DTU Byg

FINAL REPORT

EUDP 13-II, COMBINED THERMAL SOLAR ENERGY DEMONSTRATION

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Table of content

1. Project details

Project title	EUDP 13-II, Combined Thermal Solar energy demonstration
Project identification (program abbrev. and file)	Journal no.: 64013-0520
Name of the programme which has funded the project	Energiteknologisk Udviklings- og Demonstrationsprogram (EUDP) - Solenergi
Project managing company/institution (name and address)	Aalborg CSP A/S
Project partners	DTU Byg
CVR (central business register)	21142042
Date for submission	16. February 2018

2. Short description of project objective and results

The project objective was to prove the possibility and the advantages of making a combination solar heating plant consisting of flat plate panels and parabolic trough collectors (CSP), in order to gain optimum harvesting of heat and to demonstrate the system configuration and control for reliable and relative high fixed temperatures.

Also a simulation program for the solar collector field was developed and validated based on measured data obtained from the plant.

All issues have shown positive output.

Projektet formål var at bevise muligheder og fordele ved et kombinations solvarmeanlæg bestående af plane paneler og parabolske trug som solfangere, for at optimere energihøsten og for at demonstrere sammensætning af et anlæg samt styre stabile og relative høje temperaturer.

Endvidere blev et simuleringsprogram for solfangeranlægget udviklet og vurderet med baggrund i de målte data.

Alle emner viste positivt resultat.

3. Executive summary

The project proves that technically a combination plant is “state-of-the-art” for harvesting energy and control of HTF temperatures for district heating system including possible heating storage (for some days) at a temperature close to 100°C. The constant and high resulting temperature is considerably more valuable than energy at a lower temperature as that need to be boosted (adding other type of energy) in order to be direct usable.

For a combination plant is the need of “night cooling” with related electricity consumption avoided/reduced, when continuously sunny days occur in summer period where heat demand is decreased and the harvesting energy cannot be used. The CSP part of the plant can be taken out of focus (energy harvesting turned off).

4. Project objectives

The project objective was to prove the possibility and the advantages of making a combination plant consisting of flat panels and parabolic trough (CSP), in order to gain optimum harvesting of heat (flat panels have highest efficiency at lower temperatures, while CSP using receiver pipes enclosed in vacuum glass tubes, which mean heat loss is small no matter temperatures) and to demonstrate the system configuration and control for reliable and relative high fixed temperatures.

The tilt of the flat panels, and the direction of the CSP – parabolic trough were chosen considering the land available for the plant, and also in relation to cover the highest percentage of the heat demand in spring and autumn, no matter total higher harvesting of heat could be achieved using different tilt/directions, but this would lead to more waste.

Also confirmation of DTU and Aalborg CSP simulation programs based on data obtained from the plant should be evaluated.

The control philosophy for smoothly running of the plant was uncertain as the combination was untried before. Revision during test trial was found beneficial and was carried out.

Afterwards the operation of the plant was as intended.

5. Project results and dissemination of results

Text in section 1.5 is from DTU “Applied Energy” (see appendix), from where further details including plant layout, var. figures, curves etc. can be seen.

The plant is a hybrid solar heating plant with a 5960 m^2 flat plate collector field and a 4039 m2 parabolic trough collector field in series situated in Taars, Denmark (latitude: 57.39 °N, longitude: 10.11 °E, altitute:48 m). The plant was put into operation in August 2015. The solar collector fluid of the parabolic trough collectors is water, while that of FPC is a glycol/water mixture (35%). The return water from the district heating network is heated up to 65–75°C by the heat exchanger connected to the flat plate collector field. Then the quired temperature by going through the parabolic trough collector field. The orientation of parabolic trough collectors was 13.4° towards west from south. The parabolic trough collectors track the sun from east to west when the collectors work during the whole day. There are six rows of parabolic trough collectors and the row distance is 12.6 m. The length of each row parabolic trough collector loop is about 125 m. The orientation of flat plate collectors is south and the collector row distance is 5.67 m. The tilt of the flat plate collectors is 50°. The parabolic trough collectors are delivered by Aalborg CSP A/S. The flat plate collectors consist of two types of the flat plate collectors, namely HTHEATboost 35/10 and HTHEATstore 35/10, manufactured by Arcon-Sunmark A/S. 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 consists of two natural gas boilers (9.1 MW in total). Two tanks with a total volume of 2430 m3 are used as heat storage.

5.1. Control strategy

The plant is oversized for the heat demand in the summer months. To avoid overheating issues in the storage for several days in the summer, collectors are sometimes put out of focus. Feed forward control is used in the summer. The parabolic trough collectors keep a constant outlet temperature by the flow control in the parabolic trough collector field.

5.2. Measurements

The system is well equipped with different accurate sensors and the monitoring data are automatically transferred to the computers. Global solar radiation on the horizontal surface and total radiation on the tilted flat plate collectors are measured with Kipp & Zonen SMP11. DNI is measured with a PMO6-CC pyrheliometer with the sun tracking platform Sunscanner SC1. The inlet and outlet temperatures of the collector fields are measured with SIEMENS TS500 temperature sensors, flow rates of both the FPC field and the PTC field are measured with Sitrans FM MAG3100P flow meters SIEMENS. Measured thermal performance is calculated based on the measured parameters.

5.3. Theory

A Trnsys model was set up to simulate the thermal performance of both the flat plate collector and the parabolic trough collector field. The TRNSYS model was based on the quasi dynamic method. TRNSYS type 1290 was used to simulate the thermal performance of the collector fields. Type 3b was used as the pump unit in the collector fields. Type 5b was the heat exchanger unit in the FPC field.

Type 30 simulated the shadows between the collector rows. Type 4 was used to simulate the tanks. The TRNSYS model was validated by the measurements and was accurate enough to predict the thermal performances of both solar collector fields. Detailed information and validation of the TRNSYS model and uncertainties of measurements are given in [40, 41], “Applied Energy”.

5.4. Thermal performance of FPC collectors

The thermal performance of the flat plate collector field was low during the winter because of the low solar radiation. The max monthly thermal performance of the flat plate collector field was higher than 70 kWh/m2 in May 2016. Both measured and modelled yearly total thermal performances of the flat plate collector field were 2670 MWh for the period Sep. 2015 - Aug. 2016.

5.5. Thermal performance of PTC collectors

The parabolic trough collector field did not produce much heat during the winter because of low DNI. But in the spring and summer, the parabolic trough collector field performed very well. The parabolic trough collector field should have worked best in the summer, when the solar radiation was high. However, the parabolic trough collector field was defocused sometimes on the sunniest days of summer (such as in May-August) because the flat plate collector field was oversized and the heat demand in the summer was low. The simulated thermal performance illustrates that the potential monthly thermal performance of the parabolic trough collector field is higher than 90 kWh/m2/month if the parabolic trough collector field could continue to operate without defocusing. The measured thermal performance of the parabolic trough collector field for the period September 2015 - August 2016 was 354 kWh/m2, while the modelled value with defocus was 359 kWh/m2.

The simulated thermal performance of the parabolic trough collector field without defocus was 490 kWh/m2 for the period Sep. 2015 - Aug. 2016. That is: a reduction of 136 kWh/m2 was calculated due to defocusing of the parabolic trough collector field.

5.6. Solar fraction

The Taars district heating network consists of approximate 850 buildings with about 1900 consumers. Measured heat load and total thermal performance of the solar collector fields per collector area from Aug. 2015 to Sep. 2016 are loged. The solar fraction, defined as the ratio between the solar heat and the heat demand, was very high in the summer when the heat load was low and the weather was sunny. 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 was close to 0, which is normal for the Nordic area.

The measured total energy output of the solar heating plant was 4100 MWh and total heat load was 18,460 MWh during Sep. 2015 to Aug. 2016. The solar fraction of the solar heating plant was 22.2% from Sep. 2015 to Aug. 2016. If the parabolic trough collectors were not defocused, the parabolic trough collectors could have a better thermal performance in the summer. Furthermore, only in June the simulated thermal performance is higher than the heat demand if the parabolic trough collector field was not defocused. By applying large heat storage tanks, the parabolic trough collector field could work normally without defocus in the summer, even in June. In this way solar fraction would have been close to 100% in the months from May to August. The yearly thermal performance of the combined solar collector field without defocusing of parabolic trough collectors in the summer can reach 4650 MWh and the solar fraction would increase from 22.2% to 25.2%. 550 MWh solar heat was lost because of defocusing of parabolic trough collectors in the sunny days in the summer.

The average daily efficiency of the flat plate collector field is about 0.48. Max daily solar heat production of flat plate collector field is below 5 kWh/m2.

The parabolic trough collectors were not put into defocus from Sep. 2015 to Apr. 2016. 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 would increase to about 0.70 and the parabolic trough collector field would produce more than 5 kWh/m2 per day in the sunny days.

Both beam radiation and diffuse radiation influence thermal performance of the flat plate collector field, while the thermal performance of the parabolic trough collector field is mainly influenced by the beam radiation. To compare performances of both collector fields in a fair way, global radiation was chosen as a benchmark. The thermal performance of the parabolic trough collector field without defocus was modelled to investigate the maximum potential of parabolic trough collector field. It is seen that the thermal performance of the parabolic trough collector field was zero mainly because of defocus while the weather was sunny. It is found that when the daily global radiation was lower than about 2 kWh/m^2, the parabolic trough collector field did not perform better than the flat plate collector field. Furthermore, the parabolic trough collector field produced more heat than the flat plate collector field, when daily global radiation was higher than about 2 kWh/m2.

5.7. Discussions

The Taars solar heating plant is the first large hybrid solar heating plant, which integrates both flat plate collectors and parabolic trough collectors to provide heat for a district heating network. The oversize of the flat plate collector field and low heat demand in the summer were the main reasons why the parabolic trough collectors were defocused in summer periods. The potential of the Taars plant in the DRY (Design Reference Year) is shown in this section.

The measured global radiation in the Taars solar heating plant from Sep. 2015 to Aug. 2016 is 980 kWh/m2, while that of DRY is 1030 kWh/m2. It is found that there was less sun shine from Sep. 2015 to Aug. 2016 compared to DRY.

The heat demand of the Taars solar heating plant in the DRY is a bit higher than measured values from Sep. 2015 - Aug. 2016.

Annual thermal performance are calculated for the Taars solar heating plant in the DRY, by use of 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 to be 55 °C and 80 °C respectively based on the measurements. The parabolic trough collector field is assumed to work without defocus. The potential thermal performance of the Taars solar heating plant in the DRY is 5180 MWh, while the heat demand in DRY is 21,590 MWh. Furthermore, the solar fraction is 24%. The thermal performance of flat plate collectors can be higher than 500 kWh/m2 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, so that the parabolic trough collector field is not put out of focus in the summer. An increase of the heat load of the district heating network in the future can increase the thermal performance of the plant. Furthermore, a larger heat storage could also be helpful to harvest the advantages of the parabolic trough collectors in the summer. The advantages of the hybrid solar heating plants are that the flat plate collector field produces about 60 kWh/m2 one year more than the normal solar heating plants with only flat plate collectors, and the defocus of the parabolic trough collectors increases the flexibility of the solar heating plants in the whole energy supply system. This study not only demonstrates the feasibility and potential of the hybrid solar heating plants at a high latitude with low solar radiation resource, but also introduces a novel design concept of higher efficient solar heating plants for high solar radiation areas.

5.8. Conclusions and future work

Both measured and simulated annual thermal performances of the Taars solar heating plant were analysed for the whole year from September 2015 to August 2016. The thermal performance of the Taars solar heating plant in DRY for the northern part of Jutland was also investigated. These findings can be used in the design of new large-scale solar district heating plants in the near future. The conclusions are as follows:

The solar fraction of the Taars solar heating plant was 22.2% during the period from Sep. 2015 to Aug. 2016. If the parabolic trough collector field had not been defocused, the total thermal performance would have increased from 4100 MWh to 4650 MWh, that is from 410 kWh/m2 to 465 kWh/m2 and the solar fraction would have reached 25.2%.

Potential annual thermal performance of the Taars solar heating plant in the DRY for northern Jutland could reach 5180 MWh (518 kWh/m2) and a solar fraction of 24% if defocusing of the parabolic trough collectors is avoided.

Further studies on the optimization of the thermal performance and control strategy of the hybrid solar district heating plant are required to formulate comprehensive design rules for such hybrid solar heating plants.

5.9. Presentations at conferences

1 Bengt Perers, Simon Furbo, Zhiyong Tian , Jörn Egelwisse, Federico Bava and Jianhua Fan, ”Tårs 10000 m² CSP + Flat Plate Solar Collector Plant - Cost-Performance Optimization of the Design”, International Conference on Solar Heating and Cooling for Buildings and Industry 2015,Istanbul, Turkey, December 2-4,2015.(Poster)

2 Zhiyong Tian, Bengt Perers, Simon Furbo and Jianhua Fan, ”Thermal performance of a novel combined solar heating plant with parabolic trough collectors and flat plate collectors”, 4th International Solar District Heating Conference, Billund, Denmark, September 21-22,2016.(Oral).

3 Zhiyong Tian, Bengt Perers, Simon Furbo and Jianhua Fan, ”Analysis of measured and modeled solar radiation at the Taars solar heating plant in Denmark”, 11th International Conference on Solar Energy for Buildings and Industry-Eurosun 2016, Mallorca, Spain, October 11-14,2016. (Poster).

4 Zhiyong Tian, Bengt Perers, Simon Furbo and Jianhua Fan,”Thermal Performance of Taars combined plant”, 2nd Expert Meeting of IEA- SHC Task 55, Aalborg, Denmark, March 14-16, 2017. (Oral).

5 Zhiyong Tian, Bengt Perers, Simon Furbo and Jianhua Fan, ”Thermal-economic optimization of a hybrid solar district heating plant with flat plate collectors and parabolic trough collectors in series”, 3rd Expert Meeting of IEA- SHC Task 55, Abu Dhabi, United Arab Emirates (UAE), October 27 – 28, 2017. (Oral).

6 Zhiyong Tian, Bengt Perers, Simon Furbo and Jianhua Fan, ”Performance and optimization of a novel combined solar heating plant with flat plate collectors and parabolic trough collectors in series for district heating”, The joint conference Solar Word Congress 2017 & International Conference on Solar Heating and Cooling for Buildings and Industry 2017, Abu Dhabi, United Arab Emirates (UAE), October 29 to November 02, 2017. (Oral).

7 Fabienne Sallaberry, Zhiyong Tian, Odei Goñi Jauregi, Simon Furbo, Bengt Perers, Andreas Zourellis and Jan Holst Rothmann, " Evaluation of the Tracking Accuracy of Parabolic-Trough Collectors in a Solar Heating Plant in Denmark", SolarPACES 2017 conference, Santiago, Chile, September 26-29, 2017. (Poster).

