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THERMAL PERFORMANCE OF SOLAR DISTRICT HEATING PLANTS IN DENMARK

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Abstract

The market for solar heating plants connected to district heating systems is expanding rapidly in Denmark. It is expected that by the end of 2014 the 10 largest solar heating plants in Europe will be located in Denmark. Measurements from 23 Danish solar heating plants, all based on flat plate solar collectors mounted on the ground, shows measured yearly thermal performances of the solar heating plants placed in the interval from 313 kWh/m² collector to 493 kWh/m² collector with averages for all plants of 411 kWh/m² collector for 2012 and 450 kWh/m² collector for 2013.

Theoretical calculations show that for temperature levels higher than about 55°C the thermal performance of a solar collector field based on concentrating tracking solar collectors is higher than the thermal performance of a solar collector field based on flat plate collectors.

It is estimated that there are potentials for further improvements of the cost/performance ratio for solar collector fields, both with flat plate collectors and with concentrating tracking solar collectors.

It is recommended to continue monitoring and analysis of all large solar heating plants to document the reliability of the solar heating plants. It is also recommended by parallel theoretical and experimental approach to investigate in detail the thermal performance of differently designed solar collector fields in such a way that their thermal performance can be determined by theoretical calculations in the future. This will be useful in connection with development of improved solar collectors for solar heating plants and in connection with optimization of future solar heating plants.

Furthermore, it is recommended to continue the development of long term heat stores for solar heating plants and to elucidate how best to integrate solar heating systems in the future energy system

Keywords: Solar heating plants, solar collector fields, flat plate collectors, concentrating tracking collectors, district heating systems, thermal performance, measurements, calculations.

1. Introduction

In the period 2005-2014 the number of Danish solar heating plants connected to district heating systems has increased from 7 to 58, and the total collector area of Danish solar heating plants has also increased strongly, see figure 1. Denmark is today the country with most solar heating plants in operation and with the largest collector area of solar heating plants connected to district heating systems. By the end of 2013, 9 of the 10 largest European solar heating plants were installed in Denmark, [1]. It is believed that by the end of 2014 the 10 largest solar heating plants in Europe will be in operation in Denmark, and that the strong growth in Denmark in this field will continue in the coming years. Figure 2 shows a photo of the solar collector field of the largest European solar heating plant in Dronninglund with a collector area of 37573 m² installed in 2014.

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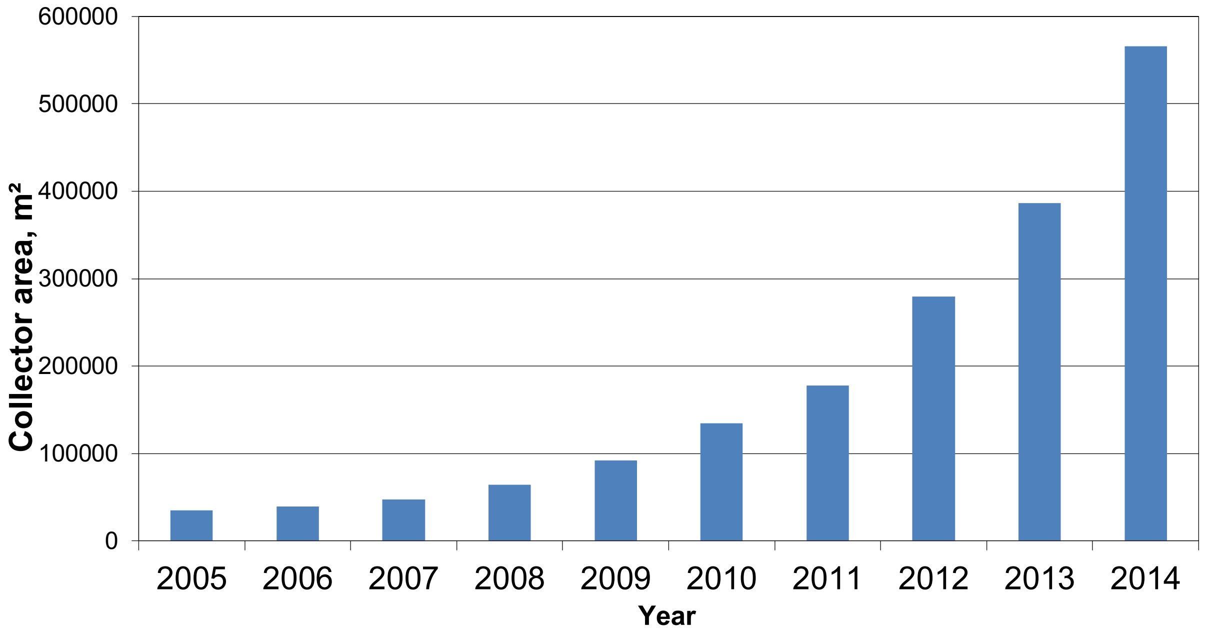

