Final report

1.1 Project details

Project title	Pilot Installation of Hybrid Solar Collectors in a Solar District Heating
Project identification (program abbrev. and file)	64015-0595
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	POLYCSP ApS, Møllegade 21, 9750 Østervrå
Project partners	DTU Byg Sæby Varmeværk a.m.b.a
CVR (central business register)	34893314
Date for submission	12.09.2015

1.2 Short description of project objective and results

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1.2 Short description of project objective and results

ENGLISH

The overall target of the project was to demonstrate and validate that the hybrid collectors are competitive solar collectors enabling the district heating utilities to increase the percentage of energy supplied from solar heating plants significantly, and these plants having similar low complexity, high robustness and long lifetime as conventional flat plate collector based solar heating plants.

The project team was successful in reaching this target based on measurements on the test set-up at DTU Byg and Sæby Varmeværk and identification of further optimization potentials on panel construction and design.

The project has thus shown that the idea behind a solar tracking hybrid collector panel is viable and the market potential is being investigated through an industry partner.

DANSK

Hovedmålet for projektet var at validere at den nye hybride solfanger er konkurrencedygtig og muliggør at fjernvarmeselskaberne kan forøge den andel af energien de frembringer fra solvarmeanlæg betydeligt, samt demonstrere at disse anlæg har tilsvarende lav kompleksitet, høj robusthed og lang levetid som de konventionelle anlæg med plane solfangere.

Projektgruppen har med succes nået målene baseret på målinger af test setup ved DTU Byg og Sæby Varmeværk samt identifikation af yderligere potentiale for forbedring af panelernes konstruktion og design.

Projektet har dermed vist at ideen bag en soltrackende hybrid solfanger er levedygtig og markedspotentialet er ved at blive undersøgt nærmere sammen med en industripartner.

1.3 Executive summary

The aim of this project was to develop and test a new concept for thermal solar collectors in a solar district heating plant and verify the benefits of the new type of solar collectors.

The background of the project was the development of a new type of collector for thermal solar heating plants, especially optimized for the temperature range of 90-160 °C. These collectors can potentially be installed in various applications such as heating supply systems for industries, for domestic heating purposes and in solar district heating plants. The purpose in this project was to demonstrate the technical performance and the competitiveness of these new collectors in Danish solar district heating plants, and based on that evaluate the performance and competitiveness on a European and global level.

The main activities in the project have been optimization of the collector design, test and characterization of the hybrid collectors regarding performance and efficiencies, design of a 55.6 m² pilot installation based on the hybrid collectors and the establishment of this pilot installation in connection to an existing solar district heating plant. During a 1 year operation period, this system has been monitored, experiments on control algorithms have been performed, performance data was analyzed and the overall feasibility of the new type of collectors and system was evaluated regarding technical performance and economic feasibility. Through modeling of the technical and economical characteristics, the benefits and competitiveness of the new hybrid collectors used in scaled systems have been calculated and evaluated.

The above mentioned activities have been carried out in a close cooperation between DTU Byg, Sæby Varmeværk, and POLYCSP with DTU Byg delivering analysis on measurements of the thermal performance plus theoretical knowledge, Sæby Varmeværk delivering test site facilities and know how on district heating requirements, and POLYCSP delivering the hybrid panels and knowledge on construction and design.

1.4 Project objectives

The project objectives were from the start of the project described in several work packages:

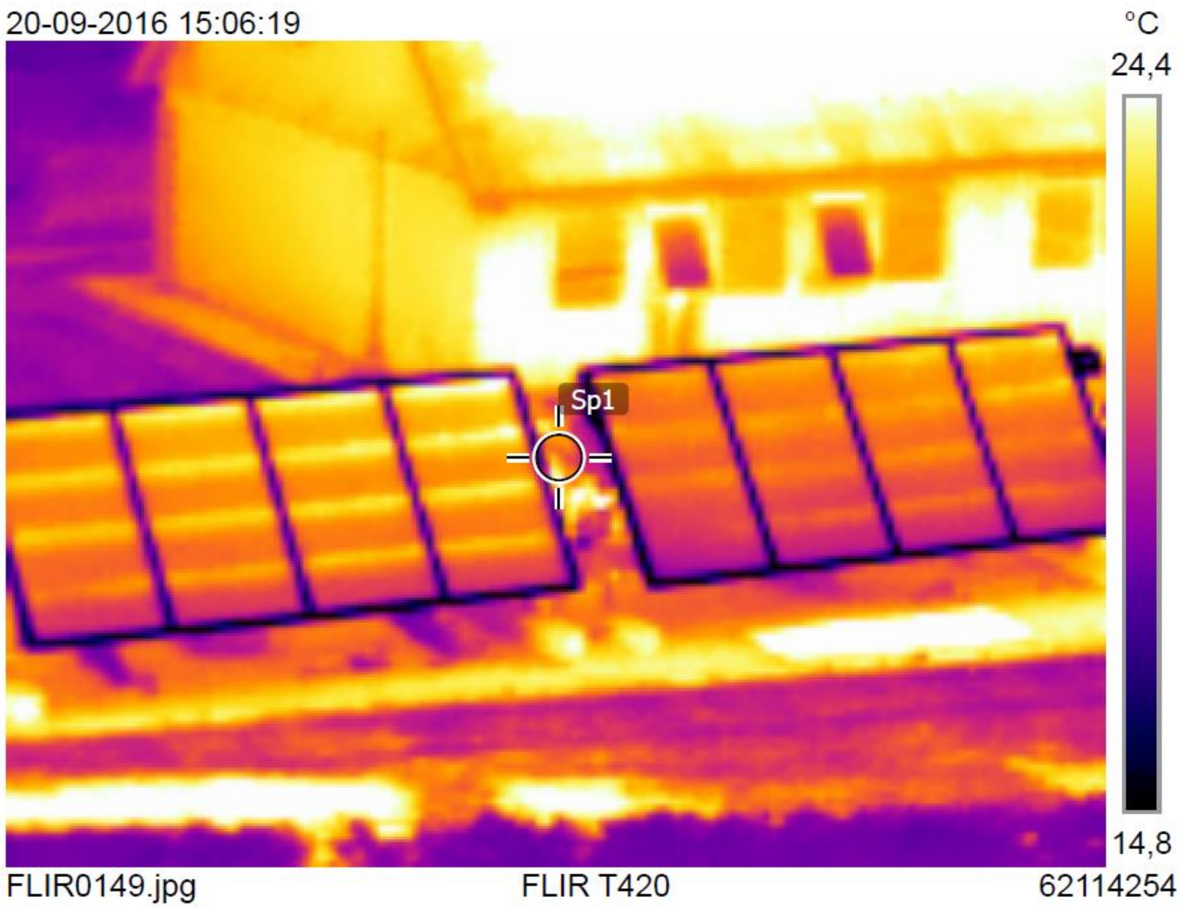
WP 1: Hybrid collectors

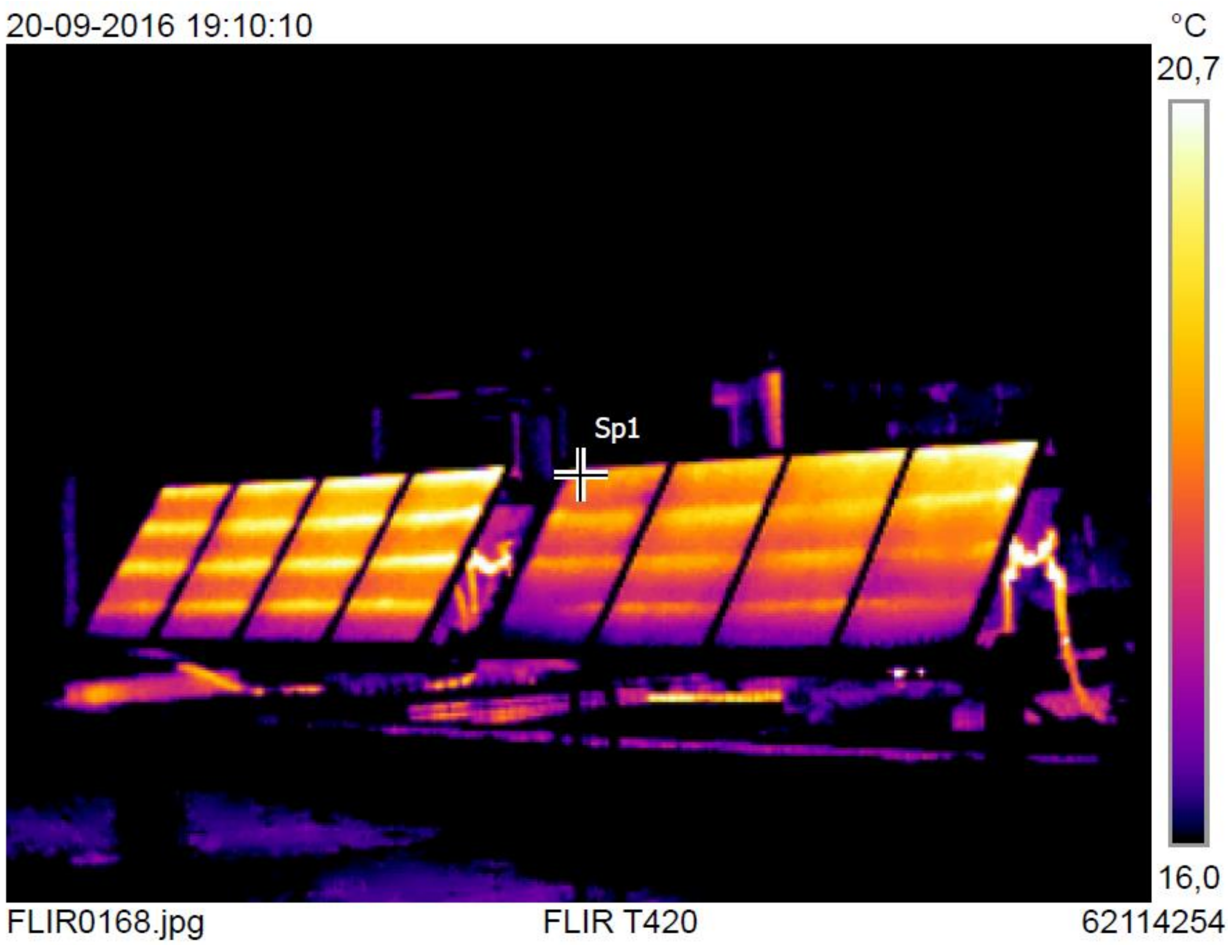
1.1 Optimization of collector design

Two tracking hybrid solar collectors with and without a foil around the absorbers were investigated in DTU's solar collector test facility, see photo.