8 Zhiyong Tian, Bengt Perers, Simon Furbo and Jianhua Fan," Long-term measured and simulated thermal Performance of a combined solar district heating plant with flat plate collectors and parabolic trough collectors in series", 5th International Solar District Heating Conference, Graz, Austria, April 11-12, 2017. (Oral, Accepted).

5.10. Publications

1 Jörn Egelwisse," Solar heating plants based on CSP and FP collectors", DTU Master Thesis, July 2015.

2 Miquel Cantavella Tomas," Solar Heating Plants combining FP collectors and PTC collectors", DTU Master Thesis, July 2016.

3 Bengt Perers, Simon Furbo, Zhiyong Tian , Jörn Egelwisse, Federico Bava and Jianhua Fan, "Tårs 10000 m² CSP + Flat Plate Solar Collector Plant - Cost-Performance Optimization of the Design", Energy Procedia, 2016, 91: 312-316.

4 Zhiyong Tian, Bengt Perers, Simon Furbo and Jianhua Fan, "Analysis of measured and modeled solar radiation at the Taars solar heating plant in Denmark", Proceedings of the ISES EuroSun 2016 conference.

5 Fabienne Sallaberry, Zhiyong Tian, Odei Goñi Jauregi, Simon Furbo, Bengt Perers, Andreas Zourellis and Jan Holst Rothmann, " Evaluation of the Tracking Accuracy of Parabolic Trough Collectors in a Solar Heating Plant in Denmark" , Proceedings of SolarPACES 2017 conference.

6 Zhiyong Tian, Bengt Perers, Simon Furbo and Jianhua Fan," Analysis and validation of a quasi-dynamic model for a solar collector field with flat plate collectors and parabolic trough collectors in series for district heating ", Energy, vol. 142, pp. 130–138, 2018.

7 Zhiyong Tian, Bengt Perers, Simon Furbo and Jianhua Fan," Annual measured and simulated thermal performance analysis of a hybrid solar district heating plant with flat plate collectors and parabolic trough collectors in series ", Applied energy, vol. 205, pp. 417–427, 2017.

8 Zhiyong Tian, Bengt Perers, Simon Furbo and Jianhua Fan," Thermal-economic optimization of a hybrid solar district heating plant with flat plate collectors and parabolic trough collectors in series", (Energy Conversion and Management, under review).

5.11. Specialized events / publications:

Solarfield Show Autumn 2015. District business partners in Denmark were invited. DTU, Taars District Heating, JPH Consulting Eng., Arcon and Aalborg CSP were speakers.

21 sep. 2016, Lecture in operation experience for the Solar Receiver Group, Danish Districh Heating Society.

SDH (solar district heating) Exebition Sep. 2016, i Billund (DK) and April 2017 i Graz (Austria)

Maskinmesteren (Society of Mechanical Engineers) July 2015. Article about Combination plant in Taars.

Exebition Dansk Fjernvarmes landsmøde (Danish District Heatin Society - yearly meeting) Okt. 2015, 2016 and 2017.

Plus several arrangements as speakers in Denmark and around the world, where Combination plants has been part of Aalborg CSP general marketing.

Taars District Heating, DTU and Aalborg CSP have on site made several presentations for groups from Denmark along with many delegations from other counties like: Sweden Norway, Germany, Austria, Spain, France, Italy, China, Japan, USA, Kuwait, Brazil, South Africa and Australia.

6. Utilization of project results

Based on the plan a cost out process for CSP components and system has been carried out and led to future more cost effective plants.

The result of the CSP part of the plant led to evaluation and a test plant for establish of high temperature CSP plant in Denmark and later establishment of a 16 MWp plan with thermal oil as HTF (312oC) deliver energy to district heating / a ORC plant for Brønderslev Varme (Waste heat is transferred to district heating system). Delivery of energy to the district heating system has been in operation in 2017 and operates and perform as planned. This project is also supported by EUDP.

Aalborg Business plan for the area:

Further cost out for components and plantsystem by optimizing design, increases the use of standard products and cooperation with suppliers.

Marketing activities in countries where: Energy prices are high, local laws or subsidies are in favour of Thermal Solar Energy.

At the moment this is actual Germany, Australia, China and Middle East. Aalborg CSP sales activities are high in the mentioned countries.

No patents have been actual in relation to the Combination plants.

The project has proven that increased use of reliable solar energy is possible.

Zhiyong Tian at DTU has carried out his PhD study with focus on analyses of measurements from the Taars solar heating plants. It is expected that he will finish his PhD study in the autumn 2018.

DTU students following DTU courses on solar heating have learned about the project results as part of the course.

7. Project conclusion and perspective

The intension of the project has been fulfilled and can led to optimum plant configuration of future plants for district heating systems and general heat energy for Industrial use.

The measurements showed that the solar radiation inclusive the DNI (direct normal irradiance) radiation is high enough to make tracking concentrating solar collectors interesting in Denmark.

The project also showed that water with advantage can be used as solar collector fluid in the CSP solar collectors.

Also “an add on“ CSP solar collector field to existing flat plate solar collector plants is a possibility to improve the energy harvesting efficiency and to obtain higher and constant temperatures from solar collector fields.

As always perspectives for renewable energy is much related to Political decisions within the area. The instability/uncertainty concerning the requirement to energy saving in Denmark during the last couple of years has definitely been a setback for the speed of establishing high performing solar heating plants in Denmark.

Aalborg CSP is marketing all our set ups for thermal solar receivers in many countries. But as the cost of fossil fuel the latest year has decreased, direct competition has been difficult.

However some countries subsidise Thermal Solar Heat, or local transport cost for fossil fuel is high, making Thermal Solar Heat attractive

A huge market for Thermal Solar Heat in China is in progress these years (Political supported). Big problems with air pollution require alternative solutions to fossil fuel and brings Thermal Solar Heat in favour.

Right now Aalborg CSP is executing the first order in China as sub supplier for a high temperature steam production plant for production of electricity (50 MWe - 24/7). HTF is Molten Salt.

Combinations plants like the Taars plant is very suitable to various Industries like food industry and others requiring hot water.

Aalborg are experience growing interest for this type of plants and are expecting additional orders very soon.

8. Annex

8.1. Validation Energy

Analysis and validation of a quasi-dynamic model for a solar collector field with flat plate collectors and parabolic trough collectors in series for district heating

Zhiyong Tian*, Bengt Perers, Simon Furbo, Jianhua Fan

8.2. Applied Energy

Annual measured and simulated thermal performance analysis of a hybrid MARK solar district heating plant with flat plate collectors and parabolic trough collectors in series.

Zhiyong Tian , Bengt Perers, Simon Furbo, Jianhua Fan

9. Links

1.Bengt Perers, Simon Furbo, Zhiyong Tian , Jörn Egelwisse, Federico Bava and Jianhua Fan, " Tårs 10000 m² CSP + Flat Plate Solar Collector Plant - Cost-Performance Optimization of the Design", Energy Procedia, 2016, 91: 312-316. https://www.sciencedirect.com/science/article/pii/S1876610216303228

2. Zhiyong Tian, Bengt Perers, Simon Furbo and Jianhua Fan, "Analysis of measured and modeled solar radiation at the Taars solar heating plant in Denmark", Proceedings of the ISES EuroSun 2016 conference. http://proceedings.ises.org/?conference=eurosun2016

3. Fabienne Sallaberry, Zhiyong Tian, Odei Goñi Jauregi, Simon Furbo, Bengt Perers, Andreas Zourellis and Jan Holst Rothmann, " Evaluation of the Tracking Accuracy of Parabolic-Trough Collectors in a Solar Heating Plant in Denmark" , Proceedings of SolarPACES 2017 conference. http://www.solarpaces-conference.org/proceedings.html

(Not yet available 14.02.2018)

4. Zhiyong Tian, Bengt Perers, Simon Furbo and Jianhua Fan," Analysis and validation of a quasi-dynamic model for a solar collector field with flat plate collectors and parabolic trough collectors in series for district heating ", Energy, vol. 142, pp. 130–138, 2018. https://www.sciencedirect.com/science/article/pii/S0360544217316572

5. Zhiyong Tian, Bengt Perers, Simon Furbo and Jianhua Fan," Annual measured and simulated thermal performance analysis of a hybrid solar district heating plant with flat plate collectors and parabolic trough collectors in series ", Applied energy, vol. 205, pp. 417–427, 2017. https://www.sciencedirect.com/science/article/pii/S030626191731005X

6. Zhiyong Tian, Bengt Perers, Simon Furbo and Jianhua Fan," Thermal-economic optimization of a hybrid solar district heating plant with flat plate collectors and parabolic trough collectors in series", (Energy Conversion and Management, under review). https://www.sciencedirect.com/journal/energy-conversion-and-management

(Not yet available 14.02.2018)

9.1. Aalborg CSP documents

- **1_Aalborg CSP_SDH sep. 2016**
- **Taars VV og ACSP 20092016**
- **Aalborg CSP - Presentation for Gleisdorf 2016**
- **Aalborg CSP presentation for Berlin 10-11-2016**

9.2. Other publications

- **2014.10.01 Building-supply.dk:** Taars får avanceret solvarmeanlæg
- **2014.10.01 Energy-supply.dk:** Taars får avanceret solvarmeanlæg
- **2014.10.01 Fif-marketing.dk:** Tårs får Danmarks mest avancerede solvarmeanlæg og lavere priser
- **2014.10.01 Fjernvarmeindustrien.dk:** Tårs får Danmarks mest avancerede solvarmeanlæg og lavere priser
- **2014.10.01: Fleksenergi.dk:** Tårs får Danmarks mest avancerede solvarmeanlæg

- **2014.10.02: NORDJYSKE:** Billigere varme på vej i Tårs
- **2014.10.06: Ing.dk:** Kombineret solvarmeanlæg skærer en femtedel af varmeregningen
- **2014.10.06: Organictoday.dk:** Tårs får avanceret solvarmeanlæg
- **2014.10.07: Computerdk.com:** Kombineret solvarmeanlæg skærer en femtedel af varmeregningen
- **2014.10.07: Danskfjernvarme.dk:** Taars får avanceret solvarmeanlæg
- **2014.10.07: Sol-og-vind.blogspot.dk:** Kombineret solvarmeanlæg skærer en femtedel af varmeregningen
- **2014.10.07: Uge Posten:** Tårs får Danmarks mest avancerede solvarmeanlæg og lavere priser
- **2014.10.17: Tekniskenyheter.no:** Dansk fjernvarmeselskap monterer avansert solvarmeanlegg
- **2015.01.08: Danskfjernvarme.dk:** Tårs bygger avanceret solvarmeanlæg
- **2015.01.08: Energy-supply.dk:** Første spadestik til avanceret solvarmeanlæg i Tårs
- **2015.01.08: NORDJYSKE:** Varmeværk har set lyset
- **2015.01.13: Uge Posten:** Byggeriet af Damarks mest avancerede solvarmeanlæg skudt i gang
- **2015.02.06: Cospp.com:** Solar-district heating plant opens in Denmark
- **2015.05.20: Building-supply:** Bravida laver rørarbejde på avanceret solvarmeanlæg
- **2015.05.28: Energy-supply.dk:** Aalborg CSP arbejder på højtryk i Tårs
- **2015.05.28: Nordjyskerhverv.dk:** Opsætning af innovativt solvarmeanlæg skrider frem
- **2015.06.10: Vendelbo Posten:** Sparer penge og CO2
- **2015.07: MASKINMESEREN:** Tårs får verdens første hybrid-solvarmeanlæg
- **2015.08.11: Uge Posten:** Så er Tårs Varmeværk ved at være klar
- **2015.08.17: Vemk.dk:** Spændende solvarmeanlæg indvies i Tårs
- **2015.08.18: Energy-supply.dk:** Nu indvier Tårs sit hybrid-solvarmeanlæg
- **2015.08.20: DanskFjernvarme.dk:** To topmoderne solvarmeanlæg indvies fredag
- **2015.08.21: Fjernvarme.no:** TO TOPPMODERNE SOLVARMEANLEGG INNVIES I DANMARK I DAG
- **2015.08.21: NORDJYSKE Vendsyssel:** Tårs følger solen hele dagen
- **2015.08.24: NORDJYSKE:** Tårs følger solen hele dagen
- **2015.08.24: NORDJYSKE (Thy-Hannæs/Thisted Dagblad):** Tårs følger solen hele dagen
- **2015.08.25: Uge Posten:** Opening in Tårs

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Analysis and validation of a quasi-dynamic model for a solar collector field with flat plate collectors and parabolic trough collectors in series for district heating

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ABSTRACT

A quasi-dynamic TRNSYS simulation model for a solar collector field with flat plate collectors and parabolic trough collectors in series was described and validated. A simplified method was implemented in TRNSYS in order to carry out long-term energy production analyses of the whole solar heating plant. The advantages of the model include faster computation with fewer resources, flexibility of different collector types in solar heating plant configuration and satisfactory accuracy in both dynamic and long-term analyses. In situ measurements were taken from a pilot solar heating plant with 5960 m^2 flat plate collectors and 4039 m^2 parabolic trough collectors in series in Taars, Denmark from Sep.2015 to Aug.2016. The simulated thermal performances of both the parabolic trough collector field and the flat plate collector field have a good agreement with the measured performances. The thermal performance of the hybrid solar district heating plant is also presented. The measured and simulated results show that the integration of parabolic trough collectors in solar district heating plants can guarantee that the system produces hot water with relatively constant outlet temperature. The daily energy output of the parabolic trough collector field can be more than 5 kWh/m^2, while the daily energy output of the flat plate collector field is less than 5 kWh/m^2 under Danish climate conditions. The simplified and validated TRNSYS model can be a useful tool to simulate and optimize thermal performance of solar heating plants with both flat plate and parabolic trough collectors.

1. Introduction

The number of large scale solar heating plants for district heating increased very fast in Europe during the last couple of years, especially in Denmark [1], [2]. More than 70% of large scale solar heating plants for district heating around the world are constructed in Denmark so far [3]. Most of the collectors in the existing plants are flat plate collectors. Due to collector heat losses, the efficiency of flat plate solar collectors is significantly lower at operation temperatures of 85°C–95 °C compared to the efficiency at temperatures of 40°C–60 °C. Parabolic trough collectors typically have a low heat loss coefficient and are therefore less affected by the operation temperature level of the collectors. Parabolic trough collector is the most used technology currently among solar concentrating power collector technologies [4]. Parabolic trough collectors are mainly used for electricity production at temperatures of 200–400 °C so far [5], [6]. Industry process temperatures found in industrial processes are manifold, ranging from low ($T < 100$ °C), medium (100 °C $< T <$ 250 °C) to high ($T >$ 250 °C) operating temperatures [7]. Parabolic trough collector is also suitable for these temperature ranges [7]. More and more parabolic trough collectors have been employed in the industry process heat production in the recent years [6,8–11]. Most small scale parabolic trough heating plants are applied for industry processes using glycol/water as heat transfer fluid in recent years [7]. Parabolic trough collector also can be used with advantage operated at temperature range 85–95 °C in solar district heating plants. The feasibility of parabolic trough collectors in large scale solar heating plants for district heating has been validated in the pilot Thisted plant in Denmark in 2013 [12]. A pilot solar collector system with flat plate collector and parabolic trough collector fields for district heating networks in series can harvest the advantages of the flat plate collectors at low temperature levels and the parabolic trough collectors at high temperature levels. A combined solar heating

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plant with 5960 m^2 flat plate collectors and 4039 m^2 parabolic trough collectors in series for a district heating network was constructed in Taars, Denmark in 2015 [13–15]. A general solar collector field model for both flat plate and parabolic trough collectors would be essential for the evaluation of the combined system.

