Thermal Performance Analysis of a Solar Heating Plant

Jianhua Fan[1], Junpeng Huang[1], Ola Lie Andersen[1], Simon Furbo[1]

[1] Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark

Abstract

Detailed measurements were carried out on a large scale solar heating plant located in southern Denmark in order to evaluate thermal performances of the plant. Based on the measurements, energy flows of the plant were evaluated. A modified Trnsys model of the Marstal solar heating plant was developed to calculate thermal performances of the plant. In the Trnsys model, three solar collector fields with a total solar collector area of 33,300 m^2, a seasonal water pit heat storage of 75,000 m^3, a simplified CO_2 HP, a simplified ORC unit and a simplified wood chip boiler were included. The energy consumption of the district heating net was modeled by volume flow rate and given forward and return temperatures of the district heating net. Weather data from a climate station on the site of the plant were used in the calculations. The Trnsys calculated yearly thermal performance of the solar heating plant was compared to the measurement result. Validity of the Trnsys model was analyzed. Recommendations are given with an aim to develop a Trnsys model that can be used to optimize design of a solar heating plant under different scenarios.

Keywords: Solar heating plant, Thermal performance, Monitoring, Trnsys simulations, Design optimization

1. Introduction

Modern district energy systems provide heating and cooling services using technologies and approaches such as combined heating and power (CHP), thermal storage, large scale heat pumps and solar heating. District energy creates synergies between supply and demand of process heating and cooling, space heating, cooling, domestic hot water and electricity. Tackling the energy transition of district heating to a sustainable future will require the intelligent use of synergies, flexibility, and short and long term energy storage solutions (Lund etc. 2014).

Denmark is one of the leading countries in district heating. Around 60% of Danish buildings are connected to district heating and district heating covers more than 50% of the total heating demand of Denmark (Nussbaumer & Thalmann 2014). The development of Danish district heating targets the transition from current 3rd generation district heating to the future 4th generation low temperature district heating with a large share of renewable energies. In 2009, a total 54,500 m^2 solar collectors were installed in Denmark, of which 35,000 m^2, i.e. 64%, were used in large solar district heating systems. In 2015, the solar collector areas installed in solar district heating plants reached 241,000 m^2, increased by 342% in six years. Supplemented by cogeneration technologies for biomass and large scale heat pumps fueled by electricity from wind power, it is possible to achieve a district heating and cooling system with 100% renewable energy. In these large scale solar heating plants, seasonal water pit thermal energy storages (PTES) are implemented. PTES is a viable solution of thermal energy storage both economically and environmentally since it is simple in construction and relatively cheap. Larger storage volumes lead to increased efficiency in practice, since the heat losses do not increase with the volume proportionally. With a large water pit heat storage, solar fraction of a district heating system could be significantly increased to for example 50% of the heat demand. Examples of large scale solar heating plants are the Marstal plant (33,300 m^2 solar collectors and 75,000 m^3 PTES), the Dronninglund plant (37,573 m^2 solar collectors and 60,000 m^3 PTES), the Vojens plant (70,000 m^2 solar collectors and 200,000 m^3 PTES) and the Gram plant (44,801 m^2 solar collector and 120,000 m^3 PTES) (PlanEnergi 2016).

Thermal behaviors of water pits have been investigated both experimentally and theoretically. Kielsgaard Hansen et al. (1983) investigated for the first time a small 500 m^3 pilot water pit heat storage at the campus of the Technical University of Denmark. Later, Kübler etc. (1997) presented investigations on a pilot heat storage of about 600 m^3 volume built in Rottweil. The pilot heat storage was applied as short term storage in connection with a combined heat and power (CHP) plant. The storage container was made of concrete with a stainless steel liner and mineral wool as insulation. The aim of the paper was to demonstrate the feasibility of the technology and to gain practical experience for the construction of larger stores. A gravel /water storage pit was built in Steinfurt, Germany (Pfeil M.

doi:10.18086/swc.2017.06.05 Available at http://proceedings.ises.org

2000). The ecological compatibility of the used materials in the storage was proved. Another focus of the paper was analysis of the cost-reduction potential of the PTES (Pfeil M. 2000). Thermal behavior of a model PTES was experimentally investigated in a test rig and numerically investigated by means of CFD simulations (Chang and Wu, 2017). The investigated PTES was a scaled down model that facilitates measurements on a test rig. However experimental investigations on thermal behaviors of large solar district heating plants in real operation were not found.

Theoretical investigations were carried out to gain knowledge and to optimize thermal performances of solar heating plants. Trnsys (Trnsys 2016) is used to calculate performance of a combined solar thermal and ground source heat pump (HP) system and to investigate different operation strategies of the system (Li H., 2018). Tian et al. investigated thermal performance of a solar heating plant with combined parabolic trough collectors and flat plate solar collectors. The focus of the investigation was on thermos-economic analysis of the plants with different types of collectors connected in series (Tian Z., et al. 2018). Cioccolanti et al. investigated performance of a solar trigeneration system for residential applications by means of a modelling study. The potential of a small scale concentrated solar Organic Rankine Cycle (ORC) plant coupled with an absorber was investigated using a Trnsys simulation analysis of a small scale 50 m^2 CPC solar field, a 3.5 kWe ORC and a 17.6 kWc absorption chiller to satisfy respectively heating, electricity and cooling needs of a residential user (Cioccolanti L., et al. 2018). However there is a lack of theoretical investigations on large scale solar heating systems with PTES.

