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Optimizing Efficiency of Biomass—Fired Organic Rankine Cycle with Concentrated Solar Power in Denmark

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Abstract

A first of its kind concentrated solar power (CSP) installation has been integrated together with a biomass heat and power (CHP) plant using an organic rankine cycle (ORC) unit. The plant has been deployed in the northern part of Jutland in Denmark, right next to the city of Brønderslev. The plant has been supplying heat to the local district heating network since the end of 2016. Aalborg CSP has developed and built the CSP plant consisting of parabolic trough collectors with an aperture reflecting area of 26,920 m^2. The CSP plant is able to deliver 16.6 MWth at its peak while it can supply the district heating or the ORC with approximately 16,000 MWh of heat annually. This paper serves as a description of the technical aspects of the system with specific focus on the CSP field as well as present the first measured performance from the Summer of 2017.

Keywords: Solar Energy, Concentrated Solar Power, CSP, Concentrated Solar Heat, CSH, Solar-Thermal, Integrated Energy System, Organic Rankine Cycle, ORC, Biomass

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1. Introduction

Solar energy is abundant and increasingly utilized in domestic systems to supply space heating and cooling. However, over the last couple of decades the world energy demand has increased dramatically due to both industrial growth and population increase.

1.1 Concentrated Solar Power in Denmark

Concentrated solar power (CSP) plants have so far mainly been built to produce electricity for export to the grid, however, numerous advantages have been identified in industrial setting as well. Due to the technology's flexibility to produce high and mid temperature heat, it provides an ideal solar-thermal solution for industrial purposes. Parabolic trough CSP plants are typically found in countries around the solar belt, but economic viability has also been proven in a place with limited solar resources, in Denmark, where efficiency of the system was monitored and compared with flat solar-thermal panels. The report concluded that CSP produces more energy per square meter above 50 °C, provides a better economy over the system's 25-years lifetime and ensures a year-round energy production even in Nordic climate conditions compared to flat panel systems [1]. It has also be seen that even when operating in higher temperature the parabolic trough collectors maintain a high heat yield per square meter or aperture area [2], [3]. That is because the heat is concentrated in a central receiver tube enclosed in a vacuum glass envelope.

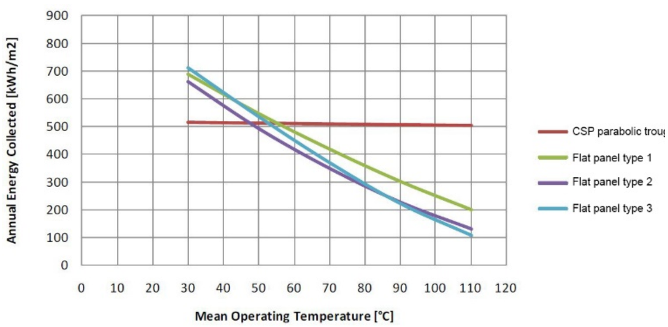


Figure 1: Parabolic trough collector performance vs. flat plate collectors in low heating temperatures

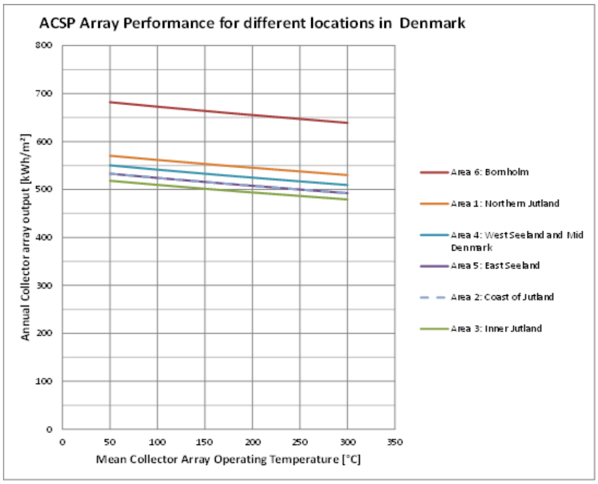


Figure 2: Parabolic trough collector performance in different Danish regions and high temperatures [3]

2. Technology description

2.1. Parabolic Trough Collectors (PTC)

The parabolic troughs reflect the rays of the sun onto a receiver pipe filled with heat transfer fluid. The receiver pipe is located in the central focal point of the troughs. In the receiver pipe, the fluid is heated up and pumped into the heat consumer.