1.1. Single solar collector model

Many test methods for single solar collectors have been developed [16–28]. The test methods can be divided into the steady–state method, quasi-dynamic method and dynamic method. The quasi-dynamic method is used in the model in this paper. The quasi-dynamic test (QDT) method described in most of the common standards such as EN 12975-2 [16], ISO 9806:2013 [17] and ASHRAE 93 [18] is an efficient model applicable to both concentrating and non-concentrating collector designs, which is firstly developed by Bengt Perers in 1990s [19–21]. Fischer, S., et al. [22] also showed that the QDT method can be used to predict the performance of single parabolic trough collector. Some improved dynamic methods were developed by Deng J. and Kong W. et al. [23–28].

1.2. Solar collector field model

B. Perers [29] had introduced several solar collector models to MINSUN simulation program, which can simulate the thermal performance of different collector fields in 1990. The results had shown that parabolic trough collectors with good optical performance had thermal performance comparable to flat plate or evacuated tube collectors at high latitudes. B. Perers. et al. also investigated the application of parabolic trough collectors in a small scale pilot plant in Thisted, Denmark [12]. This was the earliest research about the practical application of parabolic trough collectors at high latitudes. Guadalfajara M. et al. developed a simple method to simulate the performance of central solar heating plants with seasonal storage [30]. The simple method could give an overview of the thermal performance of solar heating plant which can be helpful for pre-design of the large solar heating plants. The disadvantage of the simple method is that the control strategy is not taken into consideration. Marco. et al. [31] investigated a 1070 m^2 flat plate collector field for the industry process heat, which focused on thermal performance of the solar collector field by comparing the measured field efficiency with the nominal collector efficiency. Hassine I B. et al. [32] also investigated two about 1000 m^2 solar heating plants. Control strategy in the primary and second loop was optimized to have a constant outlet temperature. Frank E. et al. [33] evaluated the operation performance of two around 1000 m^2 parabolic trough collector fields in Switzerland. A quasi-dynamic simulation model for direct steam generation in parabolic trough collector loops using TRNSYS was introduced [34].

1.3. Scope

The previous studies [16–28] mainly focus on simulation or test on a single collector in the laboratory, direct steam generation [34] and thermal performance of relatively small scale solar collector fields (1000 m^2) [30–34]. A collector array field may consist of collectors connected in series and in parallel. Thermal performance of the total collector array should be determined by both the number of modules in series and the characteristics of each module. Most studies were on the flat plate collector. Currently, the performances of large scale solar collector fields under real operation conditions have not yet been widely documented and standardized. Evaluating thermal performance of large-scale solar collector fields with good accuracy is still an important topic in the large scale solar heating industry. Technical parameters from a standard efficiency test of single collector can be used to simulate the thermal performance of total solar collector arrays. Compared to solar collector models, solar collector field model also should consider row shading, axis orientation, heat losses in pipes. etc. A simple and practical method to predict thermal performance of different solar collector fields for general use can increase confidence of large solar heating plants technology in the market. The quasi-dynamic collector model is applied to simulate thermal performance of a nearly 10000 m^2 hybrid solar collector field in Denmark. The quasi-dynamic collector field model was validated by the almost annual in-situ measurements of both flat plate and parabolic trough collector field. The validated quasi-dynamic collector field model could be a very useful tool to optimize the combined solar heating plant to determine the optimal design parameters. The novelty of this study is summarized as follows: 1, The objective is a novel large-scale solar district heating plant with flat plate collectors and parabolic trough collector in series. 2, Validation of the quasi-dynamic model for both large-scale flat plate collector and parabolic trough collector fields was shown; 3, Both simulated and measured dynamic performances of the novel hybrid solar collector field were presented; 4, The advantages of the hybrid solar heating plant were shown, which can introduce a new design concept of large-scale solar district heating plants to other places.

2. Taars solar heating plant

The Taars solar heating plant is located in Taars, 30 km north of Aalborg, Denmark. The solar heating plant is the first demonstration project with parabolic trough collectors for district heating in Europe. The plant was put into operation in August.2015, as shown in Fig. 1. Fig. 2 illustrates the layout of the solar collector field. The PTC collector field consists of six rows of PTC collectors with 4039 m^2 aperture area and the orientation of the PTC collectors is 13.4° towards west from south. The flat plate collector field in the right of Fig. 1 consists of 5960 m^2 aperture area and the orientation is south. The tilt of the flat plate collector field is 50°. The row distances for the parabolic trough collector field and the flat plate collector field are 12.6 m and 5.67 m respectively. The solar collector fluid of the parabolic trough collector field and the flat plate collector field is water and mixture of glycol/water (35%) respectively. The FPC field preheats the return water from the district heating networks to about 75 °C. Then the preheated water from the FPC field is heated by the PTC field to 95 °C. The system was measured over a year (Sep.2015–Aug.2016). Two heat storage tanks (2430 m^3 in total) were used for the heat storage of several summer days. Tables 1 and 2 show the geometrical parameters of FPC and PTC separately [13] [35].

3. TRNSYS model based on quasi-dynamic method

A flat plate collector field and a parabolic trough collector field model were established in TRNSYS [36]. In the flat plate collector field, heat exchanger unit, shadows and pipes are included. The collector arrays consist of collectors connected in series and in parallel. There are two kinds of flat plate collector with/without FEP foil between absorber and cover glass used in the flat plate collector field. The flat plate collector field has 39 rows in parallel. 6 FPC collectors without foil in series and other 6 FPC collectors with foil in series in average were used in most rows. In the parabolic trough collector loop, shadows, supply pipes and return pipes of the solar collector field are taken into consideration. The thermal performance of the total collector array is determined by the number of modules in series and the characteristics of each module. The

Fig. 1. Solar collector fields in the Taars solar heating plant [13].

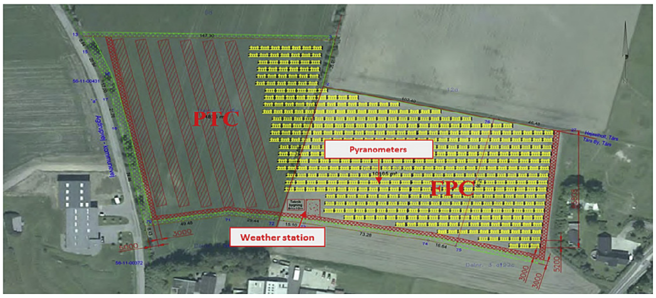

Fig. 2. Layout of the parabolic trough collector and flat plate collector fields [15].

Table 1
Geometrical parameters of the FPC in the Taars plant.

Geometrical parameters for the FPC		
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 Absorption Emission	Cu pipe/Al plate 0.95 0.05
Insulation	Backside Side	75 mm mineral wool 30 mm mineral wool
Cover(s)	Antireflex glass (AR:3.2 mm)-with/without FEP foil	

Table 2
Geometrical parameters of the PTC in the Taars plant.

Geometrical parameters for the PTC	
Absorber tube outer diameter (m)	0.070
Absorber tube inner diameter (m)	0.066
Glass envelope outer diameter (m)	0.125
Glass envelope inner diameter (m)	0.119
Parabola width (m)	5.77
Numbers of modules per row	10
Mirror length in each module (m)	12
Geometric concentration ratio	26.2

numbers of modules per row of both FPC and PTC are 12 and 10, respectively. The discretization in the modelling is done inside the collector and pipe models used. Each collector array is discretized with nodes. The solar collector field model can simulate an array of identical solar collectors hooked up in series. The number of nodes is used to specify how many collectors are hooked up in a series arrangement (outlet of first collector = inlet of second collector, etc.) for each parallel flow loop [37].

The type 1290 is used to simulate thermal performance of both parabolic trough collector and flat plate collector field. The Type 1290 is based on EN12975-2 Dynamic Efficiency Approach (ASHRAE IAMs) [37].

The solar collector model equation is given as follows,

$$\frac{Q}{A} = \eta_0 K_{\theta b}(\theta) G_b + \eta_0 K_{\theta d}(\theta) G_d - c_1 (T_m - T_a) - c_2 (T_m - T_a)^2 - c_3 \frac{dT_m}{dt} \tag{1}$$

$$K_{\theta b}(\theta) = 1 - b_0 \left(\frac{1}{COS\theta} - 1 \right) - b_1 \left(\frac{1}{COS\theta} - 1 \right)^2, \theta \leq 60^\circ \tag{2}$$

When $\theta > 60^\circ$, the IAM is linearized from the value at 60° to a value of zero at 90°.

Total radiation G is divided into the beam G_b and diffuse G_d parts in this collector model. Incident angle modifiers are used for beam radiation and diffuse radiation. $K_{\theta b}(\theta)$ is a function of the angle of incidence of the direct radiation and the constant $K_{\theta d}$ for the diffuse radiation. Thus the collector model can be used to predict the thermal performance of both the parabolic trough collectors and the flat plate collectors.

Type 30 was employed to simulate shadows from the solar collectors for both collector subfields. This component determines incident radiation upon an array of collectors with shadows from the row in front of the row in question. There are two possible modes. Model 1 considers shadows from fixed flat plate collectors with a tilt. Total, beam, and diffuse radiation are output. Model 2 is for single axis tracking parabolic trough collectors that utilize beam radiation only. Type 5 was used to simulate the heat exchanger connected to the FPC field. Type 31 was used to simulate the pipes. Measured DNI and global horizontal solar radiation and inlet temperature etc. are inputs used for model validation. Measurements and uncertainties can be found in section 4. Mathematical descriptions on the components can be found in Ref. [37].

(1) Flat plate collectors

The flat plate collectors, HTHEATboost 35/10 without FEP foil and HTHEATstore 35/10 with FEP foil, are produced by Arcon-Sunmark A/S [35]. Standard parameters for the collectors based on gross areas can be found in Table 3 [38]. Total radiation on the flat plate collector is the main input for the flat plate collector field model. Two separate 1290 type components in series are used to simulate the thermal performance of the flat plate collector without and with FEP foil in series.

Table 3
Efficiency parameters of flat plate collectors.

η_0	b_0	b_1	$K_{\theta d}$	c_1, [W/(m^2·K)]	c_2, [W/(m^2·K^2)]	c_3, [kJ/(m^2·K)]	
0.779	0.1	0	0.98	2.410	0.015	6.798	HEATboost 35/10
0.745	0.1	0	0.93	2.067	0.009	7.313	HEATstore 35/10

Table 4
Efficiency parameters of parabolic trough collectors.

η_0	b_0	b_1	$K_{\theta d}$	c_1, [W/(m^2·K)]	c_2, [W/(m^2·K^2)]	c_3, [kJ/(m^2·K)]
0.75	0.27	0	0.038	0.04	0	4

(2) Parabolic trough collectors

Peak collector efficiency η_0 and the heat loss coefficients c_1 and c_2 for the parabolic trough collectors based on aperture area were assumed to be equal to the values of the pilot plant in Thisted, Denmark [14], as shown in Table 4. Beam radiation on the PTC plane is the main input for the parabolic trough collector field model.

4. Measurements and uncertainties

4.1. Measurements

The solar heating plant system is well equipped with different accurate sensors. Total solar radiation on the collector's surface and global radiation, ambient temperature and wind speed data were measured. It also had temperature sensor inputs onto which SIEMENS TS500 thermometer with drilled thermoswell temperature sensors [39] were connected to measure inlet and outlet temperatures of both flat plate collector field and parabolic trough collector field. The volume flow rate of the solar fluid was measured using Sitrans FM MAG3100 P flow meters from SIEMENS. The TS500 temperature sensors (PT100) have an uncertainty of ±0.30 K + 0.0050*|T [K]| [39]. Sitrans FM MAG3100 P flow meters had an uncertainty of 1% (maximum).

Two pyranometers (Kipp&Zonen SMP11) are used to measure the global radiation on the horizontal surface and total radiation on the tilted flat plate collector [40]. DNI is measured by the PMO6-CC pyrheliometer [41] with the sun tracking platform Sunscanner SC1 [42], which has high accuracy and automatically cleaning function. The solar radiation sensors had an good accuracy. All the raw measurement data was logged at 2 min interval.

4.2. Uncertainties

Measured power output is calculated by eq. (3). Separate uncertainty of each parameter causes uncertainty of the measured power. As shown in section 4.1, uncertainty of the flow rate sensor is 1%. Uncertainties of density and specific heat of water or glycol/water mixture are estimated as 0.5%. By equation (4), typical uncertainties of the measured power output of the FPC field and the PTC field can be calculated. Details can be found in Figs. 5, 7, 10 and 12 in section 5.

$$Q = V \times \rho \times C_P \times (T_{out} - T_{in}) \tag{3}$$

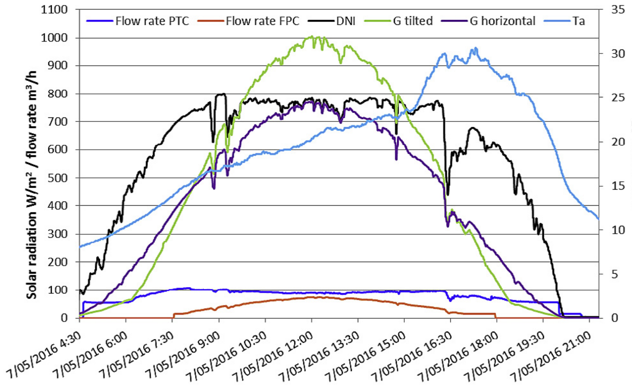

Fig. 3. Global solar radiation, total tilted radiation, DNI, ambient temperature and flow rates on the sunny day (May 7, 2016).

5. Validation

Section 5.1 shows dynamic comparisons of measured and modelled performances of the flat plate collector field and the parabolic trough collector field on a cloudy and a sunny day. Section 5.2 illustrates daily and monthly comparisons of measured and modelled performances based on the quasi-dynamic model. The time step of all the calculations is 1 min. All the performances per m^2 are based on aperture area. Inlet temperature and volume flow rate of both the FPC and the PTC field in simulation are taken from the measurements from the Taars plant.