Fig. 1: Total solar collector area of Danish solar heating plants during the last 10 years. The collector area for 2014 is estimated.

There are many reasons for the rapid growth of solar heating plants in Denmark:

- An ambitious Danish energy plan. By 2030 no fossil fuels must be used for heat, by 2035 no fossil fuels must be used for heat and electricity and by 2050 no fossil fuels must be used.
- A lot of district heating. Today 63% of all Danish buildings are heated by district heating.
- Low temperature levels in district heating systems. A typical forward temperature to towns is about 80°C and a typical return temperature from towns is about 40°C.
- High taxes for fossil fuels. Typical tax is about 0.035 euro per kWh produced heat.
- Decentralized energy supply system.
- High share of wind energy for electricity production. In 2013, 34% of the Danish electricity consumption was produced by wind turbines. By 2020, 50% of the Danish electricity consumption must be produced by wind turbines.
- Low costs for marketed solar collector fields installed on the ground.
- Relative low ground costs.
- High efficiency of marketed solar collectors.
- Long life time of marketed solar collectors. A life time for marketed solar collectors of about 30 years is estimated, [2].
- Well proven and reliable technology.
- Good thermal performance of existing solar heating plants.
- Ongoing efforts to develop and demonstrate seasonal heat storage.

Today Danish solar heating plants are in many cases competitive against natural gas driven combined heat and power systems.

Fig. 2. Dronninglund solar heating plant with a collector area of 37573 m² installed 2014.

2. System design

Danish solar heating plants are based on large, between 12 m² and 14 m², flat plate collector panels either without or with a foil mounted between the absorber and the cover glass. The aim of the foil is to decrease the heat loss of the collector. The collectors are either produced by ARCON Solar A/S or SUNMARK Solutions A/S. The collectors from ARCON Solar A/S are either with or without a foil mounted between the absorber and the cover glass, while all the collectors from SUNMARK Solutions A/S are without foil. The collectors have undergone a strong development during the last 10 years with regard to quality, efficiency increase and cost reduction, [3]. Consequently, the collectors used in the old solar heating plants are not as good as the collectors used in the new solar heating plants. Figure 3 shows a 12.53 m² ARCON collector tested in the solar collector test facility at the Technical University of Denmark in 2007.

Fig 3. Photo and skematic sketch of solar collector with foil from ARCON Solar A/S tested at the Technical Universisity of Denmark in 2007.

Figure 4 shows a schematic sketch of a solar collector field. The collector fields are in all plants placed on the ground. The collector fields consist of parallel connected rows with solar collectors in a serial connection. In some solar heating plants the same solar collector type with or without foil is used. In other solar heating plants both collectors without and with foil are used. In these plants the first collector(s) in the rows are without foil while the remaining collectors are with foil. Some of the solar heating plants have relative small areas with other types of solar collectors, such as evacuated tubular solar collectors or concentrating tracking solar collectors.