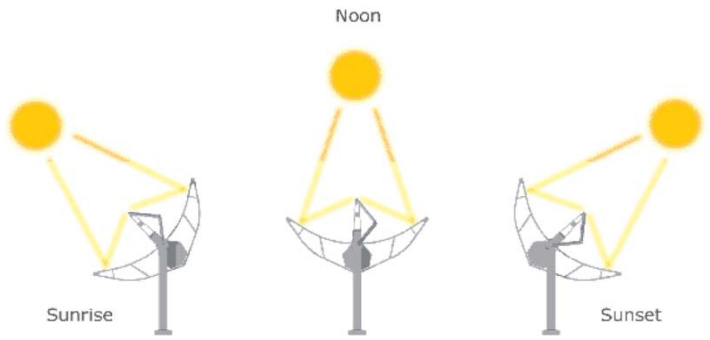


Figure 3: Sun tracking technology enabling the parabolic troughs to follow the sun's position throughout the day

The CSP technology is the most effective solar heating method for high temperature ranges. The parabolic troughs has a special glass vacuum tube guaranteeing some of the markets lowest heat losses thus providing stable energy production even at middle temperatures as the receiver pipe has very low heat losses to the ambient.

The parabolic trough uses a custom–made sun-tracking technology, where a computer calculates and calibrates the troughs into the required position to receive optimal radiation throughout the day. The sun-tracking technology achieves a very high efficiency per m^2 of aperture mirror area, thereby optimizing the use of land intended for technology placement. The PTCs track and follow the sun in a tracking window of ± 0.15° from the present solar position. The rotation is ensured by a gear and a hydraulic system.

2.2. The system

In December 2016, a world first CSP plant went into operation in the northern part of Denmark (town of Brønderslev). The plant's uniqueness lies in the fact that it was designed to be integrated with a biomass-fired Organic Rankine Cycle (ORC) which is currently still under the last stages of commissioning. This combined solution is the first large-scale system in the world to demonstrate how CSP, with an integrated energy system design can optimize efficiency of ORC even in areas with less sunshine, in this case Denmark.

Figure 4: Image of the concentrated solar power plant in Brønderslev, Denmark

Figure 5: Top view of the solar field layout

Figure 6: Photo of the AAL-Trough™ 3.0 model - third generation of Aalborg CSP's parabolic trough technology

The solar energy plant was delivered by Danish renewable energy specialist Aalborg CSP, and it is based on the company's own CSP parabolic trough technology, also called the AAL-Trough™. The plant consists of 40 rows of 125m U-shaped mirrors with an aperture area of 26,929 m^2. These 40 rows are divided in 10 loops. Each loop has an inlet and outlet connection to the main pipe, meaning that the cold thermal oil will flow through 4 rows (i.e. 500m) until it gets the right temperature and finally leaves the loop. In order to fit within the land boundaries the loops where bended into half, saving cost for extra piping at the same time. As seen in Figure 5 the solar field is tilted 29^o from the North-South axis due to specific land availability.

The curved mirrors collect the sunrays throughout the day and reflect them onto a receiver pipe, which sums up to 5 kilometer receiver tubes. This receiver pipe is surrounded by a special glass vacuum tube and inside this runs - only heated by the sun - thermal oil with temperatures up to 312 °C. This high temperature is able to drive an electric turbine to produce electricity, but the flexibility of the system also allows production of lower temperatures for district heating purposes. The solar heating system can thus alternate between providing heat and power or deliver heat exclusively. To maximize yield of energy, the waste heat is utilized and sent to the district heating circuit whereas electrical power is generated at peak price periods.

