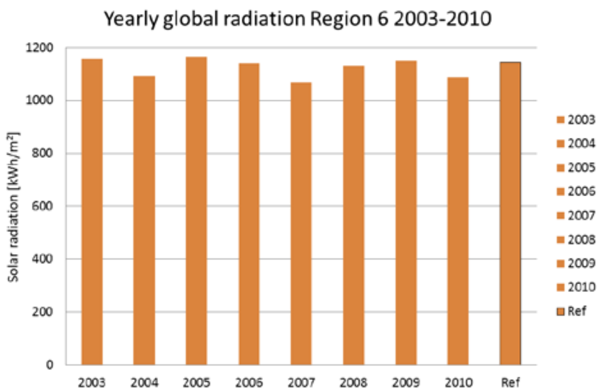

Figure 17. Measured yearly global radiation for region 6.

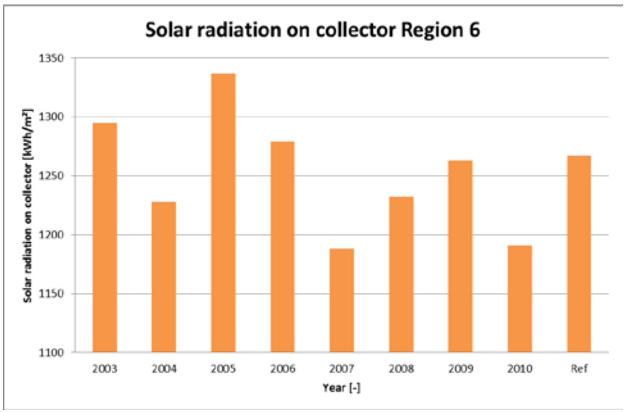

Figure 18. Calculated yearly solar radiation on collectors for region 6.

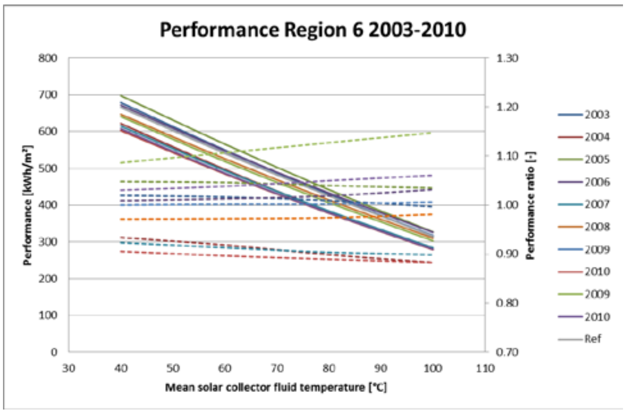

Figure 19. Calculated yearly thermal performance of collector field as a function of mean solar collector fluid for region 6.

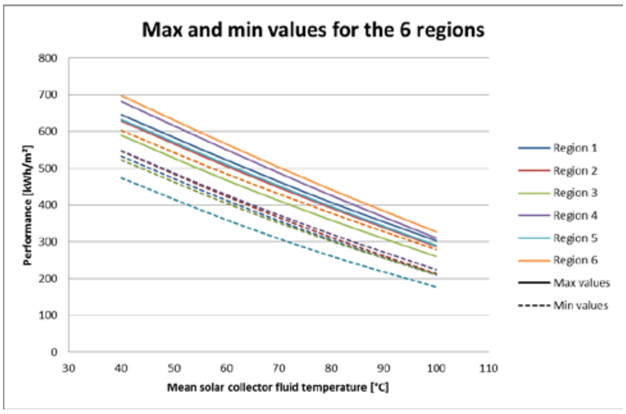

Figure 20. Calculated highest and lowest yearly thermal performance for Danish regions as function of the mean solar collector fluid temperature.

The measured yearly global radiations on horizontal are situated in the interval from 910 kWh/m² to 1150 kWh/m². The highest yearly global radiation is 26% 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 5, the Eastern part of Zealand 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 situated in the interval from 998 kWh/m² to 1337 kWh/m². The highest yearly solar radiation on the collectors is 34% 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 5, the Eastern part of Zealand 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 shown in table 3 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	360	1.42
6	566	485	1.17

Table 3. 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 situated in the interval from 360 kWh/m² collector to 566 kWh/m² collector. The lowest thermal performance is calculated for 2004 for region 5, the eastern part of Zealand. The highest calculated thermal performance is for 2005 for region 6, Bornholm. The highest yearly thermal performance is 57% higher than the lowest yearly thermal performance.

It is seen that 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 5, Bornholm, region 2, parts of Jutland close to the coastline, region 1, the northern part of Jutland, region 4, Funen & the western part of Zealand and last region 5, the eastern part of Zealand.

4. CONCLUSIONS

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

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 360 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 57%. This variation is caused by different weather conditions from year to year and from location to location.

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