Evaluation of Measurements on Parabolic Trough Collector Fields for Process Heat Integration in Swiss Dairies

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Abstract

Measurements from two solar process heat plants in Switzerland have been evaluated, both equipped with similar types of parabolic trough collectors. The analysis focusses on the description of the plants and the presentation of the performance of the collector fields. For this, both a daily evaluation of selected days is presented as well as a monthly evaluation is introduced where the energy delivery of the collector field is cumulated for each day and plotted against the cumulated direct irradiation on the one-axis tracked collector field aperture area.

Both plants have been integrated on the heat supply level aiming at solar fractions of about 7 % and 12 %, respectively. In the first plant (115 m² aperture area at an altitude of 1700 m), the collector field performance (the fraction of daily solar gains from total direct irradiation) reaches values in the range of 45 % already in April (spring time) providing outlet temperatures of about 190 °C. Due to high specific direct irradiation at this site, solar energy delivery higher than 500 kWh/d is reached (up to 4.8 kWh per m² aperture area have been measured).

In the second plant (630 m² at an altitude of 1000 m), the DNI is much lower (1183 kWh/m².a instead of 1881 kWh/m².a as in Bever). Although the design temperature of this plant is significantly lower, collector field performances did not yet reach higher values than the Bever plant. However, both the daily and the monthly evaluation presented in this paper show that the collector field performance can be high but the integration and control concept of the Saignelegier plant needs to be improved.

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1. Introduction

In Switzerland, a number of solar process heat plants (SPHP) have been realized during the last years, amongst them three with parabolic trough collectors. In this paper, two of them are described and analyzed. The two parabolic trough collector fields mentioned were set into operation in 2011 and 2012, delivering solar process heat for two dairies in Bever/Switzerland and Saignelegier/Switzerland. These two plants are equipped with similar collectors from the Swiss company NEP Solar. However, besides the locations also the collector field sizes, the design temperatures, the heat transfer fluids and the integration concepts are different.

Measurement data of the plants has been gathered and evaluated. This paper focusses on the analysis of the solar heat gain from the collector fields and the evaluation of the system behavior in general. The work presented is part of a Swiss National Research Project and the IEA SHC Task 49 on Solar Process Heat.

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2. Description of the solar process heat plants

2.1. The Bever Plant

The dairy in Bever/Switzerland is in the central alps at a latitude of 46.5506° and a longitude of 9.8897° N. Located 1712 meters above sea level, Bever has an alpine climate [1] with very low ambient temperatures in winter (down to -30°C in extremes), significant daily and seasonal fluctuations and comparably little rainfall. The average maximum snow depth is in the range of 0.9 m (measurements from the nearby location of Samedan, see [2]). The wettest month usually is August (average rainfall 108 mm) and the driest month has 41 mm average rainfall. The warmest month (July) has an average temperature of 11.4°C, the coldest (January) -9.2°C, the yearly average is 1.4°C.

The expected long-term annual DNI values (statistical data from Meteonorm [3]) is quite high (1881 W/m².a, see Fig. 1). When considering shading by the mountains at the exact location of the SPHP the global irradiance calculated with Meteonorm decreases by 3.4%. Summarizing, the site has similar annual DNI values like locations in southern France or Italy.

![Fig. 1. Map of long-term annual DNI values for Switzerland, © Meteotest (www.meteonorm.com). The indication of the Bever and Saignelegier locations have been added by the authors.](image)

In Bever, the collector type NEP Solar PolyTrough 1200 was used. The specifications are given in Table 1. The collector has been slightly adapted to the harsh conditions at the Bever site. In particular, the tracking device has been adapted to meet the requirements such as snow load and icing. Nevertheless, some failures occurred during the operation of the plant in winter (cf. [7]). Further investigations on the optical and thermal characterization and the collector efficiency in the SPF test lab have been described in detail by Rommel et al. [4].

<table>
<thead>
<tr>
<th>Collector</th>
<th>Collector length L in m</th>
<th>Aperture width W in m</th>
<th>Aperture Area A_c in m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEP Solar PolyTrough 1200 (Bever)</td>
<td>24.0</td>
<td>1.2</td>
<td>28.8</td>
</tr>
<tr>
<td>NEP Solar PolyTrough 1800 (Saignelegier)</td>
<td>20.9</td>
<td>1.85</td>
<td>36.9</td>
</tr>
</tbody>
</table>

The collector field consists of four collectors side by side which are hydraulically connected to two parallel strings with two collectors in series. The two serially connected collectors have a distance of 2.45 m, the distance between these two sub-fields is 3.42 m. The total aperture area of the collector field is \( A_c = 115.2 \text{ m}^2 \). The collector axis orientation is north-south with a deviation of 18.8° to east (following the geometry of the roof). The collectors had to be installed on concrete piles to avoid that the snow on the roof would block the tracking of the collectors in winter.
The dairy in Bever uses a steam network to provide heat for all processes from cleaning to pasteurization. An oil burner is used to supply steam with approximately 145 °C at 3.5 bar overpressure. The temperature and pressure in the steam net vary depending on the actual heat load. On the weekends the load is smaller but still some processes are applied so that almost always the solar heat can be used to supply steam to the net. The collector field has a nominal power of 70 kWth for the design outlet temperature of 190 °C. In the collector circuit thermal oil is circulated which is used to produce steam in a separate steam boiler. Whenever the steam reaches a temperature and pressure higher than in the steam network a valve opens and steam is supplied to the net. The integration concept is shown in Fig. 2. The collector field in Bever is expected to supply up to 60 MWh per year, corresponding to about 7 % of total annual heat demand.

Fig. 2. Integration scheme of the SPHP at a dairy in Bever/Switzerland, © Elektrizitätswerk der Stadt Zürich ewz.

