THERMAL PERFORMANCE OF A NOVEL COMBINED SOLAR HEATING PLANT WITH PARABOLIC TROUGH COLLECTORS AND FLAT PLATE COLLECTORS

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Abstract –Large scale solar heating plants develop fast in Europe, especially in Denmark. Most solar collectors used in the existing solar heating plants are flat plate collectors. Flat plate collectors have relatively low efficiency at high temperature levels, such as 70- 95°C, which is the supply temperature of the district heating networks. Parabolic trough collectors keep a high efficiency at high temperature levels of 70- 95°C. To maximize the advantages of flat plate collectors and parabolic trough collectors in large solar heating plants, a novel combined solar collector field with 5960 m^2 flat plate collectors and 4032 m^2 parabolic trough collectors in series has been constructed in Tårs, Denmark. The design principle is that the flat plate collectors preheat the return water from the district heating network to about 70°C and then the parabolic trough collectors will heat the preheated water from the flat plate collector field to the required supply temperature of the district heating network. The thermal performances of both parabolic trough collector field and flat plate collector field of the Tårs solar heating plant are presented in this paper. A TRNSYS model has been developed and validated by in-situ measurements of the solar heating plant as well. Calculations of the thermal performance potential of the parabolic trough collector field was simulated by the validated Trnsys to have a whole understanding of the application of parabolic trough collectors under Danish climate conditions.

1. INTRODUCTION

Nowadays, building energy consumption accounts for about 40% of the total society energy consumption in the developed countries (Balaras, C. et al., 2007). Solar heating plants for district heating can reduce the fossil energy consumption in the building sector. Large solar heating plants develop very fast in Europe, especially in Denmark (Furbo, S. et al., 2015). Several large solar heating plants have been constructed in Denmark, such as in Vojens, Marstal, Gram, etc. Solar collectors are the most important components for the solar heating plants. Most solar collectors in the existing solar heating plants are flat plate collectors (FPC).

The operation temperature of solar collectors in solar heating plants is in the range from about 40 °C to 95 °C. The efficiency of flat plate collectors decreases significantly in the range of 70°C-95°C, while parabolic trough collectors (PTC) have relatively high efficiency in the range of 70°C -95°C.

Most parabolic trough collectors were in the past used to produce electricity. With the requirement of energy savings in the industry, more and more parabolic trough solar collectors are employed to provide heat for industry processes in the recent years. IEA-SHC TASK 49 (2016) has focused on the application of solar collectors in the industry sector. Frank, E. et al., (2014) investigated the thermal performance of parabolic trough collectors in two solar heating plants in Swiss dairies and found that the thermal performance of both the solar collector fields could be high under Swiss climate conditions. Silva, R. et al., (2013, 2014) did simulations and thermo-economic design optimizations on parabolic trough collectors for heat production for industrial processes. LCOE (Levelized cost of energy) of 5 c€/kWh and a PBT (payback time) of 8 years could been achieved at the base scenario conditions considered. Hassine, I. et al., (2015) investigated the control strategy of two about 1000 m^2 solar heating plants (in Austria and Italy). Weaknesses of the collector loop controller were found in the first operation period. Based on measurements and simulations with dynamic models, potential improvements of low-level control algorithms were presented for the two solar heating plants.

Larcher, M. et al., (2016) presented experimental investigations on a parabolic trough collector under development for process heat applications. Results of quasi steady state efficiency measurements on parabolic trough collectors were shown. Kizilkan, O. et al., (2016) proposed a parabolic trough solar collector-based integrated system for an ice-cream factory in Turkey and discussed the thermal performance. The payback period of the proposed integrated system was found to be 8.5 years. The payback period was almost the same as reported by Silva, R. These investigations show that the application of parabolic trough collectors for high temperature heat production can be economical and feasible if the system is designed reasonably.

It is found that most present research is on applications of parabolic trough collectors with 500 m^2-1500 m^2 collectors for industry processes. Limited literature about detailed measurements of the thermal performance of large parabolic trough collector solar heating plants for district heating networks was available.

To harvest the advantages of both flat plate collectors and parabolic trough collectors in large solar heating plants for district heating networks, a new concept for a hybrid solar heating plant consisting of flat plate collectors and parabolic trough collectors has been proposed. The basic principle is that the flat plate collector field preheats the return water of the district heating network from 40°C to 70°C and the parabolic trough collector field heats the preheated water from 70°C to 95°C. Feasibility of application of the parabolic trough collector technology in Denmark has been primarily investigated by Aalborg CSP (2013) and Technical University of Denmark (DTU) (Perers B et al., 2013). A demonstration solar heating plant based on the mentioned principle has been constructed in Tårs and put into operation in August, 2015 (Aalborg CSP, 2015). Measured and simulated thermal performances of the combined solar heating plant for the period September 2015-July 2016 are presented in the paper.