The aim of the paper is to investigate thermal behaviors of the Marstal solar heating plant. The operation of the solar heating plant was monitored in detail in the period 2014-2016. Temperatures and fluid volume flow rates of the solar collector fields, the PTES storage, the heat pump and the district network were measured constantly. Energy flows in the plant were analyzed. A Trnsys (Trnsys 2016) simulation model of the solar heating plant is developed to investigate thermal performances of the plant. The calculated energy flows will be compared to the monitored energy flows with an aim to validate the simulation model. The Trnsys model could be used to optimize design of a solar heating plant under different scenarios in terms of levelized cost of heat (LCOH).

2. Monitoring of the plant operation

As shown in Table 1, the Marstal solar heating plant (Fig. 1) has been under continuous developments throughout the years. During the Sunstore 1 project in 1996, a 9045 m^2 solar collector field was installed with 12.53 m^2 large flat plate solar collectors produced by ARCON A/S. Additionally a 2100 m^3 accumulation tank was built as short term storage. Due to an increase of consumers of the solar heating plant, the Sunstore 2 project was introduced in 2001-2004 in which flat plate solar collectors of 8019 m^2were added in the plant. Heat produced by the collectors installed in Sunstore 1 and 2 is fed in the 2100 m^3 accumulation tank.

In 2012 the SUNSTORE 4 project was built. 15,064 m^2 solar collectors were installed and a 75,000 m^3 PTES was constructed, see Fig. 1. The aim of the Sunstore 4 project was to increase the solar fraction of the plant up to 55% of the thermal energy production, focusing on sustainability, increased efficiency and low costs. Marstal's 75,000 m^3 PTES was commissioned in 2012 and it has a capacity of 6.96 GWh according to PlanEnrgi (Jensen 2014). Heat produced by the collectors installed in the Sunstore 4 is fed in the 75,000 m^3 PTES. The operating temperatures vary depending on the season and the depth of the water layer, however the pond is designed to operate in a range of 10-90 °C. An electricity generator based on ORC and a CO_2 heat pump were added in the plant. The Organic Rankine Cycle (ORC) uses heat at around 300ºC produced by a wood chip boiler to generate electricity. The CO_2 heat pump utilizes heat from the water pit heat store as heat source to provide heating for the district heating network.

Detailed measurements were carried out in the period 2014-2016 to evaluate thermal performances of the plant. Temperatures and fluid volume flow rates of the solar collector fields, the PTES storage, the heat pump and the district network were measured constantly. The sensors in the inlet/outlet pipes of the PTES are located at the end of the transmission pipes 300 m away from the pit storage. Thirty-three temperature sensors were installed in the middle of the water pit storage to measure water temperatures at different levels. The volume flow rate is measured with flow meters in m^3/h with an accuracy of 2% (Schmidt 2013). The temperature sensors are PT resistance thermometers with an accuracy of +/- 0.1 K (Schmidt 2013).

Fig. 1: Bird view of the Marstal Solar heating plant

Tab. 1: Components of the Marstal solar heating plant

Sunstore 1	- 9,045 m^2 field consisting of arrays of 12.53 m^2 Arcon HT collectors (Collector field 1)
Sunstore 2	- 8,019 m^2 field consisting of arrays of 12.53 m^2 Arcon HT collectors (Collector field 2) -
Sunstore 4	- 15,064 m^2 field consisting of arrays of 13.88 m^2 Sunmark solar collectors (Collector field 3)
Other utilities	- 2,100 m^3 accumulation tank (Sunstore 1 & 2) - 75,000 m^3 water pit thermal storage (Sunstore 4) - 1,500 kW (produced heat) CO_2 heat pump - 4.15 MW wood chip boiler that runs a electricity producing Organic Rankine Cycle with a power of 750 kW

3. Dynamic simulations of plant thermal performances

A Trnsys model of the Marstal solar heating plant was developed in the Sunstore 4 project (Kate 2013). The Trysns model was modified in this paper to accommodate changes in the system, see Fig.2. The Trnsys model includes three solar collector fields with a total solar collector area of 32,138 m^2, an accumulation tank of 2100 m^3, a seasonal water pit heat storage of 75,000 m^3, a simplified CO_2 HP, a simplified ORC unit and a wood chip boiler. The energy consumption of the district heating net was modeled by volume flow rates and given forward & return temperatures of the district heating net. Forward temperatures of the district heating net are 72-74ºC in summer and 75-77ºC in winter. Temperatures of the fluid back to the plant vary in the range 33-41ºC from summer to winter. Weather data including total solar irradiance, diffuse solar irradiance and ambient air temperature from a climate station on the site of the plant were used in the calculations. In order to eliminate influence of initial conditions of the water pit heat storage, calculations were repeated for 2 years with a time step of 1 hour. Result from the 2nd year was used in the analysis.