In all the solar heating plants propylene glycol/water mixtures are used as solar collector fluids. In sunny periods the solar collector fluid is circulated through the solar collector field either with a constant volume flow rate resulting in a variable outlet temperature from the solar collector field or with a variable volume flow rate depending on the solar irradiance in such a way that the solar collector fluid leaving the solar collector field is maintained at an almost constant temperature level. The heat produced by the solar collector field is transferred to water in the district heating system by means of a heat exchanger. Typical temperature levels of the solar collector fluid in the solar collector fields are placed in the interval from about 40 °C to about 80 °C. In solar heating plants with large heat stores aiming at high solar fractions, the temperature level of the solar collectors is typically somewhat higher during the summer, where the heat stores are heated to high temperatures. The heat produced by the solar collectors is either transferred directly to the town to cover the heat demand or to a heat storage, where the heat is stored until the heat demand is higher than the heat produced by the solar collector field. The period, in which the solar heat is stored, is either short or long.

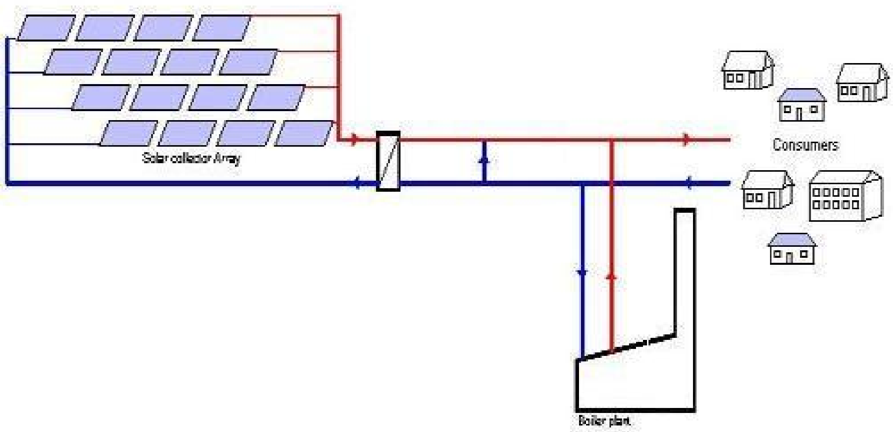

Fig. 4. Principal drawing of a solar heating plant.

In 2013 a small demonstration solar heating plant based on concentrating tracking solar collectors was installed at Thisted district heating system. The solar collectors are produced by Aalborg CSP A/S. The aperture area of the collectors defined as the optically active area of the collectors, that is the length multiplied with the width of the mirrors minus the mounting and thermal expansion gaps between the mirror elements, is 808 m² and water under a high pressure is used as the solar collector fluid. The temperature level of the solar collector fluid in the collectors is typically situated in the interval from 100 °C to 120 °C. Photos of the solar heating plant in Thisted are shown in figure 5. Detailed measurements on the thermal performance of the solar collector field were carried out in the summer of 2013 in order to evaluate the suitability of this type of solar collectors for solar heating plants under Danish weather conditions [4].

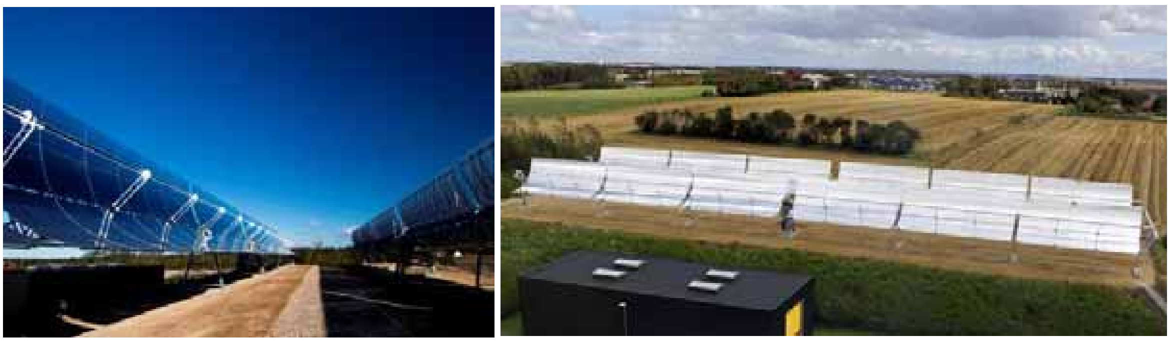

Fig 5. Concentrating tracking solar collector field in Thisted.