5.1. Dynamic performance in typical days

One typical sunny day (May 7, 2016) and one typical cloudy day (August 14, 2016) were selected to analyze the thermal performance and validate the developed model. Figs. 3 and 8 show that weather conditions, such as ambient temperature, DNI, global radiation and total radiation on the south-oriented tilted collector plate (50°) and flow rates on both days, respectively. The measured and simulated outlet temperature and power output of the FPC field shown in this section are the values of the secondary water loop of the FPC field including the heat exchanger.

5.1.1. Sunny day (may 7 of 2016)

As shown in Fig. 3, May 7 in 2016 was a typical sunny day. The maximum of global radiation on the tilted surface was about 1000 W/m^2 and the max DNI was about 800 W/m^2. The ambient temperature peaks at around 30 °C. Measured volume flow rates of both the FPC and the PTC fields are shown in Fig. 3. Since the PTC field tracked the sun from sunrise to sunset during the daytime, the operation period of the PTC field is longer than that of the FPC field.

$$S(Q) = \sqrt{\left(\frac{\partial Q}{\partial V}\bullet S_v\right)^2 + \left(\frac{\partial Q}{\partial \rho}\bullet S_\rho\right)^2 + \left(\frac{\partial Q}{\partial C_p}\bullet S_{C_p}\right)^2 + \left(\frac{\partial Q}{\partial T_{out}}\bullet S_{t_{out}}\right)^2 + \left(\frac{\partial Q}{\partial T_{in}}\bullet S_{t_{in}}\right)^2} \tag{4}$$

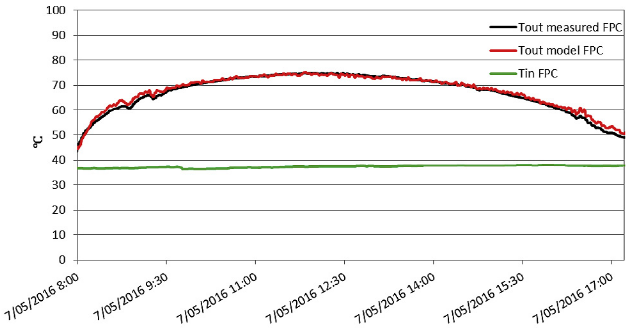

Fig. 4. Inlet temperature, measured and modelled outlet temperature of the FPC field on the sunny day.

On the sunny day, the flow rate of PTC field was almost constant. The volume flow rate of the FPC field varied with the solar radiation and was largest at noon.

1) FPC field on the sunny day

Fig. 4 shows measured inlet and outlet temperature and simulated outlet temperature of the FPC field in May 7, 2016. Fig. 5 shows measured and modelled power output of the FPC field in May 7, 2016. The maximum power output of the flat plate collector field is close to 600 W/m^2 at noon in May 7, 2016. The modelled and measured outlet temperature, the modelled and measured power output have good agreements in Figs. 4 and 5.

2) PTC field on the sunny day

Fig. 6 shows measured inlet and outlet temperature and simulated outlet temperature of the PTC field in May 7, 2016. Fig. 7 illustrates the comparison between measured and modelled power output of the parabolic trough collector field in May 7, 2016. The modelled results have similar fluctuations as the measured results. As shown in Fig. 7, the measured and modelled thermal performances of the PTC field had a good agreement. Compared to the thermal performance of the FPC field at noon, the thermal performance of the PTC field was a bit higher before and after noon. That was because of tracking the sun. It also can be seen in Fig. 7 that there was an increase of power output after sunset. That was due to discharge of the heat stored in the receiver. The low heat losses of the parabolic trough collectors means that this can be done even after sunset. It is also found that the outlet temperature of the PTC field is relatively constant, which is very important for the hydraulic balance of the district heating network.

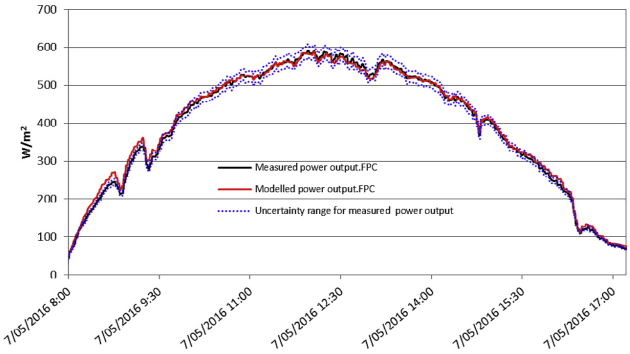

Fig. 5. Measured and modelled power output of the FPC field on the sunny day.

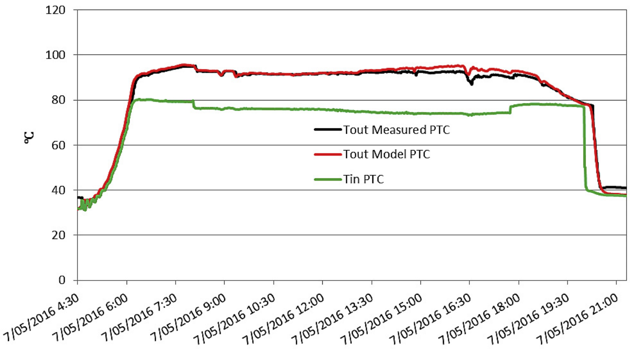

Fig. 6. Inlet temperature, measured and modelled outlet temperature of the PTC field on the sunny day.

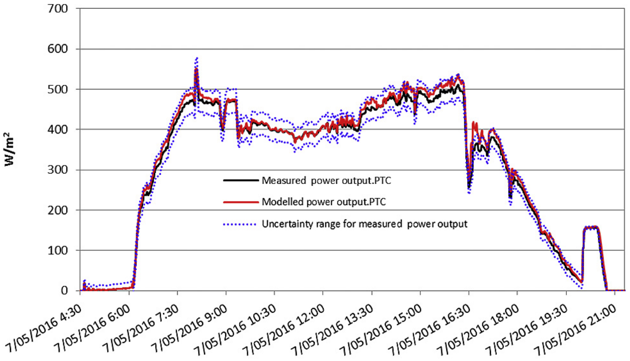

Fig. 7. Measured and modelled power output of the PTC field on the sunny day.

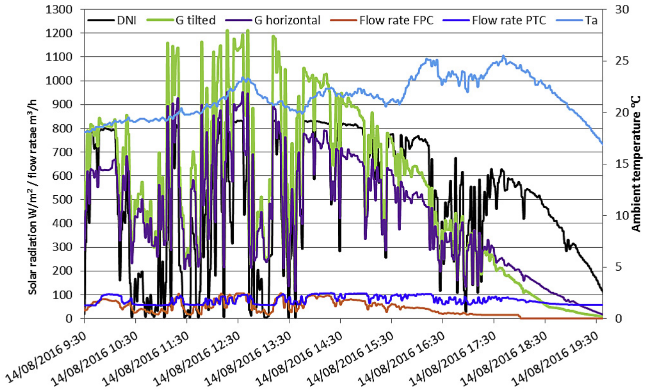

Fig. 8. Global solar radiation, total tilted radiation, DNI, ambient temperature and flow rates on the cloudy day.

5.1.2. Cloudy day (August 14 of 2016)

August 14 in 2016 was a cloudy day. As shown in Fig. 8, the maximum of DNI and global solar radiation was larger than 800 W/m^2. Fig. 8 shows the fluctuation of weather from 9:30 a.m. to 19:30 p.m. in August 14, 2016. Both the DNI and the global solar radiation fluctuated dramatically during the daytime. The total solar radiation on the tilted flat plate collector was larger than that on the horizontal surface. The largest total radiation on the tilted solar collector in short periods exceeded 1200 W/m^2. On the cloudy day, the flow rates of both collector fields fluctuated along with the solar radiation.

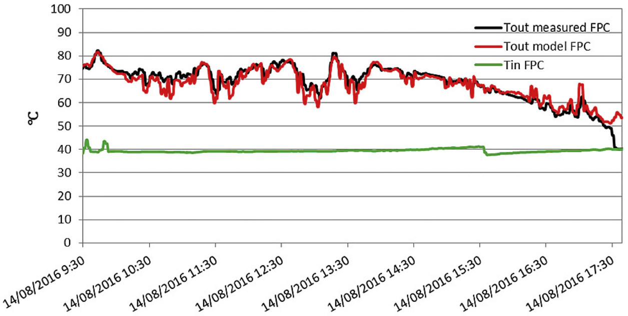

Fig. 9. Inlet temperature, measured and modelled outlet temperature of the FPC field on the cloudy day.

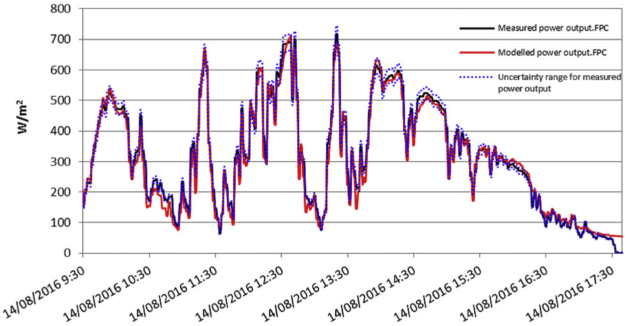

Fig. 10. Measured and modelled power output of the FPC field on the cloudy day.

1) FPC field on the cloudy day

Fig. 9 shows measured inlet and outlet temperature and simulated outlet temperature of the FPC field in August 14, 2016. Fig. 10 shows measured and modelled power output of the FPC field in August 14, 2016. The modelled and measured power outputs had very similar fluctuation trends.

2) PTC field on the cloudy day

Fig. 11 shows measured inlet and outlet temperature and simulated outlet temperature of the PTC field in August 14, 2016. Fig. 12 shows the measured and modelled power output of the PTC field on a cloudy day (August 14, 2016). The maximum of power output in August 14, 2016 was higher than 500 W/m^2. The modelled power output has almost the same fluctuating change as the measured power output.

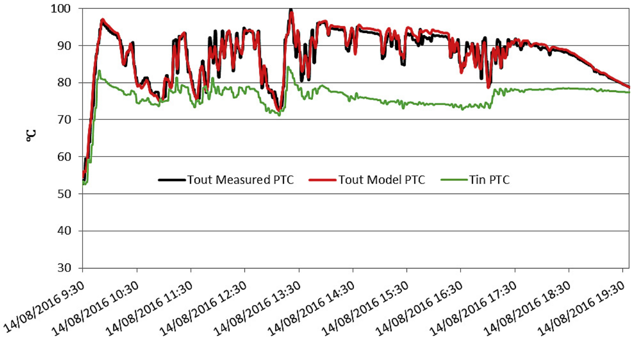

Fig. 11. Inlet temperature, measured and modelled outlet temperature of the PTC field on the cloudy day.

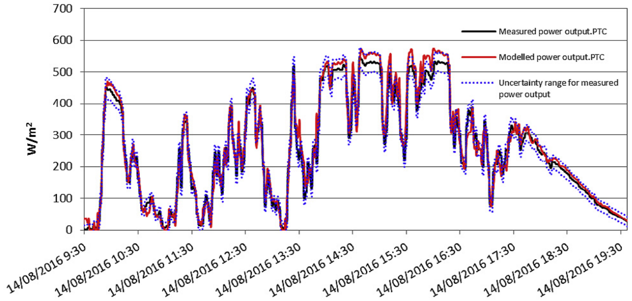

Fig. 12. Measured and modelled power output of the PTC field on the cloudy day.

The daily energy output of the FPC and PTC fields are shown in Table 5. The modelled and measured energy outputs present a good agreement on both cloudy and sunny days. The measured energy output of the PTC field is a bit lower than the modelled values on both the cloudy and the sunny days. That may be due to dirt on the mirror of the parabolic trough collectors because the mirrors have not been washed yet since August 2015. Furthermore, compared to the energy output of the FPC field, the PTC field produced about 40% more solar heat than the FPC field on the sunny day.

5.2. *Daily and monthly performance*

Calculations of daily and monthly performances of both solar collector fields are based on 1 min time step. The daily and monthly thermal performances of the parabolic trough collector field and the flat plate collector field during year-around operation are presented in Figs. 13–16.

1) Flat plate collector field

Fig. 13 shows that the measured and the modelled thermal performances are strongly linear related. Overall, the modelled results have a fine match with the measured data. The max daily solar heat production of the flat plate collector field was below 5 kWh/m^2/day.

As shown in Fig. 14, the flat plate collector field produced small heat quantities in November–January. The FPC field produced more and more heat from January to April. The FPC field produced more than 50 kWh/m^2 in April. The measured and simulated monthly solar heat productions show a good agreement from Sep.2015 to Aug.2016.

2) Parabolic trough collector field

Daily and monthly measured and modelled energy outputs of the PTC field (Sep.2015–Apr.2016) are shown in Figs. 15 and 16. In Fig. 15, a single point represents a daily result (September.2015–April.2016). There is a strong linear correlation between the measured daily thermal performance and the modelled daily thermal performance in Fig. 15, which shows the modelled values have good agreement with the measured values. Due to the oversized flat plate collector field and low heat load in the summer, the parabolic trough collector field was defocused on several sunny days in the summer. Therefore, only thermal performances of the parabolic trough collector field without defocusing during the period from Sep.2015 to Apr.2016 was presented in this section to verify the TRNSYS model. The maximum daily thermal performance of the parabolic trough collector field can be higher than

Table 5
Sum of daily solar radiation, and daily solar energy outputs of the FPC and PTC fields, May 7 and August 14 of 2016.

	$H_{Beam\ (PTC)}$, kWh/m^2	$H_{Tilted\ (FPC)}$, kWh/m^2	Measured, kWh/m^2	Modelled, kWh/m^2	Difference, kWh/m^2	Deviation	
Sunny day (May 7, 2016)	8.59	7.67	3.65	3.69	0.04	1.10%	FPC
			5.19	5.34	0.15	3.00%	PTC
Cloudy day (Aug. 14, 2016)	5.37	5.90	2.63	2.59	−0.04	−1.70%	FPC
			2.72	2.82	0.1	3.90%	PTC

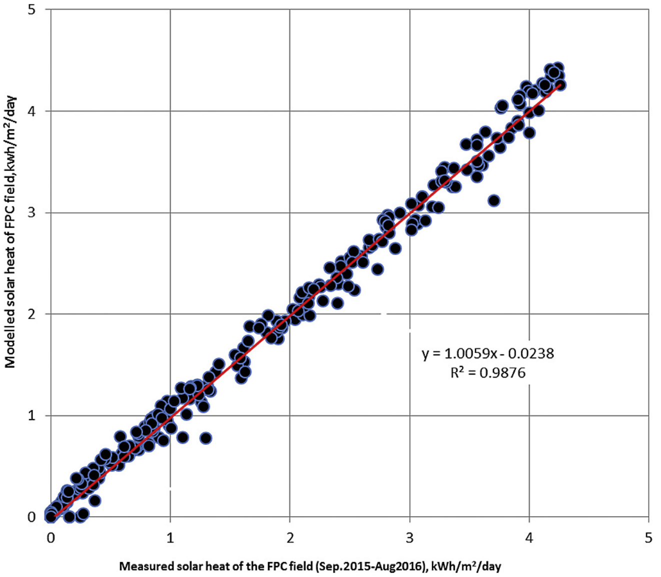

Fig. 13. Daily modelled solar energy output as a function of daily measured solar energy output of the FPC field.