Infrared photo investigations

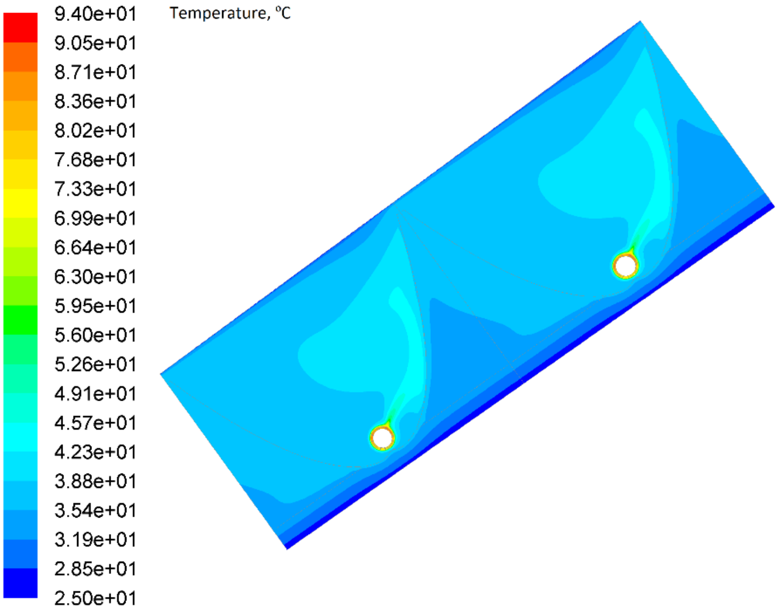
Infrared photo investigations were carried out at the test site of DTU both during day time and night time. The purpose of the infrared photo investigations is to verify the effect of using FEP foil between the collector's glass cover and the absorber. The photos showed clearly that the collector using FEP foil had lower surface temperature than the collector without FEP foil. The other purpose of using infrared photo investigations is to check the high temperature zones of the collector surface which indicate high heat loss areas. From the two infrared photos it can be seen that both the collectors had four "hot lines" on the surface indicating the high temperature zones. The analysis and results helped to optimize the design of the new concept collector. The collector without the foil is located to the left.

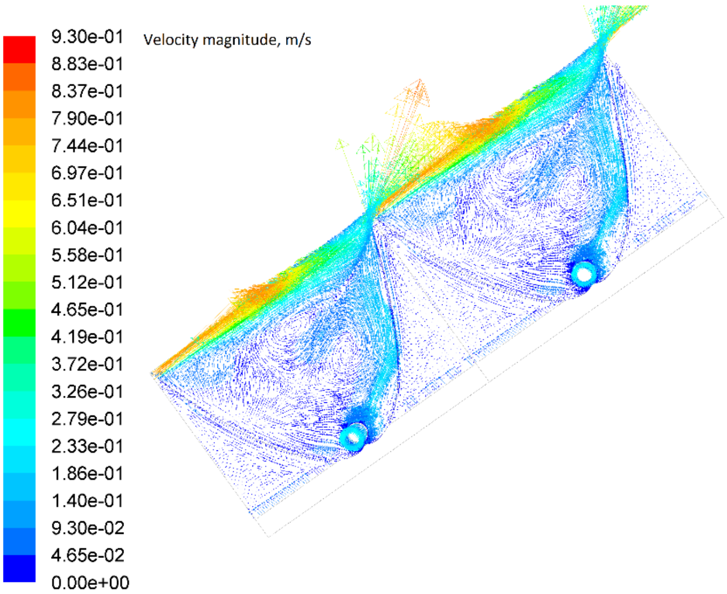




CFD simulation and validation

A CFD model was created based on the specific design of the new hybrid solar collector. The CFD model was validated by the experiments carried out at DTU. The measured temperatures of the solar collector were compared to the temperatures predicted by the CFD model. The results show that the CFD model predicts satisfactorily the temperature rises of the collector in the temperature range between 20°C and 81°C. The deviation between the measured and the calculated temperature rises is limited to ±0.2 K with a relative error of less than 2.3%. The predicted error of collector efficiency by the CFD model is within ±1.5 %. The validated CFD model is used to investigate the thermal behavior of the CPC solar collector under high operation temperatures of 100 °C and 130 °C respectively. The results show risk of local overheating due to uneven distribution of absorbed solar energy over the receiver surface.





CFD simulation for an improved collector design

The second CFD model was created based on an improved hybrid collector design. According to the calculation of the new CFD model, the improved hybrid collector has higher efficiency and lower heat loss coefficient than the existing tested hybrid collector. It is a promising collector design for solar heating plants.

1.2 Determination of collector efficiency

A QDT (Quasi-dynamic test) model was used to determine the thermal performance of the solar collector.

$$q_u = \eta_0 K_b(\theta) G_b + \eta_0 K_d G_d - a_1 (T_f - T_a) - a_2 (T_f - T_a)^2 - a_5 dT_f / dt$$

$$K_b(\theta) = 1 - b_0 [1/\cos(\theta) - 1]$$

where
q_u is thermal performance of solar collector, W/m²
$K_b(\theta)$ is incidence angle modifier for beam radiation, -
Kd is incidence angle modifier for diffuse radiation, -
θ is incidence angle for direct radiation, °
η_0 is peak collector efficiency, -
a_1 is heat loss coefficient of collector at ambient temperature, W/(m²K)
a_2 is temperature dependence of heat loss coefficient of collector, W/(m²K²)
a_5 is the thermal capacity of the collector, J/m²K
T_f is the mean solar collector fluid temperature, °C
T_a is the ambient air temperature, °C
G_b is the beam irradiance on the collector, W/m²
G_d is diffuse radiation on the collector, W/m²
t is time, s
b_0 is a constant for the incidence angle modifier, -

The parameters for the collector efficiency for the collector without the foil is shown in the table. The parameters are given for the aperture area of the solar collector.