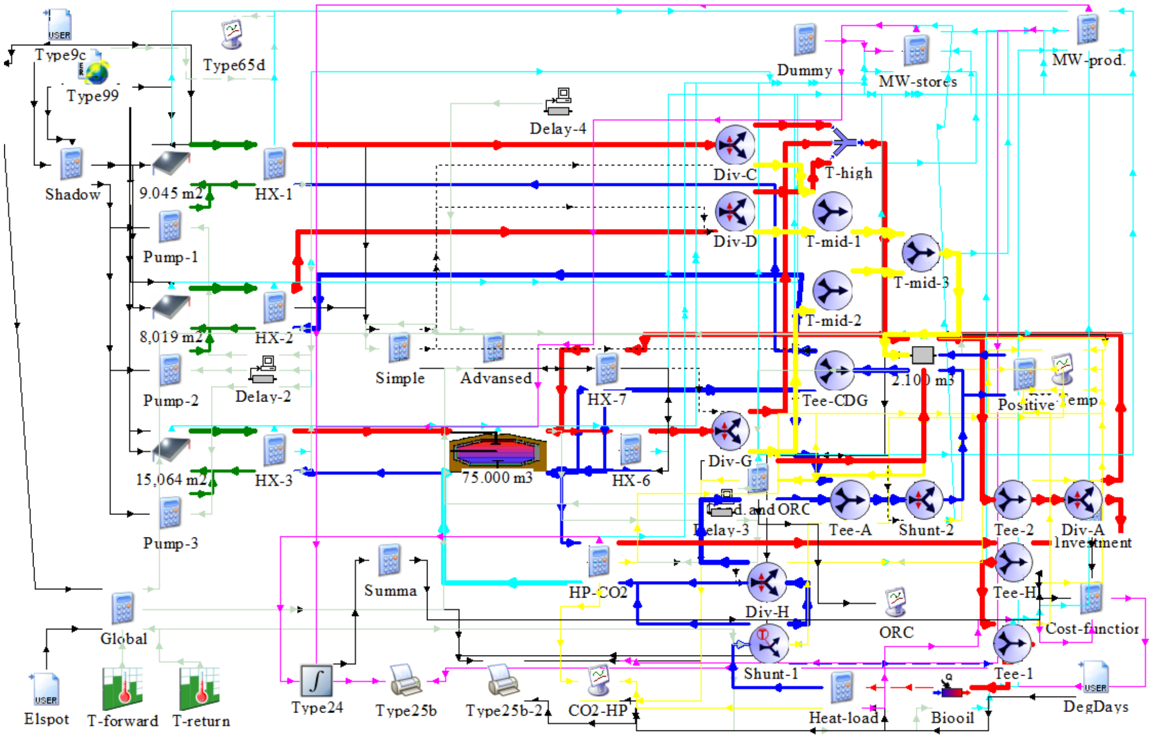

Fig. 2: The Trnsys model of the Marstal Solar heating plant

In the solar collector field model developed in Trnsys, parameters such as coefficients of the collector efficiency expressions, collector area, collector orientation, collector inclination and number of collectors per row are used as inputs. The following collector efficiency expression is used in the model.

$$\eta = \eta_0 K_\theta - \frac{a_1 (T_m - T_a)}{G} - \frac{a_2 (T_m - T_a)^2}{G} \qquad \text{(eq. 1)}$$

η_0: the start or the maximum efficiency, [-].
a_1: the first order heat loss coefficient, [W/(m^{2}K)].
a_2: the second order heat loss coefficient, [W/(m^{2}K^2)].
K_θ: incidence angle modifier, [-].
G: the total solar radiation, [W/m^2]
T_m: the mean temperature of the solar collector [ºC]
T_a: the ambient air temperature [ºC]

Table 2 show the coefficients of efficiency expressions for the collectors used in the solar collector fields. Collector efficiency for the collector field 1 is taken from a test report issued in 1991 (Fan etc., 2009). Collector efficiency expression of the collectors in the collector field 2 was reported by Vejen (2004). In the collector field 3, 13.88 m^2 flat plate solar collectors produced by Sunmark were installed. Efficiency of the collector was tested by SP Technical Research Institute of Sweden (2010).

Tab. 2: Collector efficiency expressions used in the Trnsys simulations

Collector field no.	Area, m2	η_0, -	a_1, W/(m^{2}K	a_2, W/(m^{2}K^2)
1	9045	0.76	3.5	0.002
2	8019	0.82	2.44	0.005
3	15064	0.80	3.43	0.015

The water pit thermal storage was modeled in Trnsys with a 2D multi-node storage model that includes both the water volumes at different layers and the ground soil around the storage. The Trnsys calculations starts with an uniform temperature of 35ºC for the store as the initial condition. Initial temperature of the ground was 8ºC.

Yearly thermal performances of the solar heating plant calculated by the Trnsys model were compared to the measurement results. Preliminary results calculated by the Trnsys model were analyzed.