3. Measured thermal performances

The thermal performances of all Danish solar heating plants are measured. Most of the measurements of the thermal performance hour by hour are available on the homepage www.solvarmedata.dk [5]. Information on the solar heating plants, such as on solar collector manufacturer, solar collector area, ground area of collector field, solar 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 25° to 45°. Most solar heating plants have collector tilts between 35° and 40°.

Table 1 shows the most important data on 23 solar heating plants with available measurements of the thermal performance for all months of 2012 and/or 2013. The energy is measured at the heat exchanger to the district heating plants and includes pipe losses in the collector field and also sometimes long transit pipes. Storage losses are not included as the storages are part of the district heating network anyway.

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. The collector areas of the solar heating plants are situated in the interval from 2970 m² to 33365 m². The average solar collector area for the 23 solar heating plants is 11159 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 and/or 2013. The thermal performance and the solar radiation are given per m² solar collector aperture area. The utilization of the solar radiation is defined as 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 plants are available for 2012 and measurements from 21 plants are available for 2013.

Tab. 1: Data for solar heating plants.

Solar heating plant	Collector area, m² 2014	Collector tilt, °	Year of installation	Collector manufacturer
Helsinge	4733	25	2012	ARCON
Jægerspris	13405	40	2010	SUNMARK
Sydfalster	12094	38	2011	ARCON
Marstal	33365	40	1996, 2001, 2012	ARCON/SUNMARK
Ærøskøbing	7050	38	1998, 2010	ARCON/SUNMARK
Broager	9988	40	2009, 2010	ARCON
Gråsten	19024	38	2012	ARCON
Vojens	17500	38	2012	SUNMARK
Gram	10073	38	2009	ARCON
Gørding	7424	38	2012	ARCON
Hejnsvig	5767	40	2011, 2013	SUNMARK
Tistrup	5409	40	2010	ARCON
Oksbøl	14745	40	2010, 2013	SUNMARK
Skovlund	2970	40	2011	SUNMARK
Tørring	7284	45	2009	SUNMARK
Brædstrup	18612	33	2007, 2012	ARCON
Ejstrupholm	6243	45	2011	SUNMARK
Ringkøbing	30000	30	2010, 2014	ARCON
Ørnhøj-Grønbjerg	5083	40	2012	ARCON
Feldborg	4000	38	2012	ARCON
Ulsted	5012	33	2006	ARCON
Sæby	11866	30	2011	SUNMARK
Strandby	8019	35	2008	ARCON

Tab. 2: Measured thermal performance for solar heating plants.

Solar heating plant	Solar radiation, kWh/m²		Thermal performance, kWh/m²		Utilization of solar radiation, %	
	2012	2013	2012	2013	2012	2013
Helsinge	-	1126	-	483	-	42.9
Jægerspris	1267	1363	441	493	34.8	36.2
Sydfalster	1087	1070	484	491	44.5	45.9
Marstal	1046	1055	377	419	36.0	39.7
Ærøskøbing	1274	1264	355	389	27.9	30.8
Broager	1085	1075	385	420	35.5	39.1
Gråsten	-	1103	-	438	-	39.7
Vojens	-	1124	-	414	-	36.8
Gram	1081	1138	388	419	35.9	36.8
Gørding	-	1118	-	482	-	43.1
Hejnsvig	942	-	351	-	37.3	-
Tistrup	1005	1039	453	473	45.1	45.5
Oksbøl	1106	-	423	-	38.2	-
Skovlund	-	1143	-	429	-	37.5
Tørring	1129	1233	392	466	34.7	37.8
Brædstrup	1135	1153	313	425	27.6	36.9
Ejstrupholm	1049	1095	422	485	40.2	44.3
Ringkøbing	1110	1139	453	492	40.8	43.2
Ørnhøj-Grønbjerg	-	1095	-	409	-	37.4
Feldborg	-	1072	-	425	-	39.6
Ulsted	1163	1190	445	450	38.3	37.8
Sæby	1030	1149	420	488	40.8	42.5
Strandby	1123	1082	481	458	42.8	42.3
Average	1102	1135	411	450	37.3	39.6