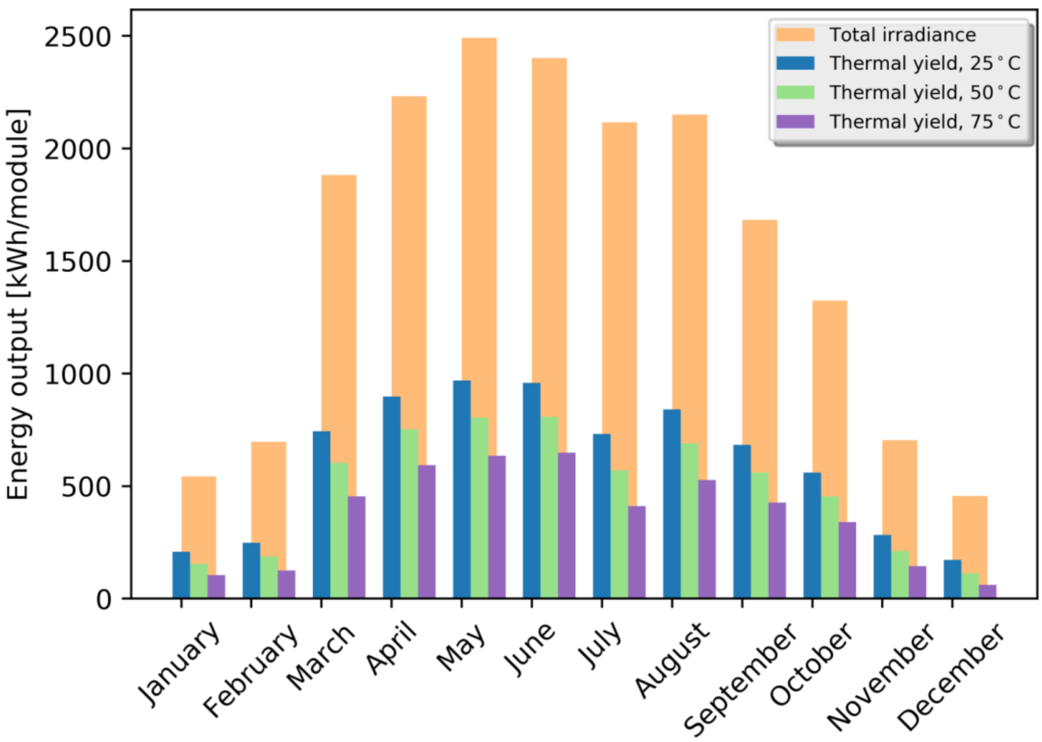
Parameter/collector	**CPC Collector**
Peak collector efficiency η_0 (-)	0.65
Incident angle modifier for beam radiation b_0 (-)	0.25
Incident angle modifier for diffuse radiation K_d (-)	0.27
Heat loss coefficient a_1 (W/m^{2}K)	0.92
Temperature dependence of the heat loss coefficient a_2 (W/m^{2}K^2)	0.0148
Effective thermal capacity a_5 (J/m^{2}K)	7518
Collector aperture area (m^2)	13.91

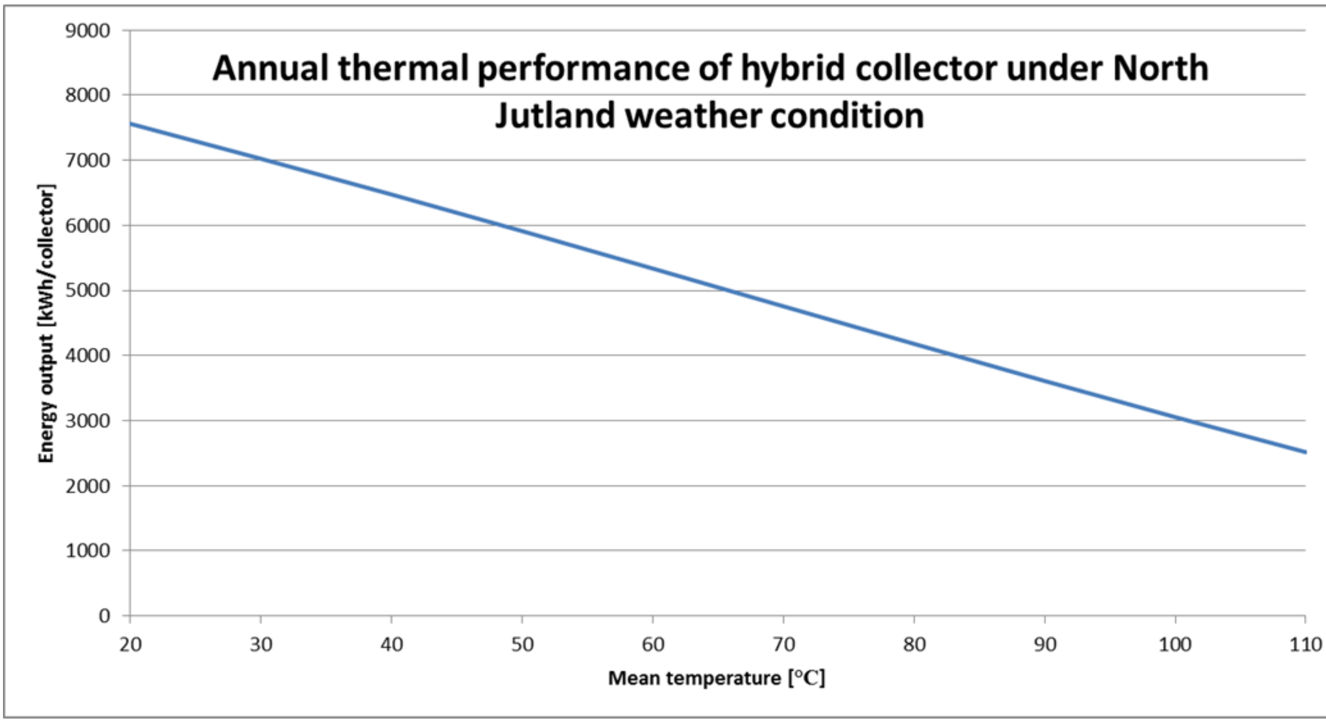
1.3 Calculation of yearly thermal performance

The monthly thermal performance calculation was calculated for the tested solar collector without foil at three fluid mean temperatures with weather data for the Northern part of Jutland, see the following table and figure.
The yearly thermal performance of the tracking hybrid solar collector assuming a perfect tracking is shown as a function of the mean solar collector fluid temperature.