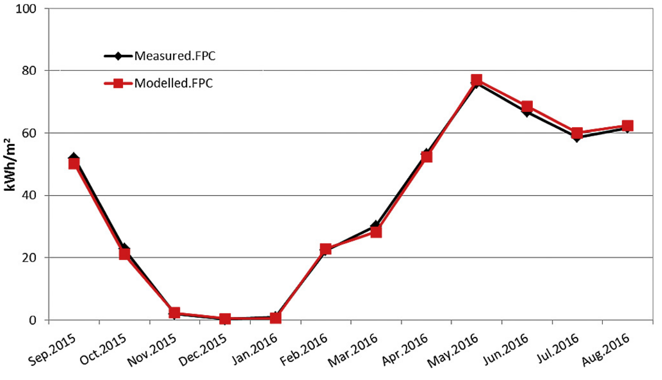

Fig. 14. Monthly measured and modelled energy output of the FPC field (Sep.2015–Aug.2016).

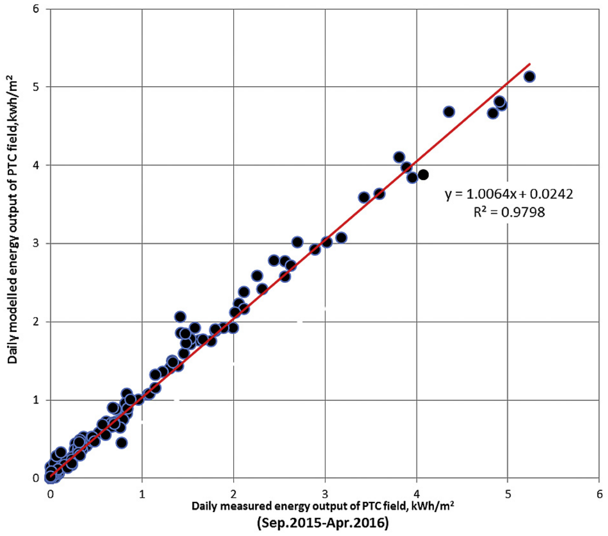

Fig. 15. Daily modelled solar energy output as a function of measured solar energy output of the PTC field.

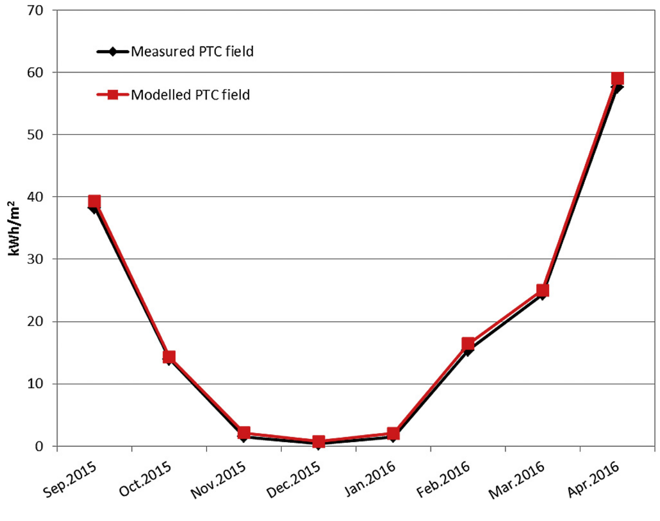

Fig. 16. Monthly measured and modelled energy output of the PTC field.

5 kWh/m^2/day, while the max daily thermal performance of the flat plate collector field is below 5 kWh/m^2/day. The thermal energy output of both the flat plate collector field and parabolic trough collector field in November, December, January is quite low because of the low solar radiation in winter. From February, the thermal energy output of the parabolic trough collector array increased dramatically because of more sunny days and the PTC field produced more solar heat than the FPC field.

6. Discussions

The flat plate collector field preheats return water from 45 °C up to about 75 °C, and then the preheated water is heated to 95 °C by the parabolic trough collector field in the Taars plant. The design strategy that the PTC field produces the high temperature water also guarantees that the FPC field has better performance and higher efficiency due to relatively low operation temperature compared to normal flat plate collector fields. In addition, section 5 shows that the TRNSYS models of the FPC field and the PTC field have quite good agreement with measurements. The PTC field was defocused sometimes in the quite sunny days in summer (May–August) because the flat plate collector field was oversized and the heat load of the district heating networks in summer was low.

So Figs. 15 and 16 only show the measured results from Sep.2015–Apr.2016. The PTC field would have higher energy output than the measured values, if the parabolic trough collectors were not defocused on sunny days in the summer. On the other hand, the defocusing of the PTC field can avoid boiling problems of the solar collector field in the summer season.

7. Conclusions and future work

The quasi-dynamic simulation model of both large parabolic trough collector field and flat plate collector field was validated by the measured thermal performance of the Taars solar heating plant in Denmark. Dynamic performance on two typical days was selected for the detailed validation. The simulated and the measured daily and monthly performances of the solar heating plant were also compared. The following conclusions can be drawn:

1. The quasi-dynamic method with the technical parameters from the standard test report based on single collector can be used to predict the thermal performance of both parabolic trough collector and flat plate collector fields.
2. The daily energy output of the parabolic trough collector field can be more than 5 kWh/m^2, while the daily energy output of the flat plate collector field is less than 5 kWh/m^2 under Danish climate conditions in this study.
3. The integration of parabolic trough collectors can increase the flexibility of solar district heating plants. The parabolic trough collectors can be easily defocused in the summer to avoid the overheat production. The flat plate collectors only work at low temperature range in the hybrid solar heating plant in order to increase the thermal performance of the flat plate collectors, compared to normal existing solar heating plants. A relatively constant and high outlet temperature of the hot water is easily achieved in the hybrid solar district heating plants.

In summary, the validated solar collector field model in this study is able to model reliable dynamic performances with a time step of 1 min. The proposed model is cost-effective, reasonable accurate and requires low computational time. The validated model may be a useful tool to analyze long-term performance, optimize design parameters and evaluate control strategy of large solar heating plants for district heating.

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Symbols

Q	Useful output power, W
A	Collector 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^2)
c_3	Effective thermal capacity, kJ/(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	Peak collector efficiency, -
dTm/dt	Time derivative of the mean fluid temperature, K/s
θ	Incident angle of the beam radiation, °
b_0	IAM coefficient(beam radiation), -
b_1	IAM coefficient(beam radiation), -
G_{tilted}	Total solar radiation on the tilted plate, W/m^2
G_h	Global solar radiation on the horizontal surface, W/m^2
$H_{Beam\ (PTC)}$	Daily beam radiation on the parabolic trough collector aperture, kWh/m^2
$H_{Tilted\ (FPC)}$	Daily total radiation on the flat plate collector aperture, kWh/m^2
T_{out}	Outlet temperature, °C
T_{in}	Inlet temperature, °C
ρ	Density, kg/m^3
C_P	Specific Heat Capacity, J/(kg·°C)
V	Volume flow rate, m^3/s
S	Uncertainty of specific parameters

Abbreviation

Parabolic trough collector	PTC
Flat plate collector	FPC
Heat transfer fluid	HTF
Incidence angle modifier	IAM
Direct normal irradiance	DNI
Heat transfer fluid	HTF
Concentrating solar power	CSP
Quasi-dynamic test	QDT
Fluorinated ethylene propylene	FEP

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Annual measured and simulated thermal performance analysis of a hybrid solar district heating plant with flat plate collectors and parabolic trough collectors in series

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HIGHLIGHTS

- A novel hybrid large-scale solar district heating plant was introduced.
- Annual thermal performance of the hybrid solar heating plant was investigated.
- Potential of parabolic trough collectors at high latitudes was shown.
- The novel design concept provides a design basis for solar heating plants.

ARTICLE INFO

Keywords:
Solar district heating plants
Parabolic trough collectors
Flat plate collectors
Thermal performance

ABSTRACT

Flat plate collectors have relatively low efficiency at the typical supply temperatures of district heating networks (70–95 °C). Parabolic trough collectors retain their high efficiency at these temperatures. To maximize the advantages of flat plate collectors and parabolic trough collectors in large solar heating plants for a district heating network, a hybrid solar collector field with 5960 m^2 flat plate collectors and 4039 m^2 parabolic trough collectors in series was constructed in Taars, 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 would heat the preheated water to the required supply temperature of the district heating network. Annual measured and simulated thermal performances of both the parabolic trough collector field and the flat plate collector field are presented in this paper. The thermal performance of both collector fields with weather data of a Design Reference Year was simulated to have a whole understanding of the application of both collectors under Danish climate conditions as well. These results not only can provide a design basis for this type of hybrid solar district heating plants with flat plate collectors and parabolic trough collectors in the Nordic region, but also introduce a novel design concept of solar district heating plants to other high solar radiation areas.

1. Introduction

Building energy consumption currently accounts for about 40% of the total society energy consumption in developed countries [1–4]. Different energy system configurations were optimized and the results showed that solar collector fields should be included in the energy supply system to achieve both the economic and environmental optimization [5]. Multi-objective optimizations on central solar heating plants with seasonal storage were carried out [6]. The results showed that the central solar heating plant led to significant environmental and economic improvements compared to the use of a conventional natural gas heating system. Overall, solar heating plants for district heating can reduce the fossil energy consumption in the building sector [7].

1.1. *State of the art*

In the early 1980s, the first several large solar collector arrays was built to connected to the district heating networks in Sweden. Then the market of large solar heating plants has increased fast in Denmark [8], Germany [9], Austria [10], Spain and Greece [11]. In 2016, 37 large-scale solar thermal systems were installed compared to 21 new installations in 2015 in Europe. Within these installations, 31 systems were installed in Denmark, 1 system in Sweden, 1 system in France and 4 systems in Germany [11]. Moreover the collector area of 5 existing Danish plants was extended in 2016. An online platform was established for almost all the solar heating plants in Denmark [12]. More than 1.3 million m^2 solar heating plants were in operation in Denmark

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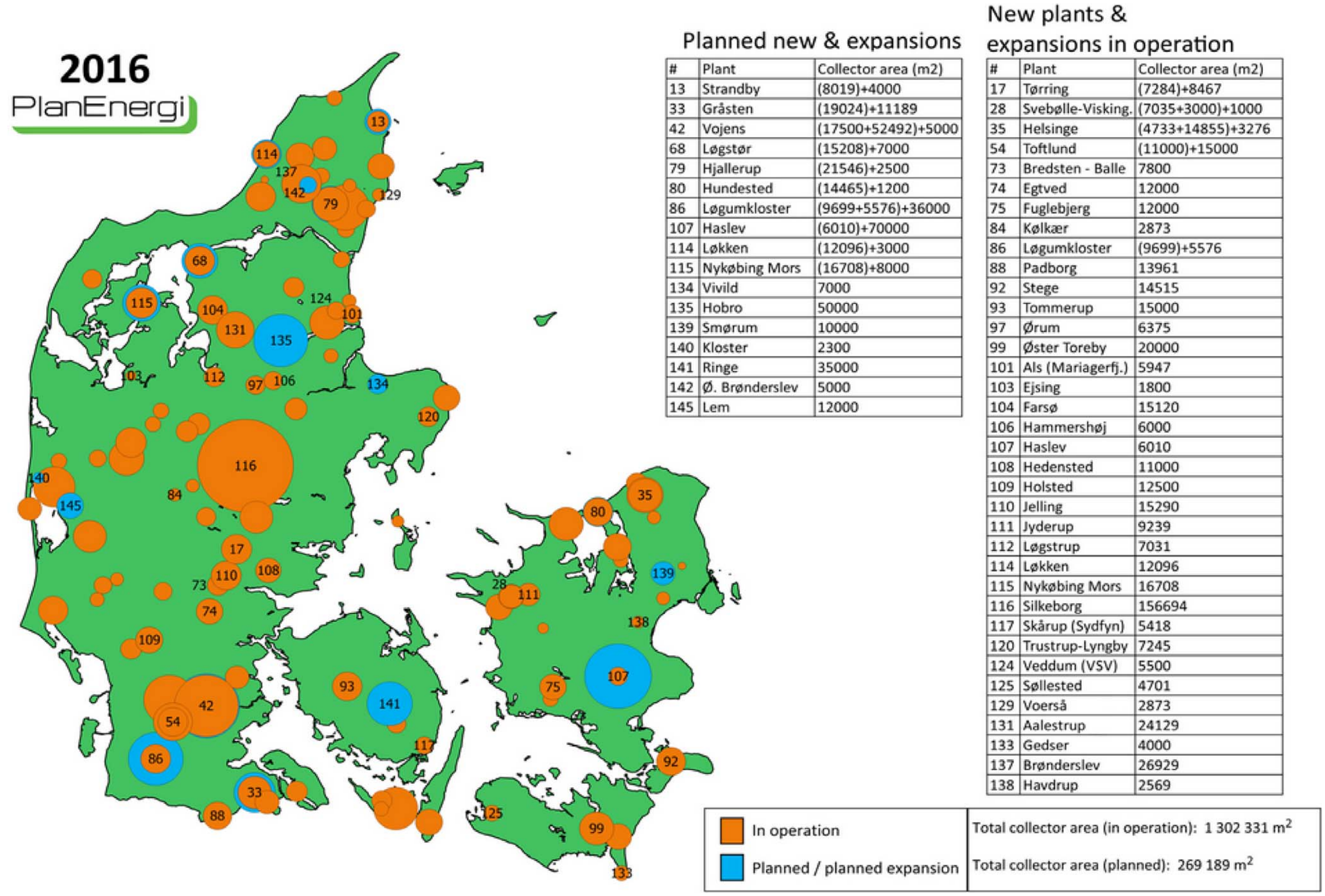
Nomenclature

Q	useful output power, W
A	collector aperture array area, m^2
c_1	heat loss coefficient at (Tm-Ta) = 0, $W/(m^2 \cdot K)$
c_2	temperature dependence of the heat loss coefficient, $W/(m^2 \cdot K^2)$
c_3	effective thermal capacity, $kJ/(m^2 \cdot K)$
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
HE	heat exchanger
DH	district heating networks
IEA	International Energy Agency
SHC	Solar Heating and Cooling Programme
SF	solar fraction

by the end of 2016 and 270 thousand m^2 solar heating plants are being planned, as shown in Fig. 1. Several large solar heating plants have been constructed in Denmark [13], such as in Vojens (70,000 m^2), Marstal (33,360 m^2), Gram (44,000 m^2), Silkeborg (156,694 m^2), etc. Denmark is the frontrunner not only in Europe but also worldwide for both large-scale systems installed as well as capacity installed in solar district heating sector. Denmark is also the only example of a mature and commercial solar district heating market around the world, which can provide references for other places. Solar collectors are the most important components for the large solar district heating plants. Most solar collectors used in the normal solar heating plants are ground mounted flat plate collectors (FPC).