The measured yearly thermal performances of the solar heating plants are placed in the interval from 313 kWh/m² collector to 493 kWh/m² collector with averages for all plants of 411 kWh/m² collector for 2012 and 450 kWh/m² collector for 2013. The measured yearly solar radiation on the solar collectors are placed in the interval from 942 kWh/m² collector to 1363 kWh/m² collector with averages for all plants of 1102 kWh/m² collector for 2012 and 1135 kWh/m² collector for 2013. The yearly utilizations of the solar radiation are placed in the interval from 27.6% to 45.9% with averages for all plants of 37.3% for 2012 and 39.6% for 2013. 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 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 for 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.

4. Calculated thermal performances

The solar collector type used in a solar heating plant will influence the thermal performance of the solar heating plant. The thermal performances of solar collector fields have been calculated with solar collectors with different efficiencies for different constant temperature levels throughout the year with weather data from the Danish Design Reference Year. The following collectors have been included in the calculations:

- HT-SA 28/10, a flat plate solar collector from ARCON with foil between the absorber and the cover glass.
- HT-A 28/10, a flat plate solar collector from ARCON without foil
- GJ 140V, a flat plate solar collector from SUNMARK without foil
- Aalborg CSP, a concentrating tracking solar collector from the company Aalborg CSP

The efficiencies and incidence angle modifiers used in the calculations are:

HT-SA 2810: $\eta = K_\theta * 0.817 - 2.205 * \frac{T_m - T_a}{G} - 0.0135 * \frac{(T_m - T_a)^2}{G}$ and $K_\theta = 1 - \tan^{4.51}(\theta/2)$ (eq.1)

HT-A 28/10: $\eta = K_\theta * 0.839 - 3.200 * \frac{T_m - T_a}{G} - 0.0137 * \frac{(T_m - T_a)^2}{G}$ and $K_\theta = 1 - \tan^{4.51}(\theta/2)$ (eq.2)

GJ 140V: $\eta = K_\theta * 0.85 - 2.300 * \frac{T_m - T_a}{G} - 0.0290 * \frac{(T_m - T_a)^2}{G}$ and $K_\theta = 1 - \tan^{5.30}(\theta/2)$ (eq.3)

Aalborg CSP: $\eta = K_\theta * 0.75 - 0.040 * \frac{T_m - T_a}{G} - 0.0000 * \frac{(T_m - T_a)^2}{G}$ and $K_\theta = 1 - \tan^{2.40}(\theta/2)$ for direct radiation and $K_\theta = 0$ for diffuse radiation. (eq.4)

where 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

θ is the incidence angle of the direct radiation on the solar collector, °

Efficiency expressions as shown above are the basis for designing and planning of the solar collector fields. The expressions are determined by tests institutes testing marketed solar collectors. During these tests often water is used as solar collector fluid, a collector tilt angle of 60° is used and a relatively high volume flow rate is used. In a solar heating plant a propylene glycol water mixture is used as solar collector fluid, a relatively low collector tilt is used and a variable volume flow rate is used. Investigations on how the test conditions influence the efficiency expressions and the thermal performances for different flat plate collectors have been carried out [6]. It is recommended in the future to change the test conditions in such a way that the efficiencies are determined with realistic boundary conditions.

Figure 6 shows calculated yearly thermal performances of the solar collectors in a solar collector field as a function of the solar collector fluid temperature. Shadows from front rows are considered in the calculations, while pipe losses and thermal capacities are disregarded in the calculations. A constant solar collector fluid temperature throughout the year is assumed. It is assumed that the flat plate solar collectors are facing south with collector tilts of 35° and with a row distance of 5 m. The mirrors of the concentrating tracking solar collectors are south/north oriented in such a way that the mirrors are pointing towards east in the morning and towards west in the evening. A row distance of 15 m is assumed for these collectors.

The thermal performances of the two ARCON collectors are shown in figure 6. The thermal performance is a strong function of the temperature level of the solar collector fluid. The higher the temperature level, the lower the thermal performance. Further, the thermal performance of the ARCON collector with foil is for all temperature levels between 30°C and 100°C higher than the thermal performance of the ARCON collector without foil. Consequently, the ARCON collector without the foil should only be used of costs reasons.