4. Thermal performances of the solar collector fields

4.1 Analysis of the collector fields by the input/output method

Thermal performance of the solar collector fields were calculated by the Trnsys model with a time step of 1 hour. Fig. 3 shows the collector energy output of the solar collector field 1 in kWh/m^2/day as a function of the total solar radiation in kWh/m^2/day. It can be seen in Fig. 3 that there is a 2nd order polynomial function between the modeled collector field output and the total solar radiation on the collector panels. This is in good agreement with the collector efficiency expressions used in the calculations. The modeled outputs are however a bit scattered, which means that for the same total solar radiation on the collector panel the collector energy outputs are different. A possible explanation could be the varying collector fluid temperatures during operation. Even though there is the same total solar radiation on the panel the collector fluid temperature might vary depending on temperatures of the storage. A higher temperature of the storage means a higher temperature at the inlet of the collector field and thus a lower energy output of the field, vice versa. The measured collector outputs have a much larger deviations, most likely due to differences in collector operating temperatures and/or failures in operations of the systems. For instances there were some days with a daily total solar radiation in the range 3.5-5.5 kWh/m^2/day, however the collector outputs of the field were almost zero, indicating there was a failure or interruption in the collector field operation. There are also points with a significantly lower collector energy output than the modeled values, which could be caused by differences in collector inlet temperatures, uneven flow distribution among collector rows or malfunction of the controller etc. For the days when the collector field was in a good operation condition, the collector energy output follows nicely the trend with the simulations.

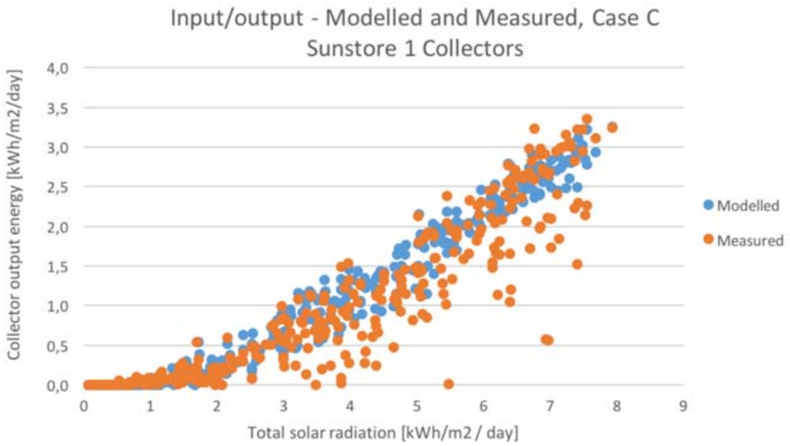

Fig. 3: Input/output diagram for the Sunstore 1 collector field with collector output [kWh/m^2/day] in 2015 as a function of total solar radiation [kWh/m^2/day]

The modeled and the measured collector energy output for the collector field 2 are shown in Fig. 4. There is a similar trend between the modeled collector energy output and the total solar radiation on the collector surface as it is for the collector field 1. With a change of the total solar radiation, the measured collector field output follows nicely a similar trend line as the modeled output does. The measured output has deviations of similar magnitude as the calculations. It is indicated that the solar collector field 2 has a much steadier operation than the solar collector field 1. It is shown that the solar collector model used in Trnsys is able to predict thermal performances of the solar collector fields with an acceptable accuracy.

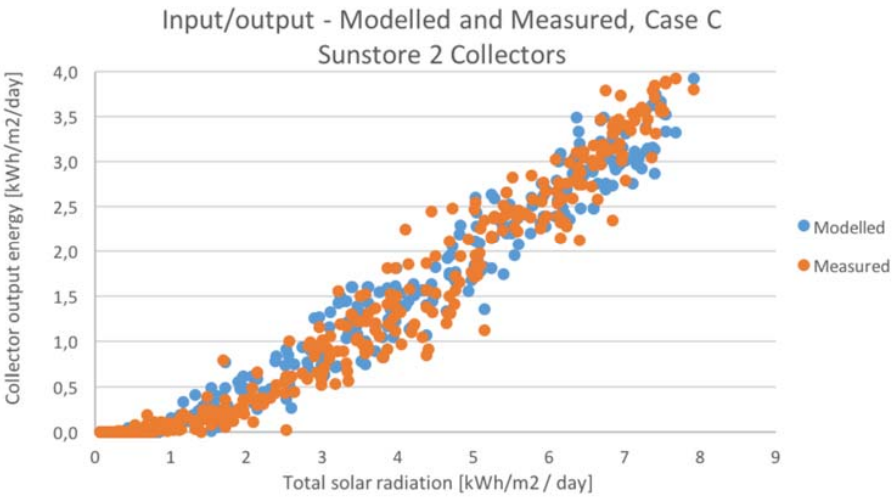

Fig. 4: Input/output diagram for the Sunstore 2 collector field with collector output [kWh/m²/day] in 2015 as a function of Total solar radiation [kWh/m²/day]