The studied solar heating plant is the first large solar heating plant (9992 m^2) developed for a district heating network in Denmark, even in the world, which integrates parabolic trough collector and flat plate collector technologies. Measured thermal performance and calculated thermal performance with a validated TRNSYS model of the Tårs solar heating plant are shown in this paper. Thermal performance potential of parabolic trough collectors in the Tårs solar heating plant was also elucidated under the Danish climate conditions.

2. TÅRS SOLAR HEATING PLANT

2.1 Overview

Figure 1 and 2 show the novel combined solar heating plant with a 5960 m^2 flat plate collector field and a 4032 m^2 parabolic trough collector field in Tårs, Denmark. The plant operation was started in August 2015(Aalborg CSP, 2015). Technical data on the combined solar collector field can been found in Tables 1-4. The solar collector fluid of the parabolic trough collectors is water, while that of FPC is a glycol/water mixture (40%). The return water from the district heating network is heated up to 65 - 70°C by the heat exchanger connected to the flat plate collector field. Then the water from the flat plate collector field is heated to the required temperature by going through the parabolic trough collector field. The orientation of parabolic trough collectors is 15° towards west from south. The parabolic trough collectors track the sun rays from east to west when the collectors work during the whole day. There are six rows of parabolic trough collectors and the row distance between PTC collectors is 12.6 m. The length of each row of parabolic trough collectors is about 120 m. The orientation of flat plate collectors is south and the collector row distance between flat plate collectors is 5.67 m. The tilt of flat plate collectors is 50°. The parabolic trough collectors were delivered by Aalborg CSP A/S. The flat plate collectors consist of two types of flat plate collectors, namely HTHEATboost 35/10 and HTHEATstore 35/10, delivered by Arcon-Sunmark A/S (2016). Half of the flat plate collector field is made of HTHEATboost 35/10, while the other half is HTHEATstore 35/10. The backup heat resource is two natural gas boilers. Two tanks with total a volume of 2430 m^3 are used as heat storage for several days.

2.2 Control strategy

Figure 3 briefly illustrates the basic principle of the Tårs solar heating plant. To achieve high solar fraction without seasonal storage, the plant is actually oversized compared to the heat demand in the summer months. To avoid overheating issues in the summer, the parabolic trough collectors are put out of focus sometimes. Feed forward control was used to keep a constant outlet temperature by the flow control in the parabolic trough collector field.

Fig.1. Picture of the Tårs solar heating plant

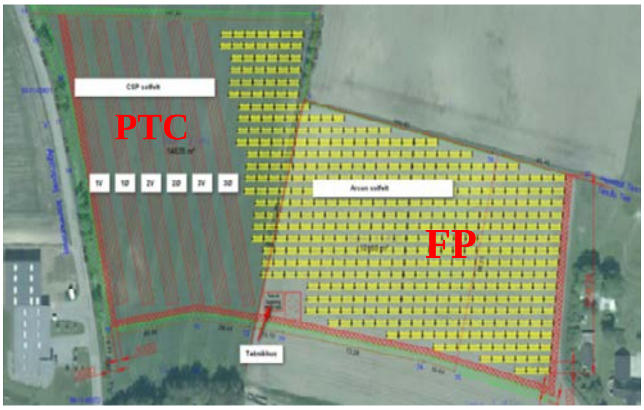

Fig.2. Layout of the combined solar collector field

Table 1. Design parameters of the Tårs plant

Parameters	Tårs (Denmark)
Latitude	57.39 °N
longtitude	10.11 °E
Altitute	48 m
parabolic trough collector field	4032 m^2
flat plate collector field(2 types in series)	5960 m^2
Fossil backup -Natural gas boiler	9.1 MW
Two storage tanks	2430 m^3

Table 2. PTC collector parameters in the Tårs plant

Geometrical parameters for the PTC collector	
Absorber tube outer diameter (m)	0.070
Absorber tube inner diameter (m)	0.066
Glass envelope outer diameter (m)	0.120
Glass envelope inner diameter (m)	0.115
Parabola width (m)	5.75
Numbers of modules per row	30
Mirror length in each module (m)	4.06
Concentration ratio	82.14