Monthly total irradiation and energy output at three fluid mean temperatures in kWh per hybrid collector

	Total radiation (kWh/collector)	Tm=25°C	Tm=50°C	Tm=75°C
January	542	208	155	104
February	697	249	187	125
March	1882	744	604	455
April	2232	897	753	593
May	2492	969	805	634
June	2401	958	808	649
July	2116	732	571	411
August	2151	841	690	526
September	1683	683	560	428
October	1324	560	455	340
November	704	283	212	144
December	457	171	112	61
Sum	**18681**	**7295**	**5912**	**4470**





1.4 Manufacturing of series of collectors

All tasks in WP 1 were completed as described in the application and almost within the estimated timeframe as the optimization of the collector design had a few loops and hence the manufacturing of the collectors was a bit delayed. Furthermore the manufacturing of multiple collectors took longer than anticipated in the project timeline.

WP 2: System integration

2.1 Overall specification and design of system
2.2 Design and manufacturing of mechanical structures
2.3 Design and procurement of fluid system
2.4 Design and procurement of data logging and control system
2.5 Installation, start up and running in system

As a result of the minor prolongation of the design optimization and also the specification/integration phases the actual installation of the string of collectors was delayed three months, and since it was then winter, the installation was postponed until the early spring 2017. Based on that the project period was granted an extension of four months, so that the data collection and the following data analysis period could take place during a full 12 months period.

WP 3: Experiments, performance analysis and reporting

3.1 Continuously monitoring
3.2 Series of experiments
3.3 Reporting on performance

Four panels of the tracking hybrid solar collector without foil were installed as an additional new last solar collector row in Sæby solar heating plant, see photo below. The four collectors are in serial connection with the flat plate solar collectors located in the row in front of new row. Therefore the temperature level for the flat plate collectors is lower than the temperature level of the tracking hybrid solar collectors.

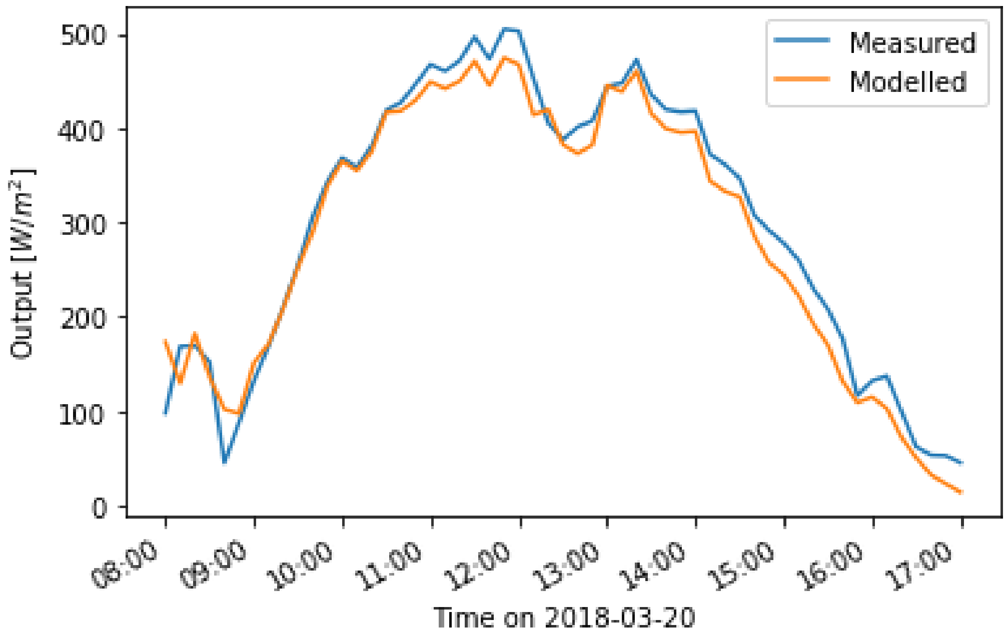
Detailed measurements of the thermal performances of the four tracking hybrid solar collectors and of four flat plate solar collectors in the row in front of the new row were carried out from the end of 2017. A summary of the measurements are given in the table below. The thermal performances are given for the four tracking hybrid solar collectors, for the four flat plate solar collectors and for the whole plant for in total 153 days with measurements available. The thermal performances are given per m² collector aperture area. The thermal performance of the tracking hybrid collectors in the 153 days is 195 kWh/m² with a weighted solar collector fluid temperature of 76.5°C, and the thermal performance of the four flat plate solar collectors is 286 kWh/m² with a weighted solar collector fluid temperature of 49.7°C. The thermal performance of the whole solar collector field is 274 kWh/m² for the period. It must be mentioned that the tracking system did not work perfect during all hours of the 153 days. This reduced of course the thermal performance of the tracking hybrid solar collectors somewhat.