1.2. *Parabolic trough collectors*

Most parabolic trough collectors (PTC) have previously been used to produce electricity. With the requirements of energy conservation in industry, more and more parabolic trough solar collectors have been employed to provide heat for industrial processes in recent years. IEA-SHC TASK 49 [15] has focused on the application of solar collectors in the industry sector. Frank et al. [16] investigated the thermal performances 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 et al. [17, 18] did simulations and thermo-economic design optimization on



Planned new & expansions

#	Plant	Collector area (m2)
13	Strandby	(8019)+4000
33	Gråsten	(19024)+11189
42	Vojens	(17500+52492)+5000
68	Løgstør	(15208)+7000
79	Hjallerup	(21546)+2500
80	Hundested	(14465)+1200
86	Løgumkloster	(9699+5576)+36000
107	Haslev	(6010)+70000
114	Løkken	(12096)+3000
115	Nykøbing Mors	(16708)+8000
134	Vivild	7000
135	Hobro	50000
139	Smørum	10000
140	Kloster	2300
141	Ringe	35000
142	Ø. Brønderslev	5000
145	Lem	12000

New plants & expansions in operation

#	Plant	Collector area (m2)
17	Tørring	(7284)+8467
28	Svebølle-Visking.	(7035+3000)+1000
35	Helsinge	(4733+14855)+3276
54	Toftlund	(11000)+15000
73	Bredsten - Balle	7800
74	Egtved	12000
75	Fuglebjerg	12000
84	Kølkær	2873
86	Løgumkloster	(9699)+5576
88	Padborg	13961
92	Stege	14515
93	Tommerup	15000
97	Ørum	6375
99	Øster Toreby	20000
101	Als (Mariagerfj.)	5947
103	Ejsing	1800
104	Farsø	15120
106	Hammershøj	6000
107	Haslev	6010
108	Hedensted	11000
109	Holsted	12500
110	Jelling	15290
111	Jyderup	9239
112	Løgstrup	7031
114	Løkken	12096
115	Nykøbing Mors	16708
116	Silkeborg	156694
117	Skårup (Sydfyn)	5418
120	Trustrup-Lyngby	7245
124	Veddum (VSV)	5500
125	Søllested	4701
129	Voerså	2873
131	Aalestrup	24129
133	Gedser	4000
137	Brønderslev	26929
138	Havdrup	2569

🟧 In operation	Total collector area (in operation): 1 302 331 m^2
🟦 Planned / planned expansion	Total collector area (planned): 269 189 m^2

Fig. 1. Solar heating plants in Denmark [14].

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 be achieved at the base scenario conditions considered. Hassine et al. [19] investigated the control strategy of two 1000 m^2 solar heating plants (in Austria and Italy). Some design faults of the collector loop controller were found in the first operation period. Based on measurements and simulations with dynamic models, the potential improvements of low-level control algorithms were suggested for the two solar heating plants.

Larcher et al. [20] 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 et al. [21] 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 [17, 18]. An experimental investigation on a small-sized parabolic trough solar collector for hot water in cold areas was carried out and showed great anti-freezing property of the proposed collector [22]. These investigations show that the application of parabolic trough collectors for high temperature heat production can be economical and feasible if the systems are designed reasonably.

A preliminary case study of parabolic trough collectors for district heating at high latitudes with low solar radiation resources was carried out in 2000 [23]. The economic comparison indicated that parabolic trough systems could be competitive with flat plate collectors, but few practical projects with parabolic trough collectors for district heating were undertaken in the following decades. On the other hand, it is found that most present research of parabolic trough collectors has been on applications with 500–1500 m^2 collectors for industrial processes [16–21] or steam and electricity production [24–33]. Limited reports with detailed measurements of the in situ annual thermal performance of large-scale solar heating fields with flat plate collector and parabolic trough collectors for district heating networks are available.

The operation temperature of solar collectors in solar heating plants in Denmark is in the range from about 40 °C to 95 °C. The efficiency of flat plate collectors decreases significantly in the range 70–95 °C, while parabolic trough collectors maintain relatively high efficiency in this range. To exploit 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 in series has been proposed. The basic principle is that the flat plate collector field preheats the return water from the district heating network from 40 °C to 70 °C and then 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 A/S [34] and Technical University of Denmark (DTU) [35] since 2013.

1.3. Scope

A demonstration hybrid solar district heating plant based on the mentioned principle was constructed in Taars of Denmark and put into operation in August 2015. The hybrid solar heating plant consists of 5960 m^2 flat plate collectors and 4039 m^2 parabolic trough collector in series. The aim of this work is to demonstrate the application of the hybrid solar heating pant with parabolic trough collectors and introduce a novel design concept for the new solar heating plants. The novelty of this paper is stressed as follows: (1) The studied solar heating plant is the first hybrid large scale solar heating plant (9999 m^2) developed for the domestic district heating network in the Nordic area, or even around the world, which integrates the PTC and FPC technologies; (2) Parabolic trough collectors with water as the heat transfer fluid in the novel combined solar heating plant are used to provide hot water for the district heating network, while parabolic trough collectors with oil as the heat transfer fluid are normally used for electricity production; (3) The idea of the hybrid solar heating plant is that the flat plate collectors only work at the low operation temperature level and the parabolic trough collectors work at relatively high temperature level; (4) The integration of parabolic trough collectors can increase the flexibility of the solar heating plants significantly in the whole district heating networks due to the possibility of defocusing; (5) Potential and feasibility of the PTC technology in the hybrid solar heating plant under the Danish climate conditions with low solar radiation resource was shown, which can provide a design basis for the development of concentrating solar power technologies in the Nordic area in the near future.

Annual measured and simulated thermal performances with a validated TRNSYS model of the hybrid solar heating plant during its first operation year from September 2015 to August 2016 are shown in this paper. The rest of the paper is organized as follows: the 2nd section introduces the Taars solar heating plant briefly, The 3rd section shows the methods, including measurements and validated TRNSYS in this study. The 4th section presents meteorological data and heat demand. The 5th section presents annual thermal performance of Taars solar heating plant, including both measured and modelled energy output, solar fraction and utilized efficiency. The 6th section shows the typical performance of the Taars plant in Design Reference Year and illustrates the potential of the hybrid plant under Danish climate conditions. Finally, the 7th section is the conclusions and future work.

2. Taars solar heating plant

2.1. Overview

Figs. 2 and 3 show the hybrid solar heating plant with a 5960 m^2 flat plate collector field and a 4039 m^2 parabolic trough collector field in series in Taars, Denmark (latitude: 57.39 °N, longitude: 10.11 °E, altitute:48 m). The plant was put into operation in August 2015 [34, 35]. Technical data on the solar collector field can be found in Tables 1 and 2. Fig. 4 briefly illustrates the basic principle of the solar heating

Fig. 2. Picture of the Taars solar heating plant.

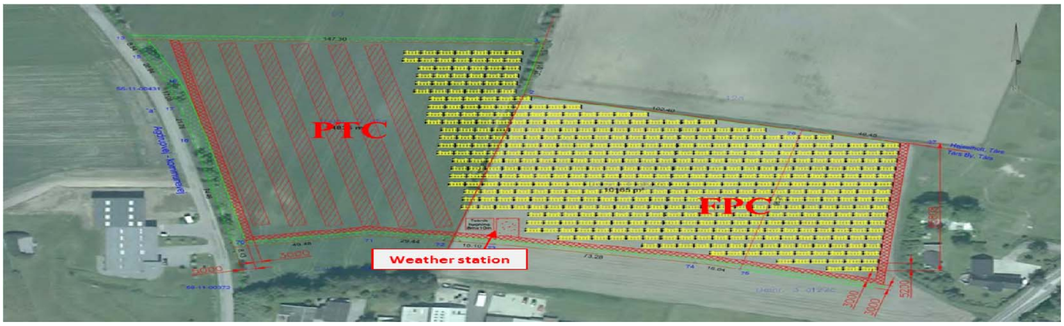


Fig. 3. Layout of the solar collector field.

Table 1
Parameters of the PTC collector in the Taars 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)	0.125
Glass envelope inner diameter (m)	0.119
Parabola width (m)	5.77
Numbers of modules per row	10
Mirror length in each module (m)	12
Geometric concentration ratio	26.2

Table 2
Parameters of the FPC collectors in the Taars 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:3.2 mm)-with/without FEP	

Table 3
Parameters of the investigated solar collectors.

η_0	b_0	b_1	$K_{\theta d}$	c_1 [W/(m^2·K)]	c_2 [W/(m^2·K^2)]	c_3 [kJ/(m^2·K)]	
0.779	0.1	0	0.98	2.410	0.015	6.798	HEATboost 35/10
0.745	0.1	0	0.93	2.067	0.009	7.313	HEATstore 35/10
0.75	0.27	0	0.038	0.04	0	4	PTC collector

plant. The solar collector fluid of the parabolic trough collectors is water, while that of FPC is a glycol/water mixture (35%). The return water from the district heating network is heated up to 65–75 °C by the heat exchanger connected to the flat plate collector field. Then the preheated 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 was 13.4° towards west from south. The parabolic trough collectors track the sun from east to west when the collectors work during the whole day. There are six rows of parabolic trough collectors and the row distance is 12.6 m. The length of each row parabolic trough collector loop is about 125 m. The orientation of flat plate collectors is south and the collector row distance is 5.67 m. The tilt of the flat plate collectors is 50°. The parabolic trough collectors are delivered by Aalborg CSP A/S. The flat plate collectors consist of two types of the flat plate collectors, namely HTHEATboost 35/10 and HTHEATstore 35/10, manufactured by Arcon-Sunmark A/S [36]. 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 consists of two natural gas boilers (9.1 MW in

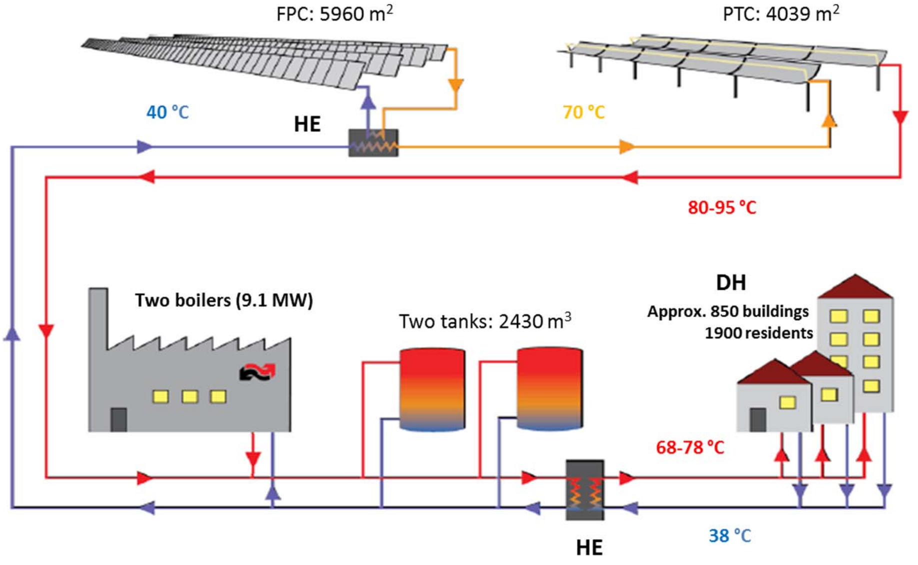


Fig. 4. Schematic illustration of the Taars solar heating plant.

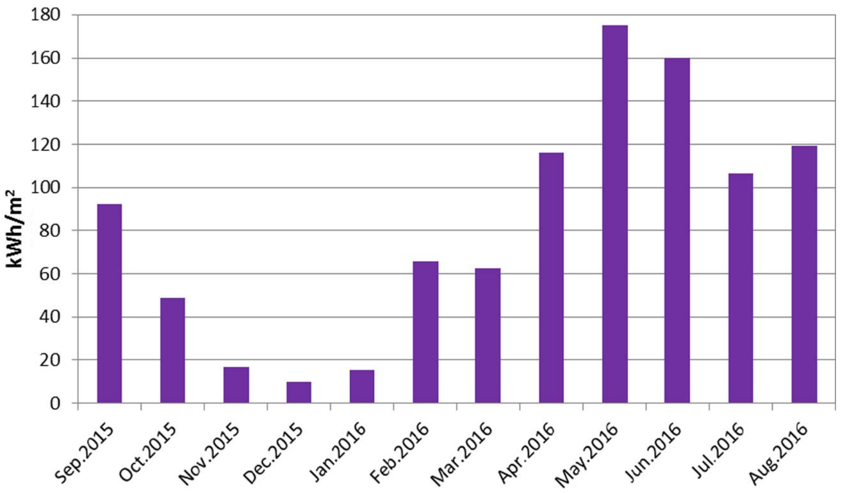


Fig. 5. DNI in the Taars solar heating plant (Sep. 2015-Aug. 2016).

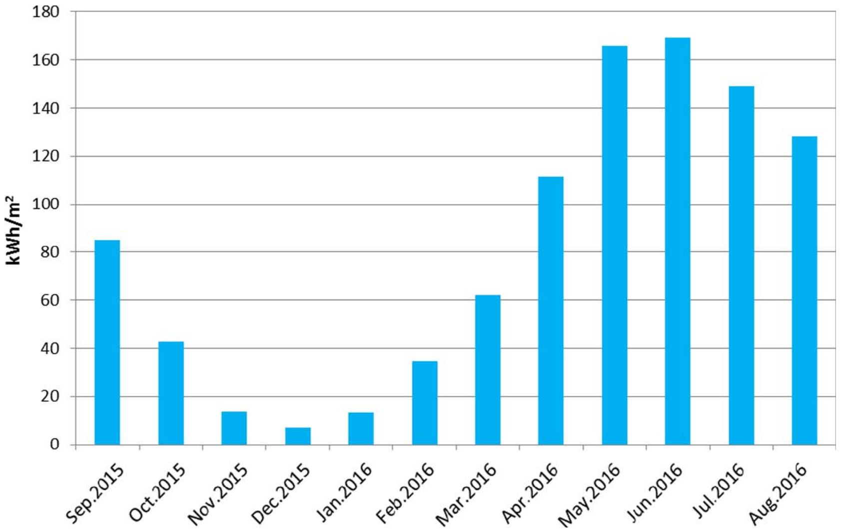


Fig. 6. Global radiation on the horizontal surface in the Taars solar heating plant (Sep. 2015-Aug. 2016).