Table 3.FPC collector parameters in the Tårs plant

Geometrical parameters for the FP collector		
Length, m		5.96
Width, m		2.27
Thickness, m		0.14
Gross area, m^2		13.57
Aperture area, m^2		12.60
Solar collector volume, L		10.6
Absorber	Material	Cu pipe /Al plate
	Absorption	0.95
	Emission	0.05
Insulation	Backside	75 mm mineral wool
	Side	30 mm mineral wool
Cover(s)	**Atireflex glass(AR:3.2mm)-with/without FEP foil**	

Table 4. Technical parameters of the solar collector field

Parameters	PTC	FPC
Aperture area, m^2	4039	5960
Solar collector fluid	Water	Glycol/water
Collector row distance, m	12.6	5.67
Number of identical rows	6	20
Azimuth,◦	-15	0
Tilt,◦	-	50

3. METHODS

3.1 Measurements

The system is well equipped with different accurate sensors and the monitoring data are automatically transferred to computers. Global solar radiation on the horizontal surface and solar radiation on the titled collector plate were measured with Kipp&Zonen SMP11, DNI was measured with a PMO6-CC pyrheliometer with the sun tracking platform Sunscanner SC1. Inlet and outlet temperatures of the collector fields are measured with SIEMENS TS500 temperature sensors, flow rates of both FPC field and PTC field were measured with Sitrans FM MAG3100 P flow meters - SIEMENS. Measured thermal performance can be calculated based on the measured parameters.

3.2 Trnsys model

A Trnsys model was set up to simulate the thermal performance of both the flat plate collector and the parabolic trough collector field. Parameters of parabolic trough collectors based on the aperture area in table 5 were determined by Technical University of Denmark (Perers B et al.,2013). Technical parameters of flat plate collectors based on the gross area are from SP Technical Research Institute of Sweden (2016). Table 5 shows the parameters of both collectors. TRNSYS model was based on the quasi dynamic equation as follows:

$$\frac{Q}{A} = \eta_0 K_{\theta b}(\theta) G_b + \eta_0 K_{\theta d}(\theta) G_d - c_1(T_m - T_a) - c_2(T_m - T_a)^2 - c_3\frac{dT_m}{dt}$$

$$K_{\theta b}(\theta) = 1 - b_0\frac{1}{COS\theta - 1} - b_1\frac{1}{COS\theta - 1}, \theta \le 60°$$

If the incidence angle is bigger than 60°, the IAM is linearized from the value at 60° to a value of zero at 90°. Parameters of both collector types can be found in the table 5.

TRNSYS type 1290 was used to simulate the thermal performance of the collectors. Type 3b was used as the pump unit in the collector field. Type 5b was the heat exchanger unit in the FPC field. Type 30 simulated the shadows between the collector rows.

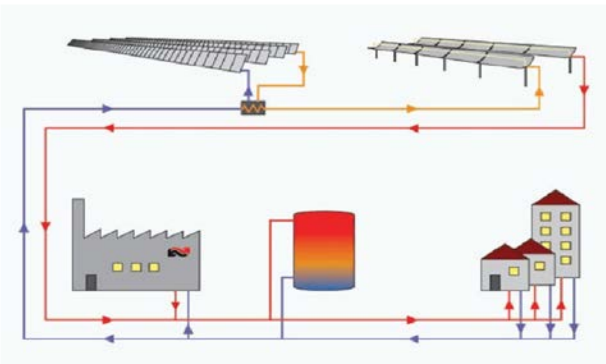

Fig.3. Simple schematic illustration of the Tårs solar heating plant layout

Table 5. Efficiency parameters of the collectors

	η_0	b_0	b_1	$K_{\theta d}$	c_1,[W/(m²·K)]	c_2,[W/(m²·K²)]	c_3,[kJ/(m²·K)]	
FPC	0.779	0.1	0	0.98	2.41	0.015	6.798	HTHEATboost 35/10-Gross area
	0.745	0.1	0	0.93	2.067	0.009	7.313	HTHEATstore 35/10-Gross area
PTC	0.75	0.27	0	0.038	0.04	0	4.00	Aperture area

4 Meteorological data and heat demand

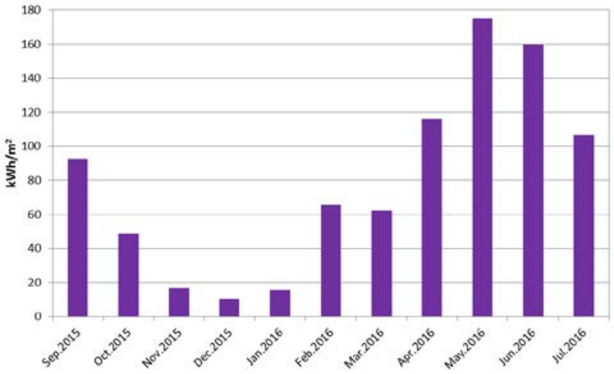

Fig.4. DNI in the Tårs solar heating plant (Sep.2015-Jul.2016)