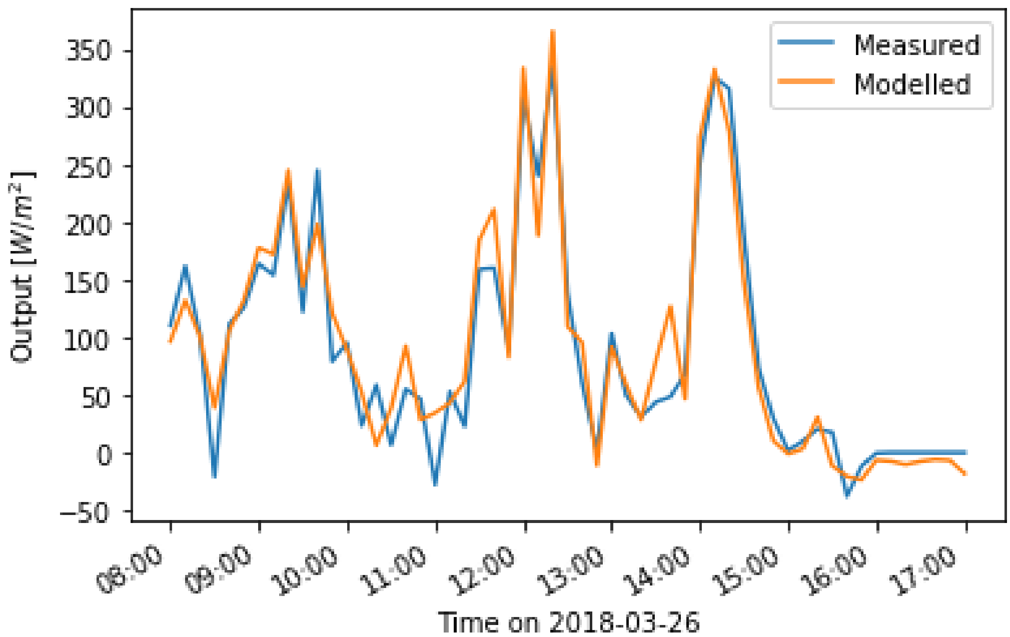
Period	Number of days with measurements	Total solar radiation on hybrid collectors, kWh/m²	Total solar radiation on flat plate collectors, kWh/m²	Measured thermal performance of 4 hybrid collectors, kWh/m²	Measured thermal performance of 4 flat plate collectors, kWh/m²	Measured thermal performance of whole solar collector field, kWh/m²	Weighted mean solar collector fluid temperature for 4 hybrid collectors, °C	Weighted mean solar collector fluid temperature for 4 flat plate solar collectors, °C
December 2017	9	2	2	0	0	0	8.0	19.7
January 2018	9	1	2	0	0	0	20.7	28.6
February 2018	26	39	38	5	5	3	67.0	46.6
March 2018	19	63	60	17	20	24	76.2	48.0
April 2018	29	123	122	33	51	51	72.0	45.9
May 2018	31	213	209	72	106	100	77.3	50.0
June 2018	30	215	209	68	104	96	78.6	51.6
Total	153	657	641	195	286	274	76.5	49.7

WP 4: Evaluation of the hybrid collector based systems

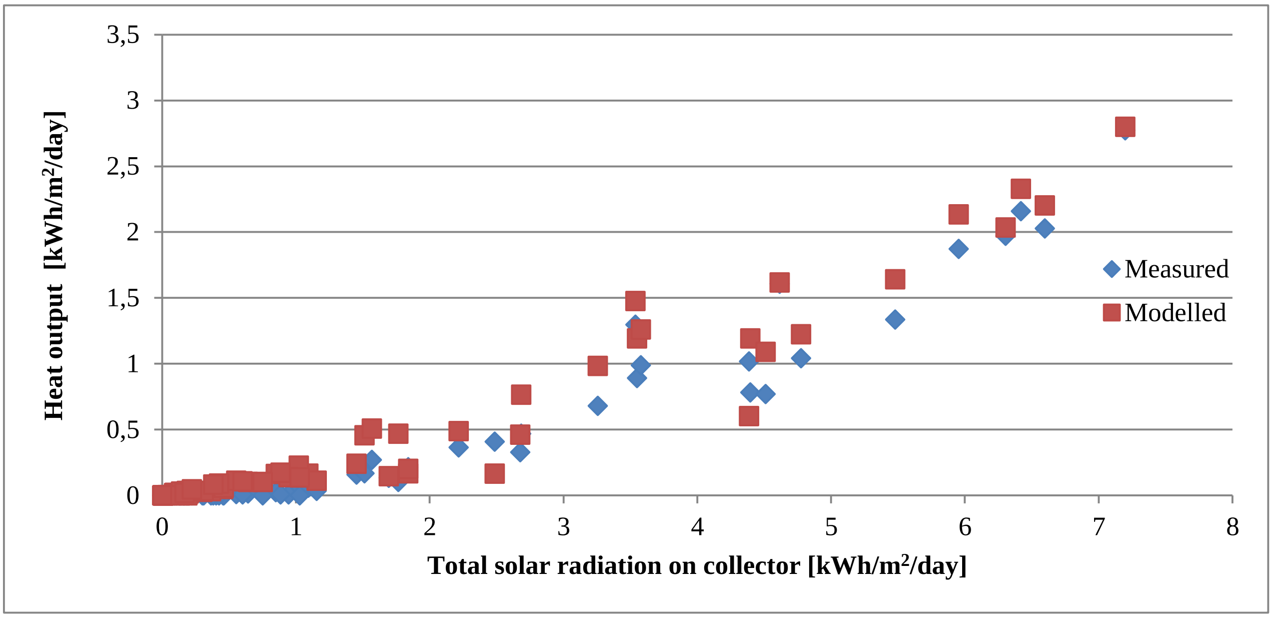
4.1 Develop mathematical model for performance
4.2 Verify/update model based on measured data
4.3 Calculate performance and economy for scaled systems

The thermal performance of the tracking hybrid solar collectors in Sæby solar heating plant is calculated with measured weather data and the efficiency expression determined by the experimental investigations in DTU's test facility for solar collectors mentioned in WP1. Shadows from the collector row in front of the collectors are also considered in the calculations. The figures below show measured and calculated thermal performances for the solar collectors during a sunny day and during a sunny day with clouds moving across the sky. There is a good agreement between measured and calculated thermal performances during both days.