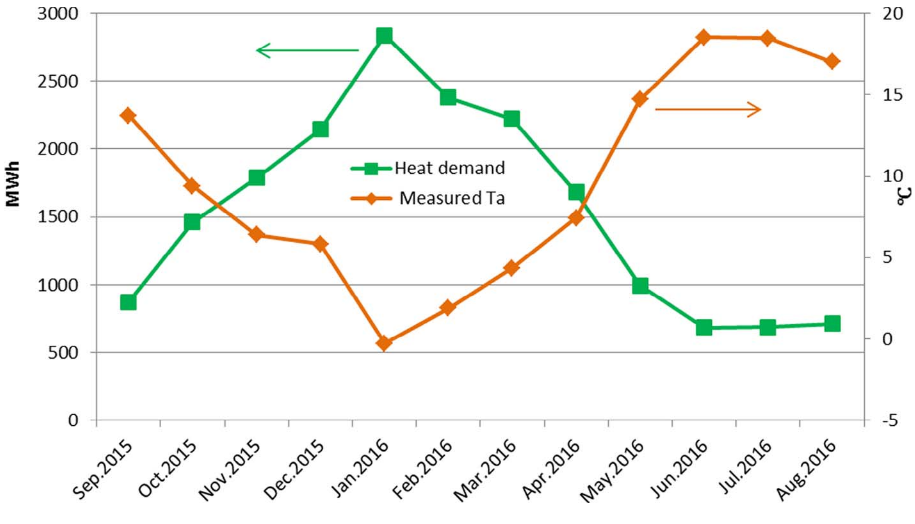


Fig. 7. Monthly heat demand and average ambient temperature in the Taars solar heating plant (Sep. 2015-Aug. 2016).

total). Two tanks with a total volume of 2430 m^3 are used as heat storage for several days in the summer.

2.2. Control strategy

The plant is oversized for the heat demand in the summer months. To avoid overheating issues in the summer, the parabolic trough collectors are sometimes put out of focus. Feed forward control is used to keep a constant outlet temperature by the flow control in the parabolic trough collector field.

Table 4
Sums of DNI, global radiation and heat demand of the Taars solar heating plant (Sep. 2015-Aug. 2016).

Items	Values
DNI, kWh/m^2	990
Global radiation on the horizontal surface, kWh/m^2	980
Heat demand, MWh	18460

3. Methods

The efficiency expressions and the incidence angle modifier of the investigated solar collectors are given by Eqs. (1) and (2). The parameters of the parabolic trough collectors based on the aperture area were determined by the Technical University of Denmark [37]. The technical parameters of flat plate collectors based on the gross area were determined by SP Technical Research Institute of Sweden [38], which are available in the reference [39]. The parameters of the investigated solar collectors can be found in Table 3.

$$\frac{Q}{A} = \eta_0 K_{\theta b}(\theta) G_b + \eta_0 K_{\theta d}(\theta) G_d - c_1 (T_m - T_a) - c_2 (T_m - T_a)^2 - c_3 \frac{dT_m}{dt} \tag{1}$$

$$K_{\theta b}(\theta) = 1 - b_0 \left(\frac{1}{\mathrm{COS}\theta} - 1 \right) - b_1 \left(\frac{1}{\mathrm{COS}\theta} - 1 \right)^2, \theta \leqslant 60^\circ \tag{2}$$

when $\theta > 60^\circ$, the IAM is linearized from the value at 60° to a value of zero at 90°.

3.1. Measurements

The system is well equipped with different accurate sensors and the monitoring data are automatically transferred to the computers. Global solar radiation on the horizontal surface and total radiation on the tilted flat plate collectors are measured with Kipp & Zonen SMP11. DNI is measured with a PMO6-CC pyrheliometer with the sun tracking platform Sunscanner SC1. The inlet and outlet temperatures of the collector fields are measured with SIEMENS TS500 temperature sensors, flow rates of both the FPC field and the PTC field are measured with Sitrans FM MAG3100P flow meters - SIEMENS. Measured thermal performance is 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. The TRNSYS model was based on the quasi dynamic method. TRNSYS type 1290 was used to simulate the thermal performance of the collector fields. Type 3b was used as the pump unit in the collector fields. Type 5b was the heat exchanger unit in the FPC field. Type 30 simulated the shadows between the collector rows. Type 4 was used to simulate the tanks. The TRNSYS model was validated by the measurements and was accurate enough to predict the thermal performances of both solar collector fields. Detailed information and validation of the TRNSYS model and uncertainties of measurements are given in [40, 41].

4. Meteorological data and heat demand

Figs. 5 and 6 show measured monthly DNI and global solar radiation in the Taars heating plant. Obviously, solar radiation from November 1 to January 31 was low in Denmark. Fig. 7 shows monthly average ambient temperature from Sep. 2015 to Aug. 2016 and the heat demand of the Taars 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 was about 18 °C, which was the highest. Table 4 shows the sums of DNI, global radiation on the horizontal surface and heat demand from Sep. 2015 to Aug. 2016. DNI and global radiation were 990 and 980 kWh/m^2 respectively. Heat demand of the Taars district heating network from Sep. 2015 to Aug. 2016 was 18,460 MWh.

5. Annual thermal performance

All the measured and modelled thermal performances given per square meter solar collector field are based on the aperture area of the solar collectors. The time step was 1 min in the calculations. The inlet temperature and volume flow rate of both the FPC and the PTC collector field in simulation were taken from the measurements.

5.1. Thermal performance of FPC collectors

Fig. 8 shows monthly measured and modelled thermal performances of the flat plate collector field from Sep. 2015 to Aug. 2016. The thermal performance of the flat plate collector field was low during the winter because of the low solar radiation. The max monthly thermal performance of the flat plate collector field was higher than 70 kWh/m^2 in May 2016. Both measured and modelled yearly total thermal performances of the flat plate collector field were 2670 MWh for the period Sep. 2015 -Aug. 2016.

5.2. Thermal performance of PTC collectors

As shown in Fig. 9, the parabolic trough collector field did not produce much heat during the winter because of low DNI. But in the spring and summer, the parabolic trough collector field performed very well. The parabolic trough collector field should have worked best in

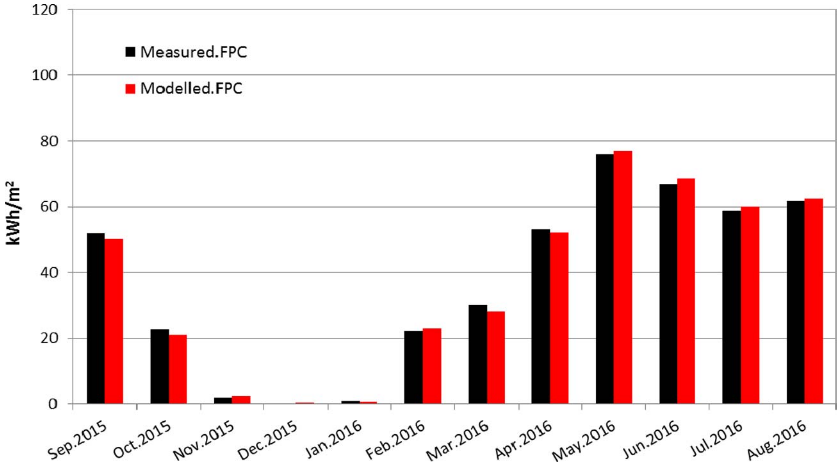


Fig. 8. Monthly thermal performance of FPC field (Sep. 2015-Aug. 2016).

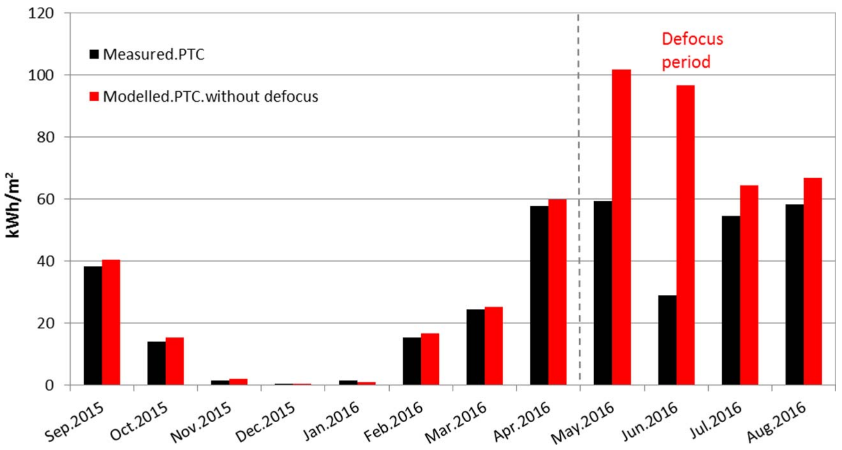


Fig. 9. Monthly thermal performance of PTC field.

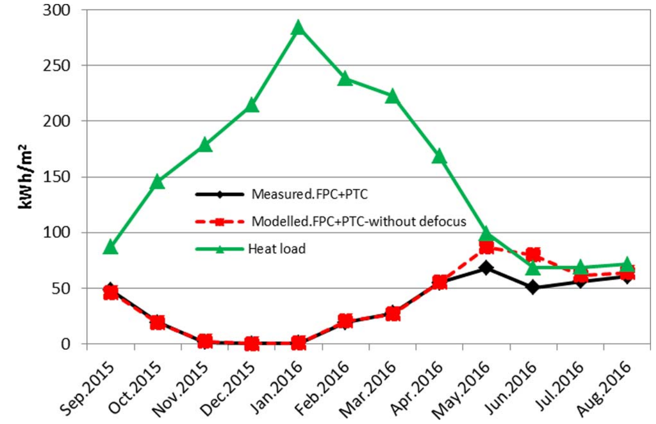


Fig. 10. Heat demand and thermal performance of Taars solar heating plant per m^2 solar collector aperture area, Sep. 2015-Aug. 2016.

the summer, when the solar radiation was high. However, the parabolic trough collector field was defocused sometimes on the sunniest days of summer (such as in May-August) because the flat plate collector field was oversized and the heat demand in the summer was low. The simulated thermal performance in Fig. 9 illustrates 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 continue to operate without defocusing. The measured thermal performance of the parabolic trough collector field for the period September 2015-August 2016 was 354 kWh/m^2, while the modelled value with defocus was 359 kWh/m^2. The simulated thermal performance of the parabolic trough collector field without defocus was 490 kWh/m^2 for the period Sep. 2015-Aug. 2016. That is: a reduction of 136 kWh/m^2 was calculated due to defocusing of the parabolic trough collector field.

Table 5
Annual thermal performance of the Taars plant (Sep. 2015-Aug. 2016).

Items	Value	Unit
Heat demand,	18460	MWh
Measured solar heat. FPC field	448 2672	kWh/m^2 MWh
Modelled solar heat. FPC field	448 2671	kWh/m^2 MWh
Measured solar heat. PTC field	354 1431	kWh/m^2 MWh
Modelled solar heat. PTC field with defocus	359 1450	kWh/m^2 MWh
Modelled solar heat. PTC field without defocus	490 1981	kWh/m^2 MWh
Measured solar heat. FPC + PTC	410	kWh/m^2
Modelled solar heat. FPC + PTC with defocus	412	kWh/m^2
Modelled solar heat. FPC + PTC without defocus	465	kWh/m^2
Measured solar fraction	22.2%	–
Modelled solar fraction (PTC with defocus)	22.3%	–
Modelled solar fraction (PTC without defocus)	25.2%	–

5.3. *Solar fraction*

The Taars district heating network consists of approximate 850

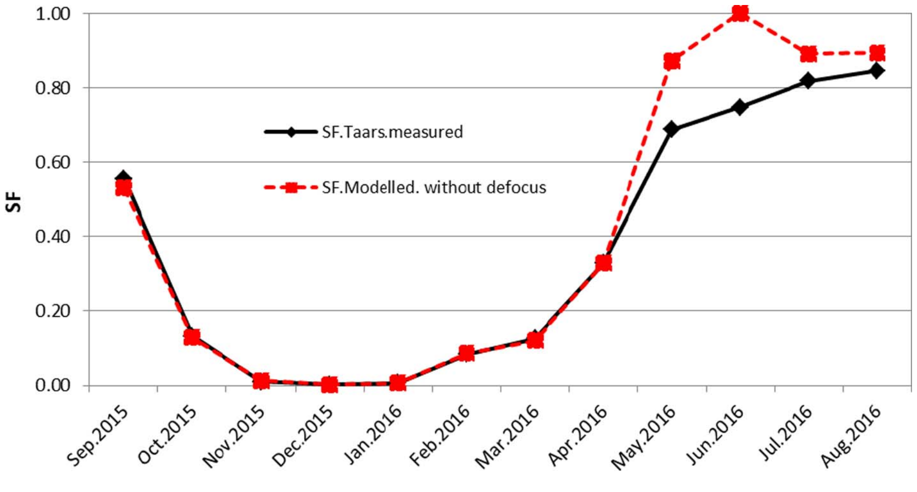


Fig. 11. Solar fraction (SF) of Taars solar heating plant (Sep. 2015-Aug. 2016).

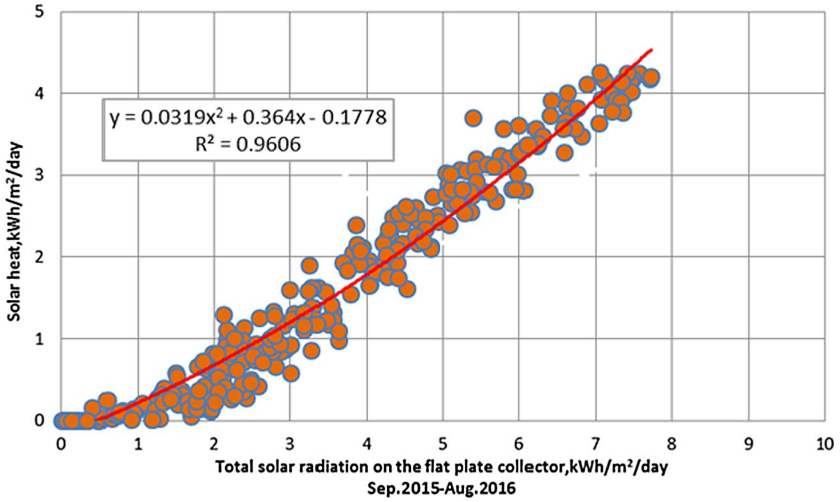


Fig. 12. Measured daily solar heat as a function of total radiation on the flat plate collectors.