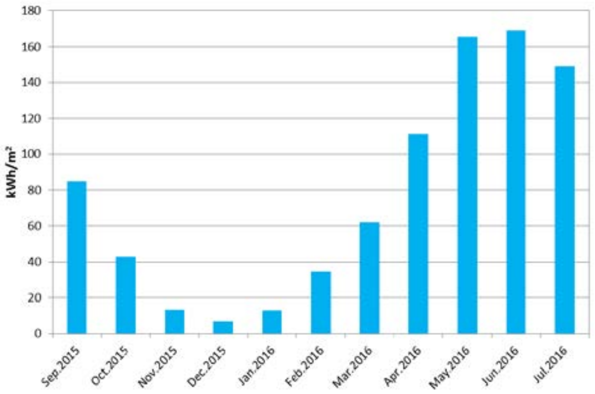

Fig.5. Global radiation on the horizontal surface in the Tårs solar heating plant (Sep.2015-Jul.2016)

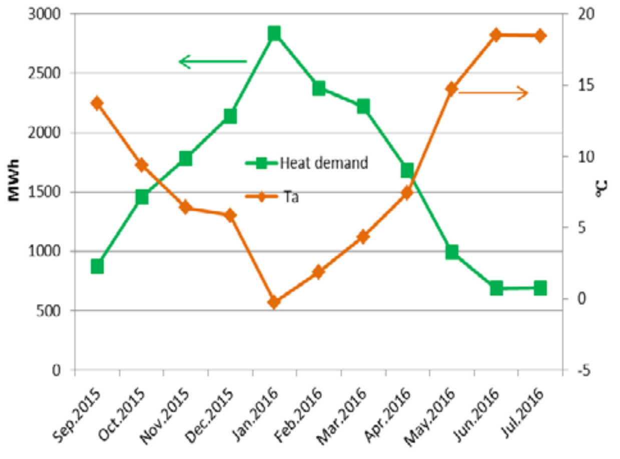

Fig.6. Monthly heat demand and average ambient temperature in the Tårs solar heating plant (Sep.2015-Jul.2016)

Figure 4 and 5 show the measured DNI and total solar radiation on the horizontal surface in the Tårs heating plant. Obviously, solar radiation in Nov. Dec. and Jan. was low. Figure 6 shows the monthly average ambient temperature from Sep.2015 to Jul.2016 and the heat demand of the Tårs district heating network. The average ambient temperature in Jan.2016 was -0.3°C, which was the lowest during the studied operation period. The average monthly ambient temperature in both June and July of 2016 is about 18 °C. Table 6 shows the sums of DNI, global radiation on the horizontal surface and heat demand from Sep.2015-Jul.2016.

Table 6. Sums of DNI, global radiation and heat demand of the Tårs solar heating plant (Sep.2015-Jul.2016)

Item	Value
DNI, kWh/m^2	869
Global radiation on the horizontal surface, kWh/m^2	854
Heat demand, MWh	17750

5 Validation of the TRNSYS model

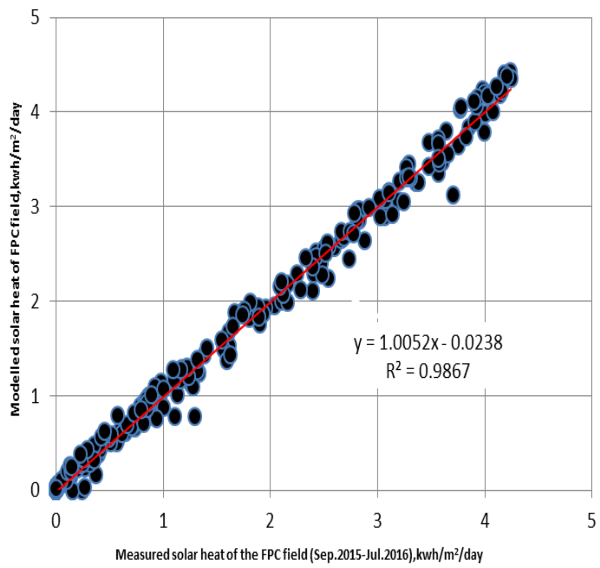

Fig.7. Comparison of daily modelled and measured solar heat (FPC field)