Figure 7 shows the thermal performances of the two ARCON flat plate collectors and the SUNMARK flat plate collector. The thermal performance of the SUNMARK collector is also strongly influenced by the temperature level of the solar collector fluid. For temperature levels lower than about 42°C the SUNMAK collector has a higher thermal performance than both ARCON collectors, in the temperature levels between about 42°C and 84°C the SUNMARK collector has a lower thermal performance than the ARCON collector with foil and a higher thermal performance than the ARCON collector without foil, and for temperature levels above about 84°C the SUNMARK collector has a lower thermal performance than both ARCON collectors.

As mentioned in section 3, the measured yearly thermal performances of the solar heating plants are placed in the interval from 313 kWh/m² collector to 493 kWh/m² collector with averages for all plants of 411 kWh/m² collector for 2012 and 450 kWh/m² collector for 2013. A reasonable assumption is that the mean solar collector fluid temperature is about 60°C. Based on figure 6 it is estimated, that the measured thermal performances of the plants are satisfactory high.

Figure 6 shows the thermal performances of the three flat plate collectors and the concentrating tracking collector. It is obvious that the thermal performance of the concentrating tracking solar collector is almost not influenced by the temperature level of the solar collector fluid. This is caused by the low heat loss coefficient of this solar collector. For temperature levels higher than about 55°C the thermal performance of the concentrating tracking solar collector is higher than the thermal performance of the three flat plate collectors.

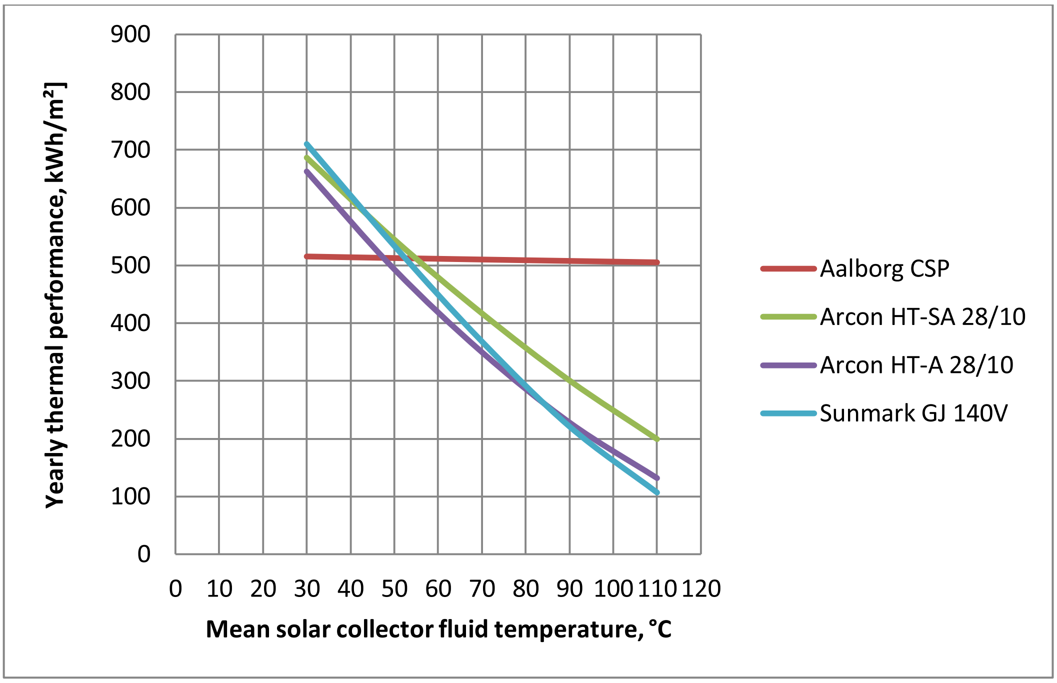

Fig 6. Yearly thermal performances of four solar collectors in a solar collector field as a function of a constant solar collector fluid temperature.