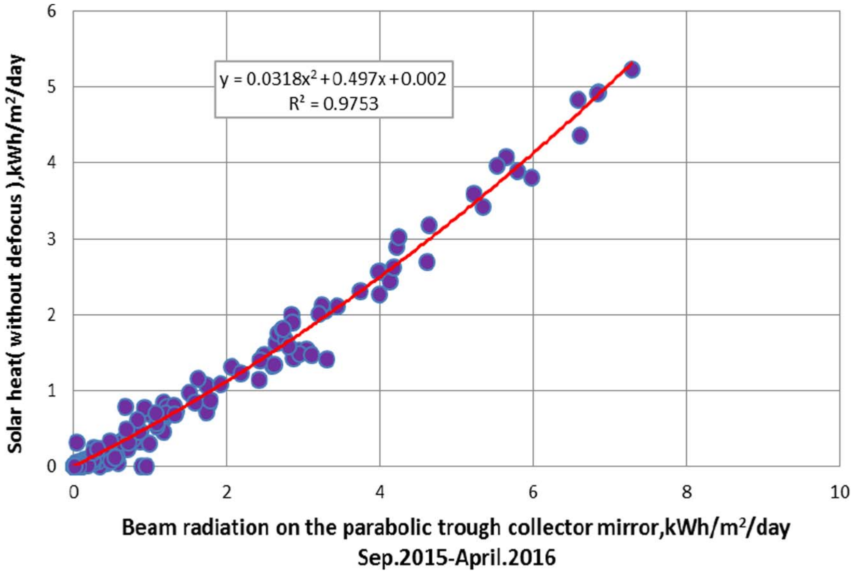


Fig. 13. Measured daily solar heat as a function of daily beam radiation on the parabolic trough collectors.

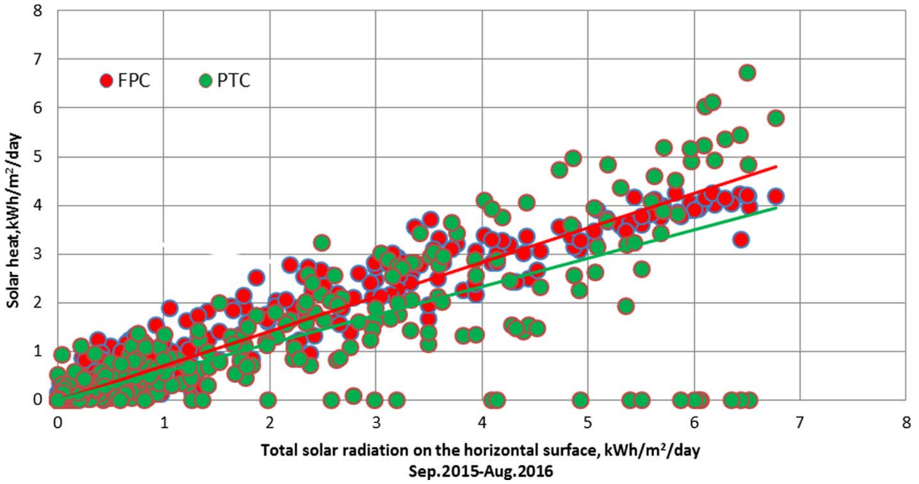


Fig. 14. Measured daily solar heat as a function of daily global radiation for both collector fields.

buildings with about 1900 consumers. Measured heat load and total thermal performance of the solar collector fields per collector area from Aug. 2015 to Sep. 2016 can be found in Fig. 10. The solar fraction, defined as the ratio between the solar heat and the heat demand, was very high in the summer when the heat load was low and the weather was sunny, see Fig. 11. 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 was close to 0, which is normal for the Nordic area. Table 5 shows a summary of annual thermal performance of the Taars plant.

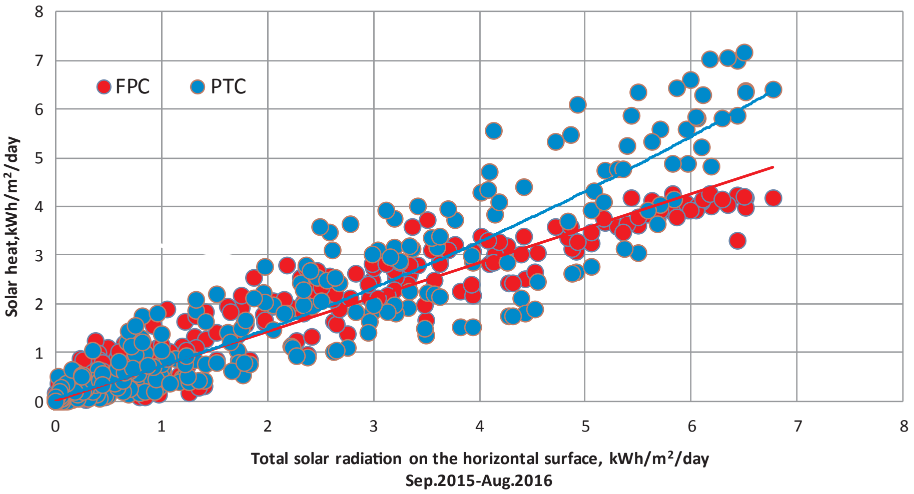


Fig. 15. Modelled daily solar heat as a function of daily global radiation for both collector fields.

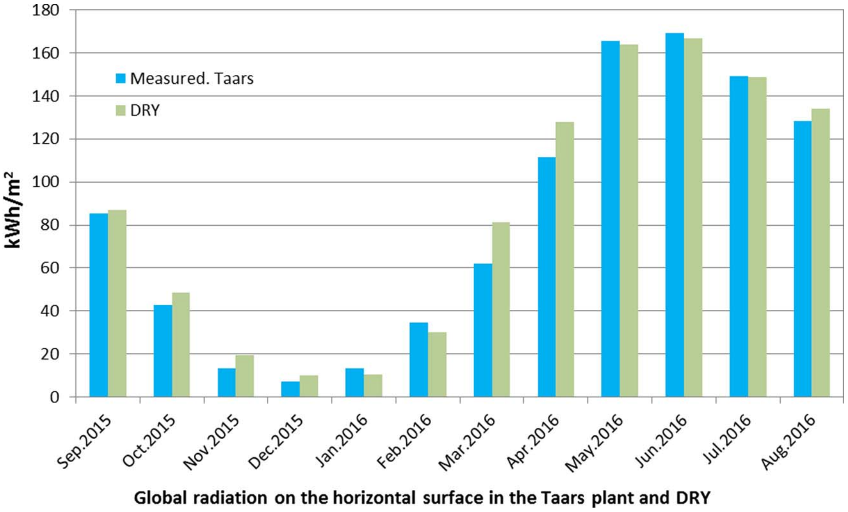


Fig. 16. Monthly global radiation in the Taars plant and in the DRY.

Table 6
Weather parameters measured in Taars (Sep. 2015-Aug. 2016) and in the DRY.

DNI, kWh/m^2	990	Sep. 2015-Aug. 2016
	1150	DRY
Total radiation on tilted FPC plane, kWh/m^2	1170 1295	Sep. 2015-Aug. 2016 DRY
Global horizontal radiation, kWh/m^2	980 1030	Sep. 2015-Aug. 2016 DRY
Heat demand, MWh	18460 21660	Sep. 2015-Aug. 2016 DRY

The measured total energy output of the solar heating plant was 4100 MWh and total heat load was 18,460 MWh during Sep. 2015 to Aug. 2016. The solar fraction of the solar heating plant was 22.2% from Sep. 2015 to Aug. 2016. As shown in Figs. 10 and 11, if the parabolic trough collectors were not defocused, the parabolic trough collectors could have a better thermal performance in the summer. Furthermore, only in June the simulated thermal performance is higher than the heat demand if the parabolic trough collector field was not defocused. By applying large heat storage tanks, the parabolic trough collector field could work normally without defocus in the summer, even in June. In this way solar fraction would have been close to 100% in the months from May to August. The yearly thermal performance of the combined solar collector field without defocusing of parabolic trough collectors in the summer can reach 4650 MWh and the solar fraction would increase from 22.2% to 25.2%. 550 MWh solar heat was lost because of defocusing of parabolic trough collectors in the sunny days in the summer.

5.4. Utilized efficiency

Fig. 12 shows the measured daily solar heat of the flat plate collector field as a function of the total radiation on the tilted flat plate collectors. According to the fitting curve, the average daily efficiency of the flat plate collector field is about 0.48. Max daily solar heat production of flat plate collector field is below 5 kWh/m^2.

The parabolic trough collectors were not put into defocus from Sep. 2015 to Apr. 2016. Fig. 13 shows the measured daily solar heat without defocusing as a function of the 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 would increase to about 0.70 and the parabolic trough collector field would produce more than 5 kWh/m^2 per day in the sunny days.

Both beam radiation and diffuse radiation influence thermal performance of the flat plate collector field, while the thermal performance of the parabolic trough collector field is mainly influenced by the beam radiation. To compare performances of both collector fields in a fair way, global radiation was chosen as a benchmark. Fig. 14. shows

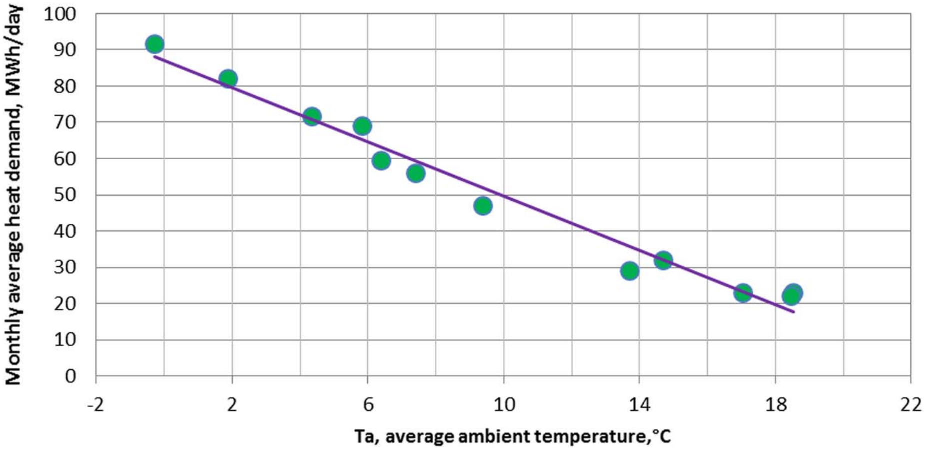


Fig. 17. Measured monthly heat demand (average value per day) as a function of average ambient temperature of Taars solar heating plant (Aug. 2015-Aug. 2016).

Table 7
Calculated annual thermal performance of Taars solar heating plant in the DRY for Northern Jutland.

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%

measured daily solar heat for both collector fields as a function of the global radiation on the horizontal surface. The thermal performance of the parabolic trough collector field without defocus was modelled to investigate the maximum potential of parabolic trough collector field, as shown in Fig. 15. It is seen that the thermal performance of the parabolic trough collector field was zero mainly because of defocus while the weather was sunny in Fig. 14. In Fig. 15, it is found that when the daily global radiation was lower than about 2 kWh/m^2, the parabolic trough collector field did not perform better than the flat plate collector field. Furthermore, the parabolic trough collector field produced more heat than the flat plate collector field, when daily global radiation was higher than about 2 kWh/m^2.

6. Discussions

The Taars solar heating plant is the first large hybrid solar heating plant, which integrates both flat plate collectors and parabolic trough collectors to provide heat for a district heating network. The oversize of the flat plate collector field and low heat demand in the summer were the main reasons why the parabolic trough collectors were defocused in summer periods. Potential of the Taars plant in the DRY (Design Reference Year [42]) is shown in this section.

Fig. 16 shows monthly measured global radiation on horizontal in the Taars plant and global radiation of the DRY of Northern Jutland [42]. Table 6 shows the summary of weather conditions in Taars (Sep. 2015-Aug. 2016) and in the DRY. The measured global radiation in the Taars solar heating plant from Sep. 2015 to Aug. 2016 is 980 kWh/m^2, while that of DRY is 1030 kWh/m^2. It is found that there was less sun shine from Sep. 2015 to Aug. 2016 compared to DRY.

Fig. 17 shows the relation between monthly heat demand (average value per day) and average ambient temperature from Sep. 2015 to Aug. 2016. The heat demand in the DRY in Table 7 is calculated by the fitting curve in Fig. 17 and the average ambient temperatures of the DRY. The heat demand of the Taars solar heating plant in the DRY is a bit higher than measured values from Sep. 2015-Aug. 2016.

Table 7 also shows calculated annual thermal performance of the Taars solar heating plant in the DRY, calculated by DTU Excel tool (Dragsted and Furbo, 2012) [42]. Mean solar collector fluid temperatures of the flat plate collector field and the parabolic trough collector field were assumed to be 55 °C and 80 °C respectively based on the measurements. The parabolic trough collector field is assumed to work without defocus. The potential thermal performance of the Taars solar heating plant in the DRY is 5180 MWh, while the heat demand in the DRY is 21,590 MWh. Furthermore, the solar fraction is 24%. Table 7 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, so that the parabolic trough collector field is not put out of focus in the summer. An increase of the heat load of the district heating network in the future can increase thermal performance of the plant. Furthermore, a large heat storage could also be helpful to harvest the advantages of parabolic trough collectors in the summer. The advantages of the hybrid solar heating plants are that the flat plate collector field produces about 60 kWh/m^2 one year more than the normal solar heating plants with only flat plate collectors, and the defocus of the parabolic trough collectors increases the flexibility of the solar heating plants in the whole energy supply system. This study not only demonstrates the feasibility and potential of the hybrid solar heating plants at the high latitude with low solar radiation resource, but also introduces a novel design concept of higher efficient solar heating plants for the high solar radiation area

7. Conclusions and future work

Both measured and simulated annual thermal performances of the Taars solar heating plant were analysed for the whole year from September 2015 to August 2016. The thermal performance of the Taars solar heating plant in the DRY for the northern part of Jutland was also investigated. These findings can be used in the design of new large-scale solar district heating plants in the near future. The conclusions are as follows:

The solar fraction of the Taars solar heating plant was 22.2% during the period from Sep. 2015 to Aug. 2016. If the parabolic trough collector field had not been defocused, the total thermal performance would have increased from 4100 MWh to 4650 MWh, that is from 410 kWh/m^2 to 465 kWh/m^2 and the solar fraction would have reached 25.2%.

Potential annual thermal performance of the Taars solar heating plant in the DRY for northern Jutland could reach 5180 MWh (518 kWh/m^2) and a solar fraction of 24% if defocusing of the parabolic trough collectors is avoided.

Further studies on the optimization of the thermal performance and control strategy of the hybrid solar district heating plant are required to formulate comprehensive design rules for such hybrid solar heating plants.

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