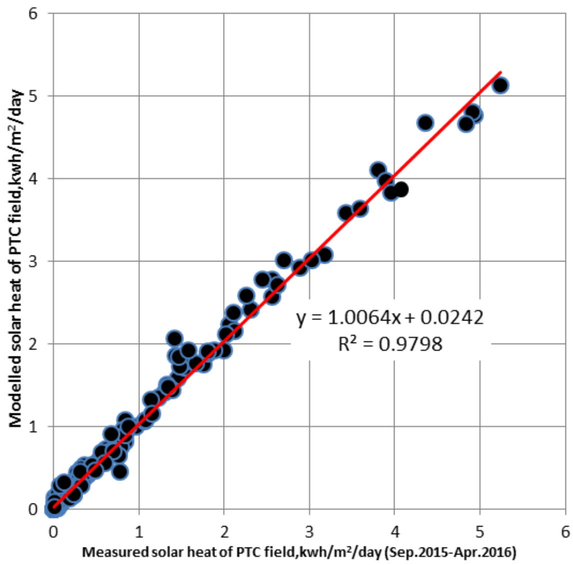

Fig.8. Comparison of daily modelled and measured solar heat (PTC field)

All the measured and modelled thermal performances given per m^2 solar collector field are based on the aperture area of the solar collectors. Figure 7 and 8 show that the modelled and measured thermal performances of both the flat place collector field and the parabolic trough collector field are in good agreement. As the parabolic trough collector field was defocused sometimes during the summer (such as May, June and July), figure 8 only shows the thermal performance of the parabolic trough collector field from Sep.2015 to Apr.2016 to verify the TRNSYS model. The maximum daily thermal performance of the parabolic trough collector field can be higher than 5 $kWh/m^2/day$, while the max daily thermal performance of the flat plate collector field is below 5 kWh/m^2. The results of Figure 7 and 8 illustrate that the TRNSYS model is validated by the measurements and is accurate enough to predict the thermal performances of both solar collector fields.

6. THERMAL PERFORMANCES

6.1 Thermal performance of FPC collectors

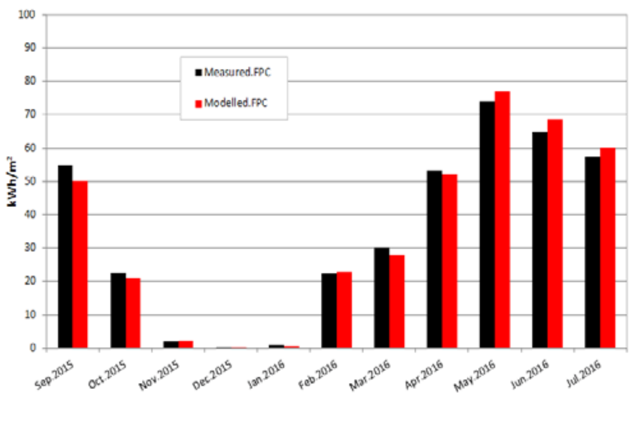

Fig.9. Monthly thermal performance of FPC field (Sep.2015-Jul.2016)

Figure 9 shows monthly measured and modelled thermal performances of the flat plate collector field from Sep.2015 to Jul.2016. The thermal performance is low during the winter because of the low solar radiation. The max monthly thermal performance of the flat plate collector field is higher than 70 kWh/m^2 in May, 2016. The total thermal performance of the flat plate collector field is 383 kWh/m^2 (aperture area) during Sep.2015 - Jul.2016. If the thermal performance per square meter solar collector field is based on the gross area, the total energy output of flat plate collector field is 356 kWh/m^2 (gross area).