The optimal solar collector type(s) for a solar heating plant is of course not only influenced by the thermal performances of the collectors, but also by the costs of the solar collectors installed in the solar collector field. The cost/performance ratio of the solar collector field is the most important factor.

For flat plate collectors as well as for concentrating tracking solar collectors there are possibilities for improvements on the cost/performance ratios both with regard to the solar collectors and with regard to the solar collector field. The following possibilities for improvements of flat plate solar collectors and solar collector fields based on flat plate solar collectors can be considered:

- Increased use of alumininium as materials for absorbers and pipes
- Increased absorptance for absorbers
- Reduced emittance for absorbers
- Improved absorber design resulting in increased heat transfer from absorber to solar collector fluid
- Improved flow distribution in absorber and in solar collector field

- Larger solar collector panels resulting in increased collector efficiency, easier installation and lower pipe losses
- Improved cover systems for solar collectors resulting in a higher start efficiency, an increased incidence angle modifier and a lower heat loss coefficient for the collectors
- Improved back side insulation, for instance new insulation materials, vacuum insulation and/or thicker insulation
- Reflectors between the collector rows
- Use of water or ethylene glycol/water mixtures as solar collector fluid instead of propylene glycol/water mixtures
- Optimal serial connection of different solar collector types for collector rows
- Optimal control strategies for solar heating plants

In connection with development of solar heating plants and of tools for optimizing solar heating plants a number of ongoing international projects must be mentioned:

- SDHplus, [7]
- IEA Task 45 Large Solar Heating/Cooling Systems, seasonal heat storage, heat pumps, [8]
- SHINE, Solar Heat Integration Network, WP1 on district heating, [9]
- Danish/Chinese cooperation project “Testing, development and demonstration of large scale solar district heating systems”, [10]

Further, solar collector fields based on evacuated tubular solar collectors should be considered. Maybe it is possible to develop large easy to install evacuated tubular solar collector panels suitable for solar heating plants.

Furthermore, long term measurements of solar collector fields with concentrating tracking solar collectors are needed to document the reliabillity of the tracking technology under Danish conditions.

5. Conclusions and recommendations

The market for solar heating plants connected to district heating systems is expanding rapidly in Denmark. It is expected that by the end of 2014 the 10 largest solar heating plants in Europe will be located in Denmark. Measurements from 23 Danish solar heating plants, all based on flat plate solar collectors mounted on the ground, shows measured yearly thermal performances between 313 kWh/m² collector and 493 kWh/m² collector with averages for all plants of 411 kWh/m² collector for 2012 and 450 kWh/m² collector for 2013. The measured yearly solar radiations on the solar collectors are between 942 kWh/m² collector and 1363 kWh/m² collector with averages for all plants of 1102 kWh/m² collector for 2012 and 1135 kWh/m² collector for 2013. The yearly utilizations of the solar radiation are placed in the interval from 27.6% to 45.9% with averages for all plants of 37.3% for 2012 and 39.6% for 2013. It is estimated that the measured thermal performances and utilizations of the solar radiation for all the plants are satisfactory high.

Theoretical calculations have shown that for temperature levels higher than about 55 °C the thermal performance of a concentrating tracking solar collector is higher than the thermal performance of flat plate collectors. It is estimated that there are potentials for further improvements of the cost/performance ratio for solar collector fields, both with flat plate collectors and with concentrating tracking solar collectors.

It is recommended to continue monitoring and analysis of all large solar heating plants to document the reliability of the solar heating plants. In this connection it is recommended to carry out quality check of the measurements, both with regard to the solar heat produced by the solar collectors and to the solar radiation.

It is also recommended by parallel theoretical and experimental approach to investigate in detail the thermal performance of differently designed solar collector fields in such a way that the thermal performance of differently designed solar collector fields can be determined by theoretical calculations in the future. This will be useful in connection with development of improved solar collectors for solar heating plants and in connection with optimization of future solar heating plants.

Furthermore, it is recommended to continue the development of long term heat stores for solar heating plants and to elucidate how best to integrate solar heating systems in the future energy system.

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