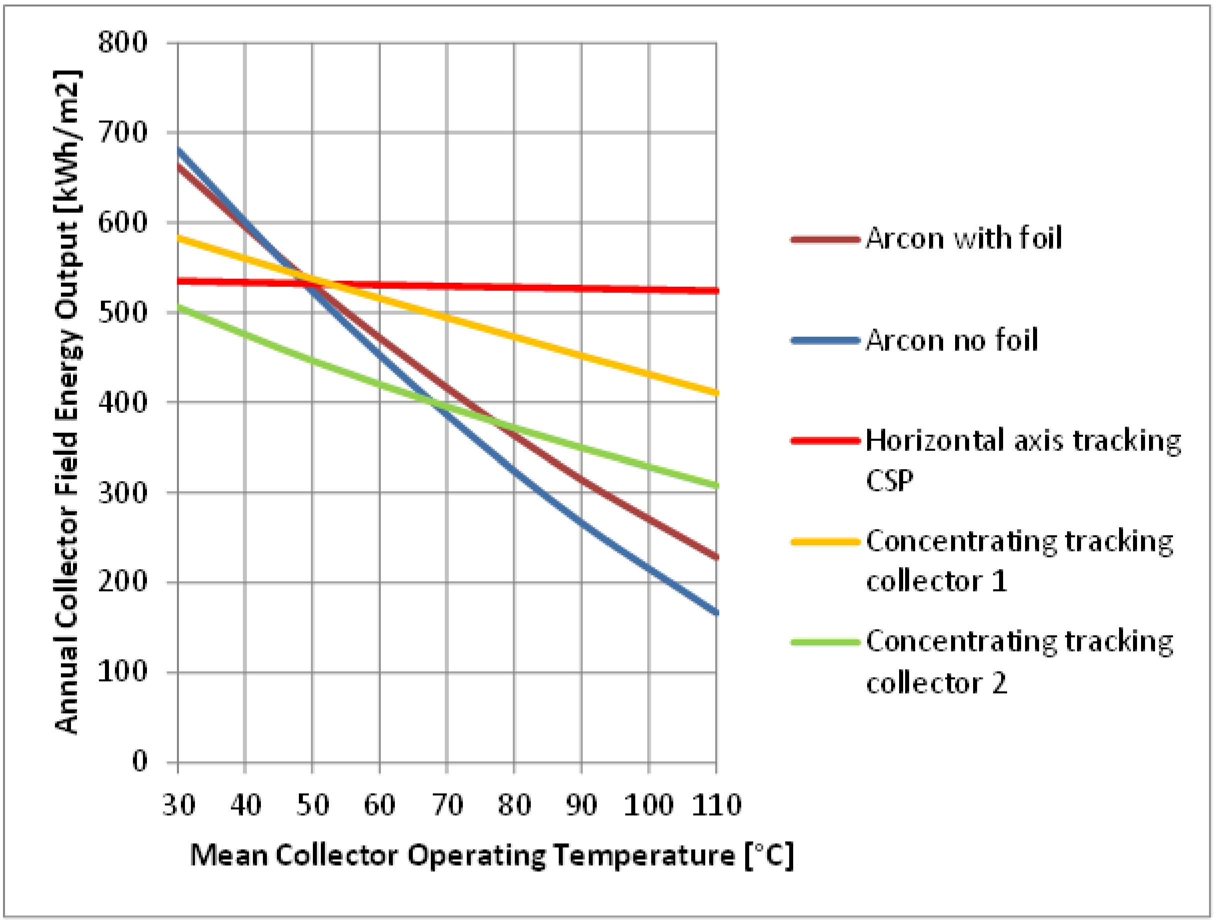




The figure below shows for different days measured and calculated daily thermal performances of the four tracking hybrid solar collectors. There is also on a daily basis a good agrement between measured and calculated thermal performances.



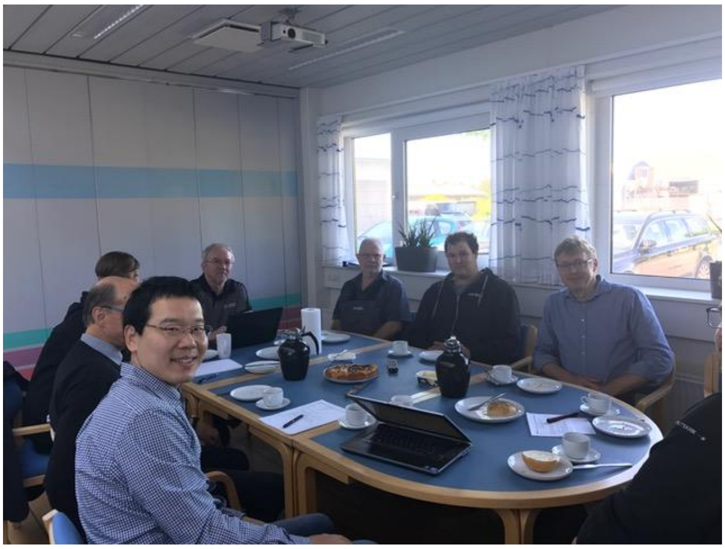
The figure below shows calculated yearly thermal performances of different solar collector fields with weather data for the Northern part of Jutland as function of the mean solar collector fluid temperature. The thermal performances are given for the aperture areas of the solar collectors. Solar collector fields based on two different flat plate solar collectors, on large tracking CSP solar collectors and on two tracking hybrid solar collectors are given. The green curve represents the tracking hybrid solar collector tested at DTU. The orange curve represents the theoretically investigated ideal tracking hybrid solar collector with improved absorber design and optical properties. A North-South tracking axis for the hybrid solar collectors is assumed and it is also assumed that the tracking is ideal during all hours. These assumptions are used to show the full potential of the tracking hybrid solar collector. The yearly thermal performance for mean solar collector fluid temperatures lower than 50°C is highest for the fields based on flat plate solar collectors. The ideal tracking hybrid solar collector performs better than the flat plate solar collectors if the mean solar collector fluid temperature is above 50°C.