6.2 Thermal performance of PTC collectors

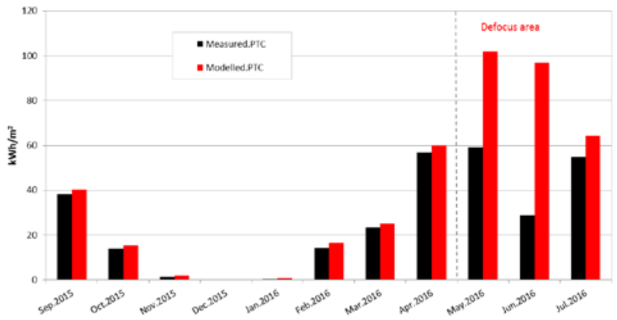

Fig.10. Monthly thermal performance of PTC field

As is shown in figure 10, the parabolic trough collector field produced not much during the winter. But in the spring, the parabolic trough collector field performed well. The parabolic trough collector field should work best in the summer, when the solar radiation is high. However, the parabolic trough collector field was defocused sometimes in the summer (such as May, June and July) because the flat plate collector field was oversized and the heat demand in the summer was low. The simulated thermal performance in figure 10 illustrate that the potential monthly thermal performance of the parabolic trough collector field is higher than 90 $kWh/m^2/month$ if the parabolic trough collector field could work without defocusing. The measured thermal performance of the parabolic trough collector field for Sep.2015-Jul.2016 is 290 kWh/m^2. The simulated thermal performance of the parabolic trough collector field could have reached about 420 kWh/m^2 (aperture area) for Sep.2015-Jul.2016 if the parabolic trough collectors were not defocused. That is: A reduction of 130 kWh/m^2 was calculated due to defocusing due to the oversized the flat plate collector field.

6.3 Solar fraction

The Tårs district heating network consists of 840 buildings with 1900 consumers. Measured heat load and total thermal performance of the combined solar collector field can be found in figure 11. To make the comparison of heat demand and solar heat produced clear, all the values in figure 11 are based on square meter solar collector field (aperture area). The solar fraction, defined as the ratio between the solar heat and the heat demand, is very high in the summer when the heat load is low and the weather is sunny, see figure 12. As the solar radiation in the winter was low, both the flat plate collector and the parabolic trough collector field produced low quantities of solar heat and the solar fraction in the winter is close to 0, which is normal for the Nordic area. Table 7 shows a summary of the thermal performance of the Tårs plant. The measured total thermal performance of the Tårs solar heating plant is 3460 MWh and total heat load of Tårs is 17750 MWh. The solar fraction of the solar heating plant is 19.5% during Sep.2015-Jul.2016. As shown in figure 11 and 12, if the parabolic trough collectors were not defocused, the parabolic trough collectors could have a better thermal performance in the summer. The thermal performance of the combined solar collector field without defocused parabolic trough collectors in the summer can reach 3990 MWh and the solar fraction would increase from 19.5% to 22.5%.

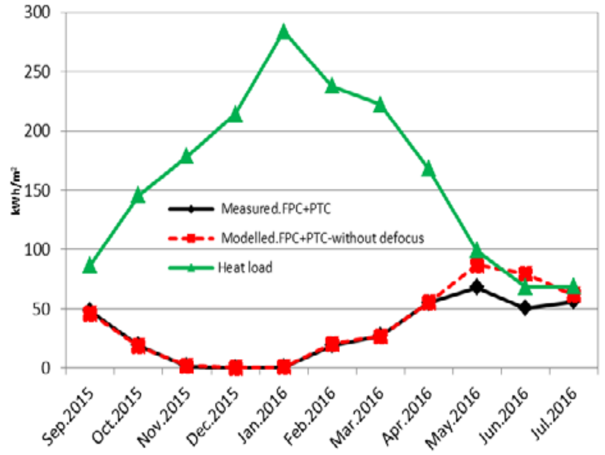

Fig.11. Heat demand and thermal performance of the Tårs solar heating plant (per m^2 solar collector aperture area, Sep.2015-Jul.2016)

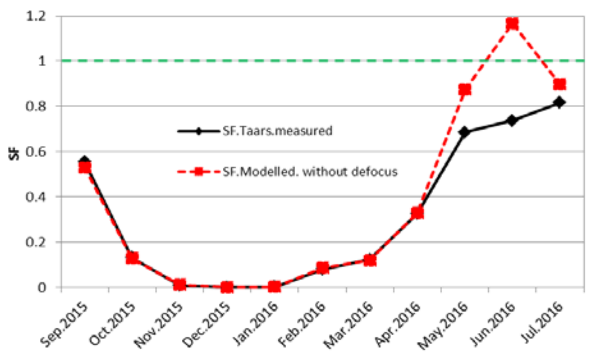

Fig.12. Solar fraction (SF) of the Tårs solar heating plant (Sep.2015-Jul.2016)

Table 7. Thermal performance of the Tårs plant (Sep.2015-Jul.2016)

Item	Value
Heat demand, MWh	17750
Measured solar heat. FPC field, MWh	2280
Modelled solar heat. FPC field, MWh	2280
Measured solar heat. PTC field, MWh	1180
Modelled solar heat. PTC field without defocus, MWh	1710
Measured solar fraction	19.5%
Modelled solar fraction without defocus	22.5%