Fig. 5 shows the modeled and the measured collector energy output for the collector field 3 installed in the Sunstore 4 project. There is a similar trend between the modeled collector energy output and the total solar radiation on the collector surface as for the collector field 1 and 2, but the deviations of the data points are much larger. That indicates larger variations of collector field output for the same total solar radiation, which could be caused by large temperature variations at the bottom of the water pit thermal storage. Since the collector field 4 is connected to the water pit thermal storage, water is taken from the bottom of the water pit and is circulated through the solar collector field 4. Water temperature at the bottom of the water pit has a larger variation throughout the year. In summer or autumn when the water pit is almost fully charged, there is a higher temperature at the bottom of the water pit, for instance, 40-50ºC, while in spring or winter when the water pit thermal storage has been discharged, there is a lower temperature at the bottom of the water pit, for instance, 20-30ºC. A temperature difference of 20 K or more will result in different collector energy outputs even though the total solar radiation on the collector panels is the same. Deviations of similar magnitudes are also seen in the measured collector output that proves conclusion of the simulations. A detailed investigation on individual days is therefore necessary in the future in order to understand thermal behaviors of the solar collector field.

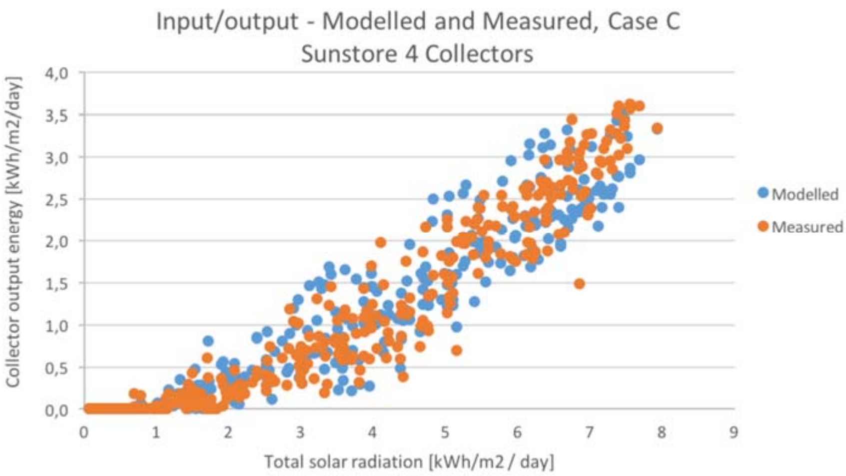

Fig. 5: Input/output diagram for the Sunstore 4 collector field with collector output [kWh/m²/day] in 2015 as a function of Total solar radiation [kWh/m²/day]

4.2 Daily collector energy outputs throughout the yearly

It is important to examine thermal behaviors of the collector fields throughout the year. Fig. 6 shows the measured and the calculated collector outputs [kWh/m²/day] throughout the year for the Sunstore 1 Collectors. Not surprisingly there is a large variation of collector energy output throughout the year. At the start of the year, there was almost no solar heat produced by the field. After the middle of March, a significant increase of collector output is seen due to increasing solar irradiance in late spring. Throughout the summer and even late autumn there are notably solar heat gains. The daily energy output of the collectors lies in the range 0.5-3.0 kWh per m^2. The calculated energy output agrees quite well with the measured ones, except an overestimation of the model occasionally in the summer and in the autumn (October).

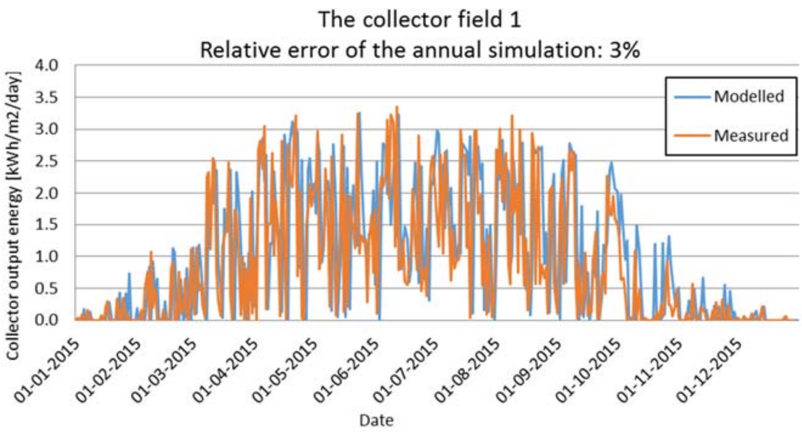

Fig. 6: The measured and the calculated collector outputs [kWh/m2/day] throughout the year 2015 for the Sunstore 1 Collectors

The measured and the calculated collector outputs for the collector field 2 and 3 are shown in Fig. 7 and 8 respectively. The Trnsys collector model predicts satisfactorily the energy outputs from the solar collector fields.