WP 5: Project management

- 5.1 Overall planning and follow up
- 5.2 Organize project meetings
- 5.3 Project progress reporting
- 5.4 Financial reporting

The management of the project has smoothly taken place between the project partners, and work groups with members from the project partners have been formed based on work packages and the needed tasks.



Some of the members of the project group from the three project partners.

1.5 Project results and dissemination of results

Technical results

The project team at DTU Byg has throughout the project made theoretical analysis of the optimization potential of the hybrid collector as well as data analysis on data collected from the test set-up at DTU Byg and, thereafter, from the site at Sæby Varmeværk. This work has resulted in several publications and presentations of which some are listed below, which also show a wide variety of ways to disseminate the technical results of the project.

Journal paper under review

Experimental and Computational Fluid Dynamics Investigations of a CPC Solar Collector for District Heating. Guofeng Yuan, Jianhua Fan, Weiqing Kong, Simon Furbo, Bengt Perers, Fabienne Sallaberry submitted to the journal Solar Energy.

Conference Papers

New CPC based hybrid collector for solar heating plants, Bengt Perers, Simon Furbo, Weiqiang Kong, Zhiyong Tian, Hans-Erik Kiil, Anders William Larsen, René Bang Madsen. SDH Conference 2016, Billund.

Suitability of the Accuracy of a Tracking System with a CPC Solar Collector Acceptance Angle, Fabienne Sallaberry, Weiqiang Kong, Simon Furbo, Bengt Perers, Hans-Erik Kiil, Anders William Larsen, René Bang Madsen, Odei Goñi Jauregi, September 26-29, 2017, Santiago, Chile.

Conference abstract

Thermal performance analysis of a CPC solar collector array with series connection to the flat plate solar collector field in Sæby solar heating plant, Weiqiang Kong, Simon Furbo, Bengt Perers, Zhiyong Tian and Janne Dragsted, The 5th International SDH conference in Graz, Austria 11-12 April 2018

Posters

Thermal performance analysis of a CPC solar collector array with series connection to the flat plate solar collector field in Sæby solar heating plant, Weiqiang Kong, Simon Furbo, Bengt Perers, Zhiyong Tian and Janne Dragsted, The 5th International SDH conference in Graz, Austria 11-12 April 2018.

Suitability of the Accuracy of a Tracking System with a CPC Solar Collector Acceptance Angle, Fabienne Sallaberry, Weiqiang Kong, Simon Furbo, Bengt Perers, Hans-Erik Kiil, Anders William Larsen, René Bang Madsen, Odei Goñi Jauregi, September 26-29, 2017, Santiago, Chile.

New CPC based hybrid collector for solar heating plants, Bengt Perers, Simon Furbo, Weiqiang Kong, Zhiyong Tian, Hans-Erik Kiil, Anders William Larsen, René Bang Madsen. SDH Conference 2016, Billund.

Presentations

Project presented for students following DTU's solar energy courses.
Thermal performance test of POLYCSP collectors. Weiqiang Kong. Projektmøde 3. november 2016.
Experimental investigations and theoretical simulation of a new CPC solar collector for district heating. Weiqiang Kong. Department meeting, DTU Byg. 01 December 2017.
Test and simulation of POLYCSP CPC collector. Weiqiang Kong. Project meeting, June 1, 2017
CFD Simulation of flat plate absorber POLYCSP CPC collector. Weiqiang Kong. Project meeting, April 3, 2018

Commercial results

POLYCSP has not been able to find a position in the market with direct sales of panels to e.g. district heating plants or solar heating construction engineering companies, primarily due to POLYCSP being a small company with short market history and the need for substantial investments in a production facility in order to be able to manufacture at low prices.
POLYCSP is therefore actively, and has been the past year, seeking an industry partner with either a production set-up that fits well the manufacturing process of the hybrid collector or a partner with the financial capacity and strategy to establish a hybrid collector facility.

1.6 Utilization of project results

POLYCSP has filed a patent and this is now patent pending in EU and China/Asia and the feedback from the patent reviewers so far has been quite positive and the patent is expected to be granted in 2019.

As stated above, further commercialization of the outcome of the project regarding the optimized hybrid panel is postponed until the right industry partner match is found.

The hybrid panel has through the project proven to be a well suited add-on to existing solar collector fields to maximise the outcome and prolong the solar harvesting season. The results of the project are thus showing positive ways to further utilise non-fossile energy supply.

It should be mentioned that the thermal advantage of the tracking hybrid solar collector and of collector fields consisting of flat plate collectors and the new collector is higher in more sunny locations than in Denmark. Further, the new collector can be attractive for solar collector fields used for medium temperature industry utilization since it can reach higher temperatures than flat plate collectors due to the lower heat loss.

1.7 Project conclusion and perspective

The project has proven the viability of a CPC collector looking at the measured yearly performance as the test site at Sæby Varmeværk, and even more so if the potential for optimization of the design and hence outcome plus the effects on manufacturing costs when taken to large scale production. POLYCSP is therefore looking for an industrial partner to cooperate on the manufacturing issues, and furthermore looking for potential licensees for the expected approved patent.

Annex

Posters, abstacts etc. derived from the project are sent as separate files.