6.4 Utilized efficiency

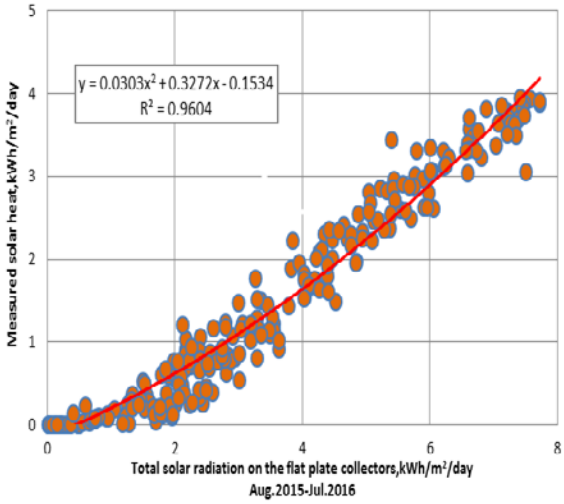

Fig.13. Measured daily solar heat and total radiation on the flat plate collectors.

Figure 13 shows the daily measured solar heat of the flat plate collector field and total radiation on the flat plate collectors. According to the fitting curve, the average daily efficiency of the flat plate collector field is about 0.48.

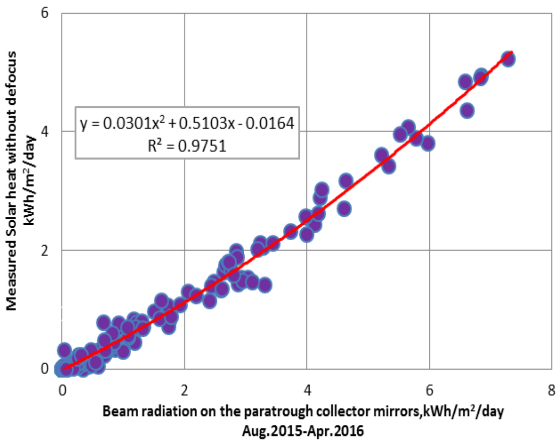

Fig.14. Measured daily solar heat and beam radiation on the parabolic trough collectors mirror.

Figure 14 shows the daily measured solar heat and beam radiation on the parabolic trough collectors from Sep.2015 to Apr.2016. The fitting curve illustrates that the average daily efficiency of the parabolic trough collector field based on the beam radiation on the parabolic trough collectors is about 0.66. If the parabolic trough collectors work without defocusing in the summer, the daily efficiency in the summer will increase to about 0.70.

7. DISCUSSIONS

The Tårs solar heating plant is the first large solar heating plant, which uses both flat plate collectors and parabolic trough collectors to provide heat for a district heating network in Denmark. The oversize of the flat plate collector field is the main reason why the parabolic trough collectors are defocused in summer periods.

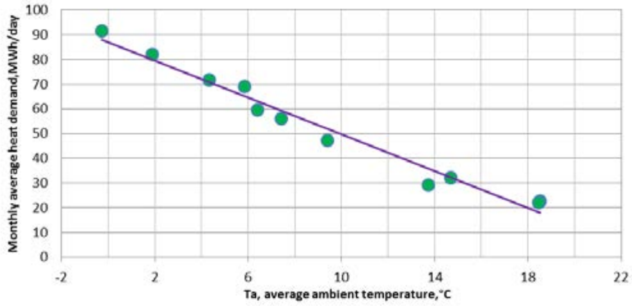

Fig.15. Measured monthly heat demand and average ambient temperature of the Tårs solar heating plant (Aug.2015-Jul.2016)