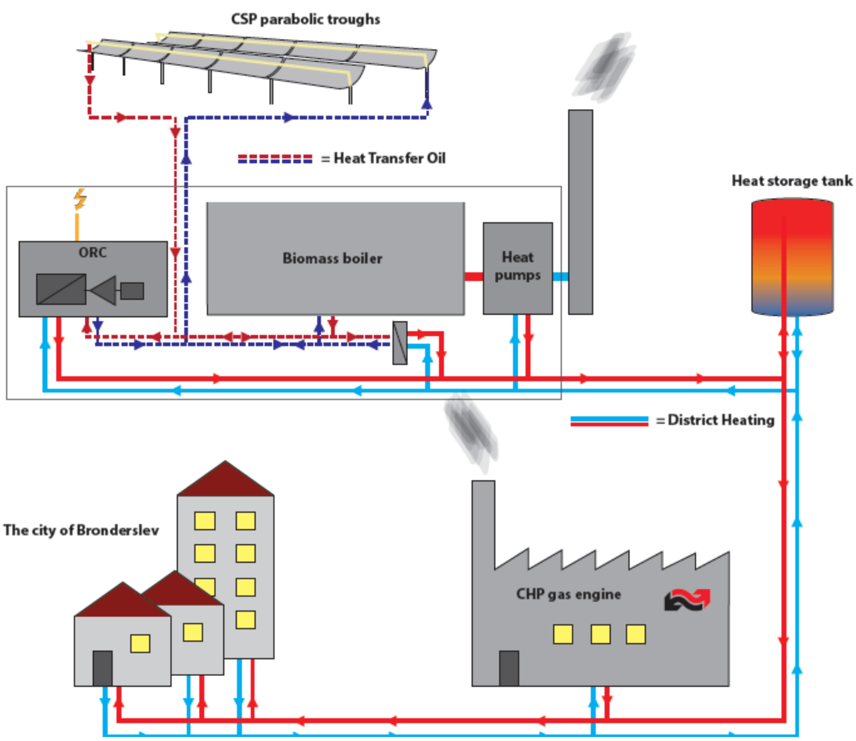


Figure 7: Flow chart of the energy distribution at the hybrid plant of Brønderslev

In Figure 7, it can be seen that the CSP field is delivering hot thermal oil to both the ORC unit and the oil-to-water heat exchanger which delivers the heat to the district heating network to the city of Brønderslev. The CSP solar field has a thermal peak effect of 16.6 MWth and is expected to deliver approximately 16,000 MWh of heat in an average weather year.

Apart from the solar field, there are two biomass boilers each of a maximum capacity of 10 MWth running with wood chips as fuel.

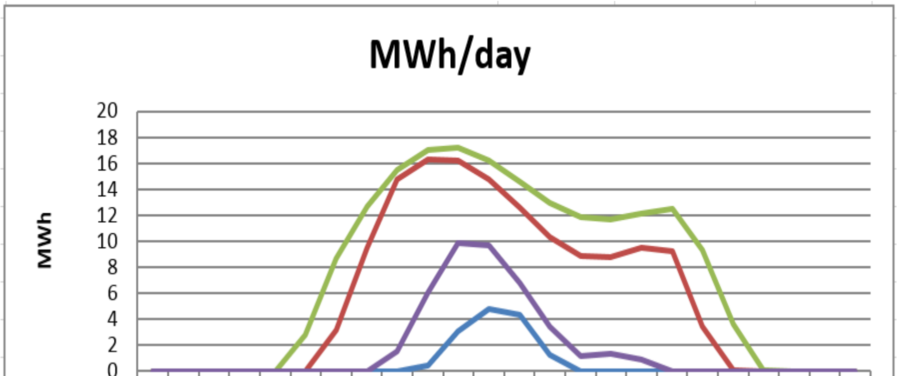
Both the CSP field and the biomass boilers are working in conjunction to supply with sufficient heat the ORC unit, which in full load is supposed to deliver 4MWe. The dissipated heat from the ORC condenser is used to provide additional heat to the district heating network. Therefore, one might notice that the hybrid system is designed in a sustainable and efficient way, avoiding to unnecessarily waste heat to the ambient. The biomass boiler house embeds a 2 MWth heat pump as well, to make use of waste heat from the biomass chimney and supply the district heating as supplementary source. In order to guarantee that the total energy demand is covered at any time, a CHP gas engine is placed as final backup

The achievement of the world's first CSP system combined with a biomass-ORC plant is supported by the Danish Government's Energy Technology Development and Demonstration Programme (EUDP).

