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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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>η</td>
<td>collector efficiency</td>
<td>-</td>
</tr>
<tr>
<td>θ</td>
<td>incidence angle</td>
<td>°</td>
</tr>
<tr>
<td>K_θ</td>
<td>incidence angle modifier</td>
<td>-</td>
</tr>
<tr>
<td>G</td>
<td>solar irradiance on the solar collector</td>
<td>W/m²</td>
</tr>
<tr>
<td>G_b</td>
<td>direct radiation on horizontal</td>
<td>W/m²</td>
</tr>
<tr>
<td>R_b</td>
<td>geometric factor</td>
<td>-</td>
</tr>
<tr>
<td>T_m</td>
<td>mean solar collector fluid temperature</td>
<td>°C</td>
</tr>
<tr>
<td>T_a</td>
<td>ambient temperature</td>
<td>°C</td>
</tr>
</tbody>
</table>

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 Denmark 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 COLLECTOR 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 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 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.
<table>
<thead>
<tr>
<th>Solar heating plant/region number</th>
<th>Solar radiation, kWh/m²</th>
<th>Thermal performance, kWh/m²</th>
<th>Utilization of solar radiation, %</th>
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</thead>
<tbody>
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<td>Mou/1</td>
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<td>- - 470 497 464</td>
<td>- - 39.9 39.1 37.3</td>
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<td>Ulsted/1</td>
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<td>445 450 - - 408</td>
<td>38.3 37.8 - - 34.3</td>
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<td>Dronninglund/1</td>
<td>- - 1054 1113</td>
<td>- - 417 426</td>
<td>- - 39.6 38.3</td>
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<td>- - 1140 1118</td>
<td>- - 496 470</td>
<td>- - 43.5 42.0</td>
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<td>Jerselev/1</td>
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<td>- - - 463</td>
<td>- - - 35.3</td>
</tr>
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<td>Sachy/1</td>
<td>1030 1149 1013 1188 1131</td>
<td>420 488 459 461 420</td>
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<tr>
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<td>- - - 399</td>
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<td>Gråsten/2</td>
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<td>Toflumd/2</td>
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<td>- - - 410</td>
<td>- - - 35.7</td>
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<tr>
<td>Christianfeld/2</td>
<td>- - 1098 1117</td>
<td>- - 506 485 481</td>
<td>- - 45.9 44.9 43.1</td>
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<td>- - 323 369</td>
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<td>Sø/3</td>
<td>1005 1039 1005 1000 1070</td>
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<tr>
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<tr>
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<tr>
<td>Tarm/3</td>
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<td>- - 452 385</td>
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</tr>
<tr>
<td>Ølby-Hall-Grønbjerg/3</td>
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<td>+ 409 442 402 417</td>
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</tr>
<tr>
<td>Vildbjerg/3</td>
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<td>- - - 433 517</td>
<td>- - - 37.7 43.7</td>
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<td>+ 425 417 352 373</td>
<td>- 39.6 41.8 40.2 36.6</td>
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<td>Frederiks/3</td>
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<td>- - 414 409 390</td>
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</tr>
<tr>
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<tr>
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<td>- - - 538</td>
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<td>- - - 39.5</td>
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<td>Svebol-Viskinge/4</td>
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<td>- - 423 511 324</td>
<td>- - 40.7 44.7 29.5</td>
</tr>
<tr>
<td>Hvidebak/4</td>
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<td>- - 474 457 432</td>
<td>- - 40.0 37.9 36.4</td>
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<tr>
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<td>44.5 45.9 44.1 41.3 43.0</td>
<td></td>
</tr>
<tr>
<td>Marstal/4</td>
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<td>- 36.0 39.7 38.4 38.2</td>
</tr>
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<td>St. Rise/4</td>
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<td>- - - 416 376</td>
<td>- - - 35.3 33.6</td>
</tr>
<tr>
<td>Ærøskøbing/4</td>
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<td>- - 1210 355 389</td>
<td>- - 378 27.9 30.8</td>
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<tr>
<td>Grenå/4</td>
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<td>- - - 469 451</td>
<td>- - - 37.7 42.0</td>
</tr>
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<td>- - 577 517 512</td>
<td>- - 50.8 45.9 45.1</td>
</tr>
<tr>
<td>Helsingør/5</td>
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<tr>
<td>Jægerspris/5</td>
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<td>34.8 36.2 36.6 35.4 35.7</td>
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<tr>
<td>Skuldelev/5</td>
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<td>- - - 451</td>
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<tr>
<td>Average</td>
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<td>411 450 463 439 435</td>
<td>37.3 39.6 41.6 39.9 37.9</td>
</tr>
</tbody>
</table>

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.
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.

<table>
<thead>
<tr>
<th>Region</th>
<th>Highest thermal performance, kWh/m² collector</th>
<th>Lowest thermal performance, kWh/m² collector</th>
<th>Ratio between highest and lowest yearly thermal performance, -</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>523</td>
<td>413</td>
<td>1.27</td>
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<tr>
<td>2</td>
<td>506</td>
<td>424</td>
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<td>3</td>
<td>468</td>
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<td>5</td>
<td>511</td>
<td>412</td>
<td>1.24</td>
</tr>
<tr>
<td>6</td>
<td>566</td>
<td>485</td>
<td>1.17</td>
</tr>
</tbody>
</table>

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%.

5. Acknowledgements

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REFERENCES