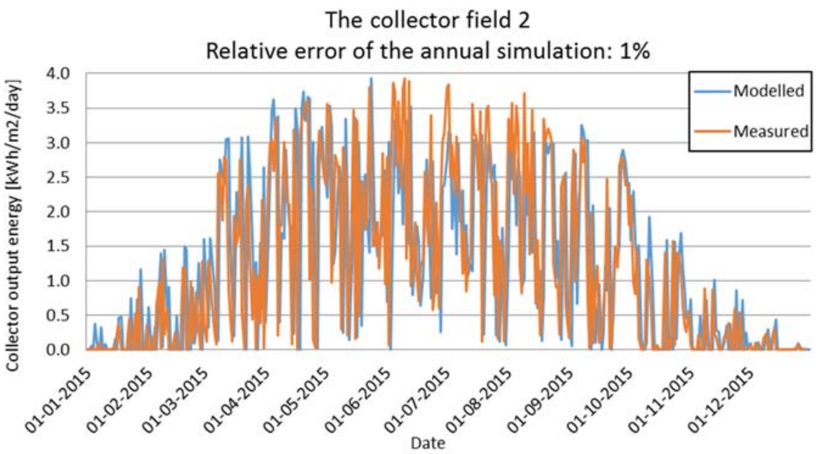

Fig. 7: The measured and the calculated collector outputs [kWh/m2/day] throughout the year 2015 for the collector field 2

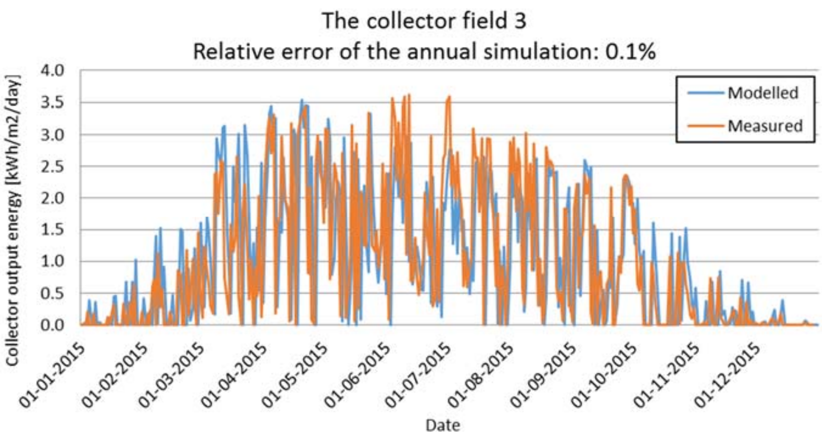

Fig. 8: The measured and the calculated collector outputs [kWh/m2/day] throughout the year 2015 for the collector field 3

4.3 Yearly collector energy outputs

The energy outputs of the collector fields are summarized and presented in Fig. 9. It is shown that the yearly energy outputs of the solar collector fields predicted by the Trnsys model agree well with the measured values. For the solar collector field 1, the Trnsys model predicts a yearly energy output of 3320 MWh in comparison to a measured value of 3430 MWh. The deviation is 110 MWh, corresponding to a relative error of 3%. For the solar collector field 2, the accumulated energy output is measured to be 3617 MWh per year, while the Trnsys model calculates an energy output of 3600 MWh per year with a deviation of less than 1%. For the solar collector field in Sunstore 4, the measured and modeled energy outputs are respectively 5620 and 5624 MWh. Heat losses through the connection pipes account for 5-10% of the energy gain of the field and are therefore subtracted in the energy calculations. It can be concluded that the Trnsys model can predict satisfactorily the yearly energy outputs of the solar collector fields.

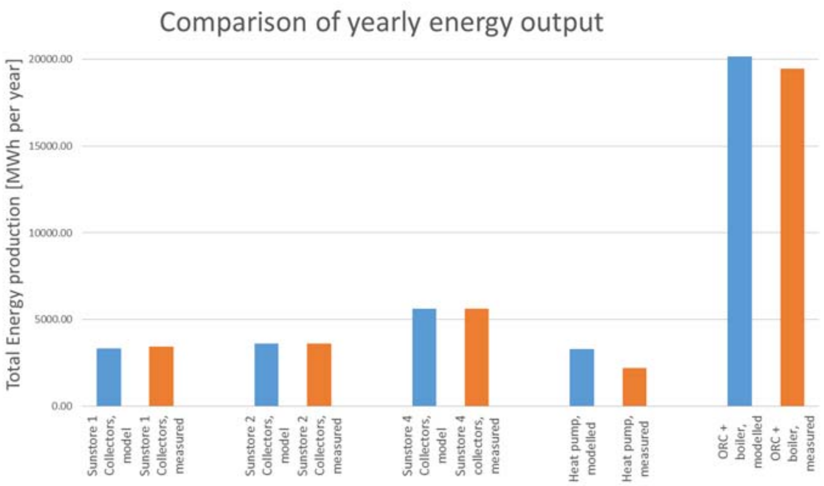

Fig. 9: The measured and the calculated yearly collector outputs in 2015 [kWh/m²/day]

5. Thermal performances of the water pit thermal storage

Thermal behaviors of the water pit thermal storage were investigated experimentally by the monitored data and numerically by the Trnsys model. Fig. 10 shows a comparison of the measured and the calculated charge power of the PTES. A charge power of up to 55 MW was observed in the measurement in the middle of June because in June 2015 there was a lower consumption in the district heating net while on the other hand the solar irradiance was quite high. The Trnsys model underestimates the charge power of the PTES with a difference up to 12 MW. The significant error of the model is most likely caused by wrong prediction of water temperatures in the PTES, which could be a consequence of oversimplified models used in the calculations. Detailed investigation is therefore suggested for the future to identify the cause of errors. During the winter when there is a low solar irradiance, the model seems to overestimate the charge power.