3. Monitoring and validating performance during the first solar season

As aforementioned, the peak performance of the plant is set to reach 16.6 MWth and the annual yield is expected to be 16,000 MWh of thermal energy. Since the CSP-plant went into operation in the end of 2016, it has been meeting the expected operational goals.

In figure 8, the CSP performance in different seasons is illustrated. It is interesting to see that the time moves from Summer to Autumn, Spring and Winter the thermal power output curve shifts down. This is happening due to the lower solar altitude from month to month. As an example Figure 8 shows the expected thermal output for a day in January, April, July and October, based on an average weather year issued by the Danish Meteorological Institute [4]. Usually, when a PTC field tracking axis is not declining from the North-South axis then the profile of the thermal output curve has two symmetrical peaks (i.e. one in the morning and one in the afternoon). In the present case it should also be mentioned that the thermal peak in the morning hours is always higher than the one in the afternoon. This is explained from the tilted tracking axis in Brønderslev which deviates 29º from the North-South. Therefore, the optical losses are lower before solar noon, because of the lower incidence angle. The incidence angle is the angle in which the solar beams hit the surface of the reflecting mirrors in relation to the normal incidence. The lower the incidence angle is, the lower the optical losses are and thus the higher the thermal output is. The incidence angle of a day in May can be seen in Figure 9.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
21-01	0	0	0	0	0	0	0	0	0	0,4	3	4,8	4,4	1,3	0	0	0	0	0	0	0	0	0	0
21-04	0	0	0	0	0	0	3,1	9,5	15	16	16	15	13	10	8,9	8,7	9,5	9,2	3,4	0	0	0	0	0
21-07	0	0	0	0	0	2,8	8,7	13	15	17	17	16	15	13	12	12	12	12	9,4	3,6	0,1	0	0	0
21-10	0	0	0	0	0	0	0	0	1,6	6	9,8	9,7	6,8	3,5	1,1	1,4	0,9	0	0	0	0	0	0	0

Figure 8: Seasonal variation on CSP thermal power output curve

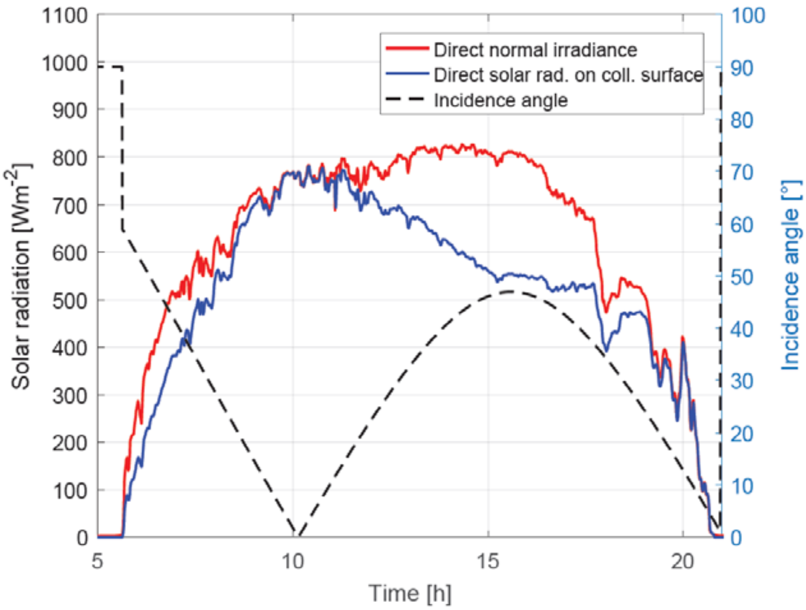


Figure 9: Incidence angle effect on thermal power output curve [2]

Figure 9 shows the effect of turning the tracking axis from exactly North South direction. The daily profile is then changed and may be adapted to the highest electricity price that at present often is in the mornings at around 8-10 [3].

The solar plant performance was monitored and cross checked during its first summer period from May 2017 to September 2017. Figure 10 illustrates the modeled versus the measured performance in kWh of heat produced per day and as it can be clearly seen the two series of data come in very good agreement when they get the same daily beam radiation as input.