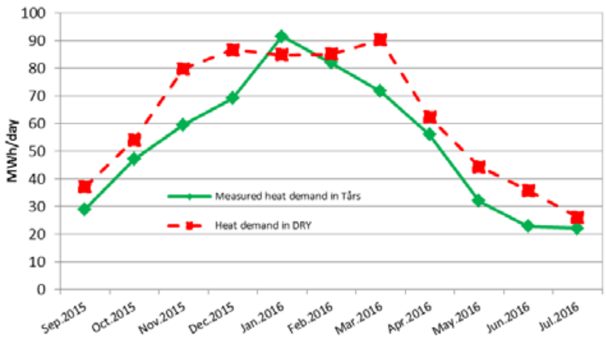

Fig.16. Measured heat demand of the Tårs solar heating plant and for the DRY

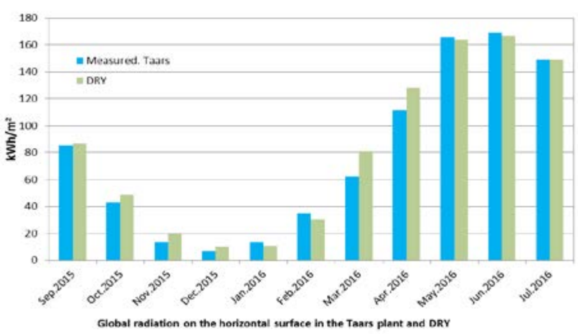

Fig.17. Monthly global radiation on horizontal in the Tårs plant and in the DRY

Figure 15 shows the relation between average monthly heat demand and average ambient temperature. The heat demand in the DRY (Design Reference Year) for the northern part of Jutland (Dragsted, J. et al., 2012) is shown in figure 16. The heat demand is calculated by the fitting curve and average ambient temperatures of the DRY. Figure 16 illustrates that the heat demand of the Tårs solar heating plant in the DRY is a bit higher than that from Sep.2015-Jul.2016.

Table 8. Calculated annual thermal performance of Tårs solar heating plant in the DRY

Item	Value
Solar heat.FPC field	510 kWh/m^2
	3040 MWh
Solar heat.PTC field	530 kWh/m^2
	2140 MWh
Heat demand	21590 MWh
Solar fraction	24%

Figure 17 shows global radiation on horizontal in the Tårs plant and global radiation of the DRY. The measured total global radiation in the Tårs solar heating plant from Sep.2015 to Jul.2016 is 854 kWh/m^2, while that of DRY is 894 kWh/m^2.

Table 8 shows calculated annual thermal performance of the Tårs solar heating plant in the new DRY, calculated by DTU Excel tool (Dragsted and Furbo, 2012). Mean solar collector fluid temperatures of the flat plate collector field and the parabolic trough collector field were assumed as 55°C and 80°C respectively based on the measurements. The thermal performance of the Tårs solar heating plant in the DRY is 5180 MWh, while the heat demand in the DRY is 21590 MWh. Furthermore, the solar fraction is 24%. Table 8 also illustrates that the thermal performance of flat plate collectors can be higher than 500 kWh/m^2 under Danish climate conditions when the flat plate collectors work at low operation temperatures like 55°C in such a combined solar heating plant.

The investigations have shown that it is very important to size the collector areas of both the flat plate collectors and parabolic trough collectors in such a way that oversizing is avoided.

An increase of the heat load of the district heating network in the future will strengthen and promote the thermal performance of the plant.

Further, a seasonal storage will also be helpful to harvest the advantages of parabolic trough collectors in the summer.

8. CONCLUSIONS AND OUTLOOK

Both measured and modelled thermal performances of the Tårs solar heating plant have been analysed for a period of almost a year. Experiences from the operation were also discussed. Thermal performance of the Tårs solar heating plant in the DRY for the northern part of Jutland was also investigated. The conclusions are as follow:

The solar fraction of the Tårs solar heating plant is 19.5% during the period from Sep.2015 to Jul.2016. If the parabolic trough collector field was not defocused, the total thermal performance would have increased from 3460 MWh to 3990 MWh, corresponding from 340 kWh/m^2 collector to 400 kWh/m^2 collector and the solar fraction would reach 22.5%.

The annual thermal performance of the Tårs solar heating plant in the DRY could reach 5180 MWh and a solar fraction of 24% if defocusing of the parabolic trough collectors is avoided.

Further studies on the thermal performance of the Tårs solar heating plant will be carried out as a part of the research project "Tårs solar heating plant with concentrating tracking and flat plate solar collectors" and a PhD study at the Technical University of Denmark.

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Nomenclature

Q	Useful output power, W
A	Collector aperture array area, m^2
c_1	Heat loss coefficient at (Tm-Ta)=0, W/(m^2·K)
c_2	Temperature dependence of the heat loss coefficient, W/(m^2·K)
c_3	Effective thermal capacity, J/(m^2·K)
G_b	Beam radiation, W/m^2
G_d	Diffuse radiation, W/m^2
$K_{\theta b}$	Incidence angle modifier for beam radiation,-
$K_{\theta d}$	Incidence angle modifier for diffuse radiation,-
T_m	Mean fluid temperature, °C
T_a	Ambient temperature, °C
η_0	Maximum efficiency,-
dTm/dt	Time derivative of the mean solar collector fluid temperature, K/s
θ	Incident angle of the beam radiation, °
b_0	First IAM coefficient(beam radiation),-
b_1	Second IAM coefficient(beam radiation),-

PTC	Parabolic trough collector
FPC	Flat plate collector
DNI	Direct normal irradiance
DTU	Technical University of Denmark
DRY	Design Reference Year
IAM	incidence angle modifier

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