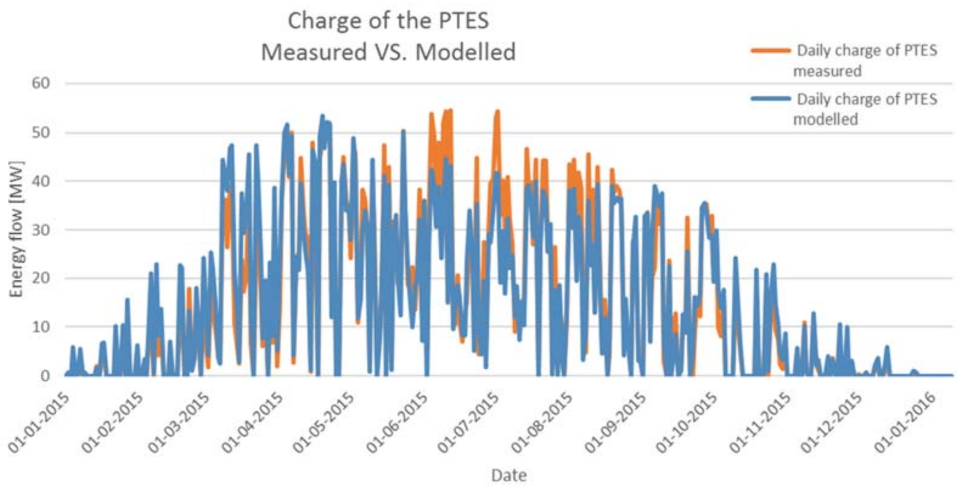

Fig. 10: The measured and the calculated charge power of the PTES in 2015

Fig. 11 show the measured and the modeled temperatures in the water pit thermal storage throughout the year. The measured temperature were shown as square or triangle dots. At the start of the year, there was a measured temperature of 62ºC at the top of the PTES, while the temperature was measured to be around 30ºC at the bottom of the PTES. Since there was a quite high temperature at the top of the PTES, heat was directly taken from the top of the PTES and was mixed with hot water produced by the wood chip boiler or the backup oil burner so a mixed temperature of around 75-77ºC can be achieved for the district heating net. The direct discharge of the PTES continues except when temperatures at the top of the PTES drops below 50-55ºC or when price of electricity is sufficiently low. In that case, the heat pump will operate in order to utilize heat in the PTES with medium or low temperatures. The operation of the heat pump created a sudden decrease of temperatures at the bottom of the PTES. For instance, in the period from March 14 to March 21 there was a significant decrease of water temperatures at the bottom of the PTES. Due to discharge by heat pump, water temperatures at the top of the PTES was significantly decreased as well. In the middle of April the PTES reached a uniform temperature of 31-33ºC. After the middle of April thermal stratification was built up again by the use of heat pump since temperature of the water flowing from the heat pump back to PTES was much lower than 30ºC. The strategy for the discharge procedure was to extract heat from the PTES as much as possible. The benefit of the use of heat pump in April was not only a higher utilization ratio of the stored heat but also an empty PTES to store more solar heat for the coming summer. After the middle of May, temperatures in the store gradually increased. At the start of October, the PTES reaches the highest heat content. In the period October-December water temperatures in the store were kept quite constant.

The Trnsys modeled store temperatures were shown in curves in Fig. 11. It can be seen that the modeled temperatures follows the trend of developments as shown by the measurements. However there is quite a large difference between the modeled and the measured store temperatures, especially after the middle of April when heat pump cooled down the whole store to much lower temperatures. The likely cause of the difference could be oversimplification of the heat pump model or the control algorithm used in the Trnsys calculations. For an example, the operation of ORC unit has a significant influence on temperatures of the store since the ORC unit will be cooled by the store if there is not sufficient consumption of the district heating net. Whether the ORC unit will operate or not depends on an economical analysis of electricity generation by the manager of the plant. A detailed decision making algorithm for operation of ORC was difficult to obtain so the Trnsys model was not able to accurately determine the operation time of the ORC unit.