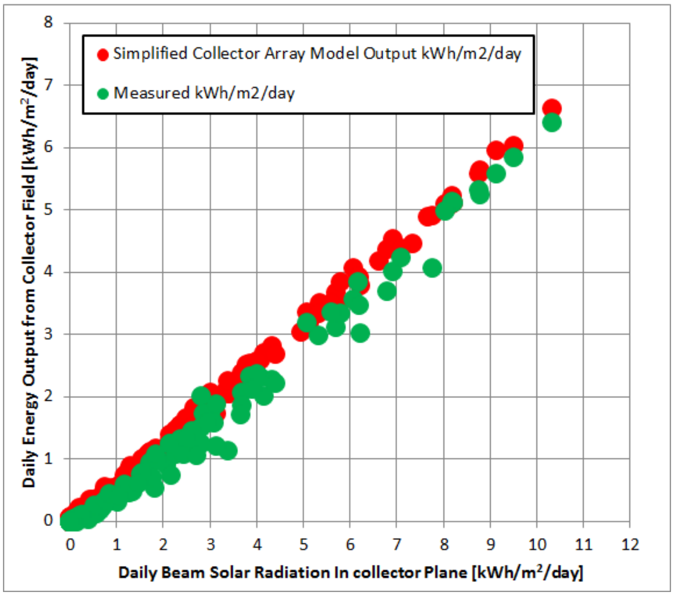


Figure 10: Validation of measured vs. computed performance for summer 2017, Perers et.al [3]

The same procedure has been followed and is presented here for a whole day of solar heat production in May. In Figure 11 the measured and calculated thermal performance of the field are presented with a yellow and a black line respectively and it becomes apparent that they are almost identical. All the heat produced by the field at that moment was delivered to the district heating network. The monitored forward water temperature to the district heating grid was also in very good agreement with the calculated one and averaging at around 80ºC. With blue and red, the measured and calculated outlet temperature of the thermal oil is shown to be peaking at around 180ºC. At that moment the ORC unit was still under construction and there was not need to operate at a higher temperature than that.

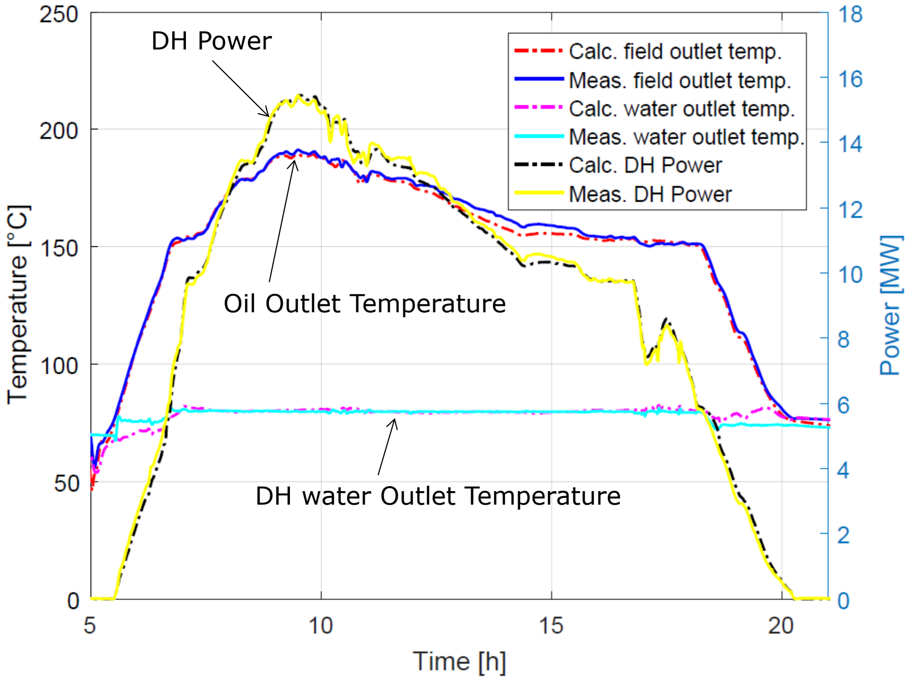


Figure 11: Measured and calculated performance of solar field [3].

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