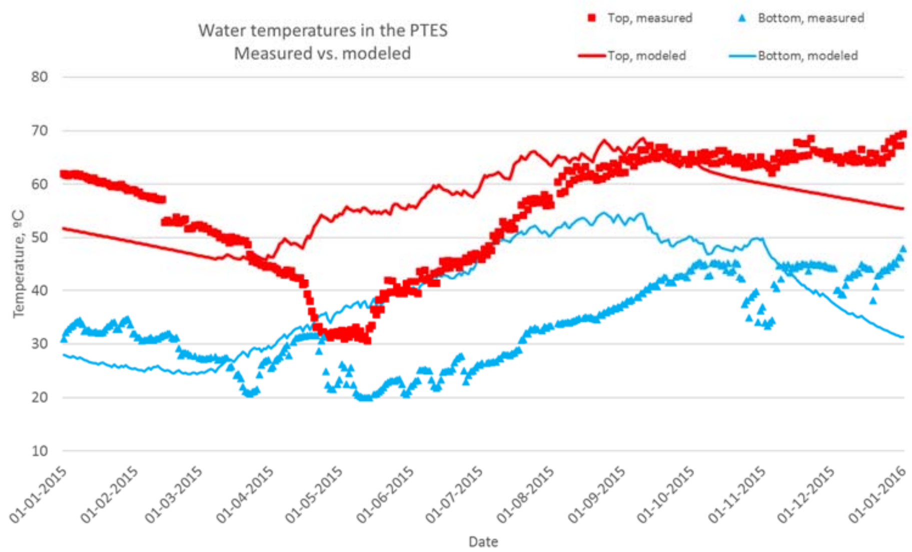

Fig. 11: The measured (orange) and the modeled (blue) temperatures through the top inlet/outlet on an hourly basis during year 2015

6. Conclusions

Detailed measurements were carried out on the Marstal solar heating plant. Based on the measurements, energy flows in the plant were calculated and thermal performance of the plant was analyzed. The monitored energy flows were compared to the energy flows calculated by a simplified Trnsys model of the plant. Preliminary results show that the Trnsys model predicts satisfactorily energy output of the solar collector fields. A max. deviation of 3% between the measured and the modeled energy output of the field was observed. A comparison between the measured and the modeled water temperatures in the PTES shows that the Trnsys model is able to predict the trend of temperature development in the store but fails to reproduce temperatures of the store especially in the period May-August. A likely cause of the error could be oversimplified heat pump model, inaccurate plant control algorithm etc. Detailed investigation is therefore suggested for the future to improve the Trnsys model with focuses on the interaction between the heat pump, the ORC unit, the collector field and the store and on accurate inputs of boundary conditions of the model. The ultimate goal is to develop a Trnsys model that can be used to optimize design of a solar heating plant in terms of levelized cost of heat (LCOH).

7. References

Chang C., Wu Z., Navarro H., 2017, Comparative study of the transient natural convection in an underground water pit thermal storage, Applied Energy, 208, 1162-1173.

Cioccolanti L., Tascioni R., Bocci E., et al. 2018, Parametric analysis of a solar Organic Rankine Cycle trigeneration system for residential applications, Energy Conversion and Management, 163, 407-419.

Collector test report, 2010, SP Technical Research Institute of Sweden, SP 509301.

Fan J., Chen Z., Furbo S., Perers B., Karlsson B., 2009, Efficiency and lifetime of solar collectors for solar heating plants, ISES Solar World Congress 2009. Johannesburg, South Africa, p. 331-340

Jensen M.V., 2014. SUNSTORE ® 4 Design of the Water Storage The SUNSTORE Plant in Marstal. In Sunstore 4 Design of the Water Storage.

Kate D. Sunstore4. http://sunstore4.eu/, 2013. [Online; accessed 01-04-2017].

Kielsgaard Hansen, K., Nordgaard Hansen, P., Ussing, V., 1983. Seasonal heat storage in underground warm water stores. Report 134, Thermal Insulation Laboratory, Technical University of Denmark.

Kübler R., Fisch N., Hahne E., 1997, High temperature water pit storage projects for the seasonal storage of solar energy Journal, Solar Energy, 61, 97-105.

Li H., Xu W., Yu Z., et al. 2018, Discussion of a combined solar thermal and ground source heat pump system operation strategy for office heating, Energy and Buildings, 162, 42-53.

Lund, H., Werner S., Wiltshire R. etc. 2014, 4th Generation District Heating (4GDH) - Integrating smart thermal grids into future sustainable energy systems, Energy, 68, 1-11.

Nussbaumer T., Thalmann S., 2014, Status report on district heating systems in IEA concountries, Zurich, Switzerland, ISBN 3-908705-28-2.

Pfeil M., Koch H., 2000, High performance-low cost seasonal gravel/water storage pit, Solar Energy, 69, 461-467.

PlanEnergi, 2016, Long term storage and solar district heating, a presentation of the Danish pit and borehole thermal energy storages in Brædstrup, Marstal, Dronninglund and Gram, https://ens.dk/sites/.../sol_til_fjernvarme_brochure_endelig.pdf

Schmidt T., 2013. Sunstore 4 Technical Reports: Design of the measurement and evaluation program.

Tian Z., Perers B., Furbo S., et al., 2018, Thermo-economic optimization of a hybrid solar district heating plant with flat plate collectors and parabolic trough collectors in series, Energy Conversion and Management, 165, 92-101.

Trnsys, 2016. Trnsys Manual 17.0, LLC 22 North Carroll Street – suite 370 Madison, WI 53703 – U.S.A.

Vejen N.K., Furbo S., Shah L.J., 2004, Development of 12.5 m² Solar Collector Panel for Solar Heating Plants Solar, Energy Materials and Solar Cells, 84, 205-223.