2.2. The Saignelegier Plant

The dairy in Saignelegier/Switzerland is located in the Jura Mountain region at a latitude of 47.2614 O and a longitude of 7.0058 N. Located 992 meters above sea level, Saignelegier has a more moderate climate than Bever. The average maximum snow depth is in the range of 0.8 m (measurements from the nearby location of La-Chaux-de-Fonds, see [2]). According to [3], the monthly average rainfall ranges from 88 to 160 mm and is almost evenly distributed over the year (statistically a bit higher in summer). The warmest month (July) has an average temperature of 15.0 °C, the coldest (January) 0.0 °C, the yearly average is 7.6 °C. The yearly sunshine hours are in the range of 1700.

The expected annual DNI values (statistical data from Meteonorm [3]) is 1183 kWh/m².a, cf. also Fig. 1. At this site, there is no shading from mountains or buildings.

In Saignelegier, the collector type NEP Solar PolyTrough 1800 was used. The specifications are given in Table 1. Further investigations on this collector type in the SPF test lab are described in detail by Rommel et al. [5]. The collector field consists of 17 collectors in parallel, one collector having a length of 20.9 m. The distance between the collector axes is alternatively 2.98 m and 3.84 m (following the roof structure). This is a relatively close spacing of the collectors, with an average factor of collector aperture to roof area of 58 %. More typical would be 30..40 %. The effect of this closer collector spacing is slower heat up in the morning due to mutual shading and some loss of performance in the evening. The total aperture area of the collector field is 627.3 m². The collector axis orientation is north-south with a deviation of 25° to the west (again following the geometry of the roof). The collectors are mounted on steel beams directly integrated into the roof structure of the newly built extension building.

The dairy in Saignelegier uses an oil heated pressurized water network to provide heat for all processes. The maximum temperature of the net is 110 °C, the operation temperature 102 °C. The load profile is fairly constant throughout seven days per week. The collector field has a nominal power of 360 kWth for the design outlet temperature of 125 °C and 900 W/m² direct irradiance. In the collector circuit a water/glycol mixture is circulated which transfers heat to the net via a heat exchanger. The integration concept is shown in Fig. 3. Depending on the
actual load and the outlet temperature of the collectors, the solar heat can be used either to deliver heat directly to the processes, load the 15 m³ water storage or preheat the return flow of the oil burners (930 kW each). As in the Bever plant, the integration concept for the solar thermal system into the existing equipment had to aim at minimal adaption and process disruption. The total annual heat demand is approximately 2200 MWh of which the SPHP is expected to supply up to 12%.

Fig. 3. Integration scheme of the SPHP at a dairy in Saignelegier/Switzerland.

3. Measurements

Measurement data of the plants has been gathered and evaluated. This paper focusses on the analysis of the solar heat gain from the collector fields and the system behavior in general.

In both sites, Pt 100 temperature sensors have been installed at the inlet and the outlet of the collector field. An ultrasonic flow meter (Bever) and a vortex flow meter (Saignelegier) are used for flow rate measurements in the solar circuit. For mass flow calculation, the specific heat capacity of the fluids is determined using temperature dependent fits for the physical properties of the respective heat transfer fluids (HTF) and a temperature signal measured with an additional Pt 100 sensor located close to the flow meter. For the heat gain calculation, the arithmetic mean value for the specific heat capacity of the HTF in the collector field has been used. Measurement data is available for both sites with a time resolution of one minute. The direct irradiation on a horizontal plane is obtained by measuring the global and diffuse irradiation with a combined sensor [6] and then converted to the one-axis tracked surfaces of the two collector field installation. In this paper, additional effects such as row shading and end losses have not been considered yet.

3.1. Description of collector field behavior

Fig 4 shows the Bever collector field inlet and outlet temperature (left axis) and the flow rate in the collector field (right axis, scaled) as well as the steam boiler temperature (left axis) and the pressure in the steam boiler (right axis, scaled). The direct irradiance on the collector field aperture (without shading) is also plotted on the right axis.

Fig. 4a shows the collector field behavior on a day with only few variations of the direct irradiance during the heating-up phase in the morning and around noon. When the collector field starts to operate the steam boiler is heated up during approx. 1.5 h from 65 °C to approx. 150 °C while the collector outlet temperature reaches approx. 190 °C. After an adjusting phase a quasi-continuous heat delivery can be observed throughout the day with collector outlet temperatures between 180 °C and 200 °C and an inlet/outlet temperature difference of about 20 K. With an operation time of 12.5 h including the heating-up on this day an average collector field power of approx. 44 kW results with a peak power of 59 kW. The total energy gain of the collector field on this day sums up to 550 kWh.

Fig. 4b shows an example of a day with a high fluctuation of direct irradiance leading to a total solar energy gain of 180 kWh on this day. For heating-up 25 kWh of solar gains are needed. After reaching the operation temperature, 126 kWh are supplied by the collector field before the heat delivery to the steam boiler is interrupted. With some
intermediate heating up of the collector field, the heat supply only starts again at about 18:30 and delivers additional 10 kWh. The remaining 19 kWh of solar gains on this day are used for transient re-heating of the loop.

Looking at the SPHP of Saignelegier, Fig. 5 shows two examples of days with fairly good direct irradiance on the collector plane (Fig. 5a) and changing weather conditions (Fig. 5b). In the example shown in Fig. 5b, despite the changing weather conditions a high cumulated direct irradiation leads to a total solar energy gain of 2026 kWh (see also Fig. 7). On this day, for heating-up 45 kWh of solar gains are used (until 08:26 when a step in the flow rate can be observed). After reaching the operation temperature, 1980 kWh are supplied by the collector field to the processes and storage. On this day the SPHP is operated with a low flow rate before 12:00 to maintain the outlet temperature. Also during the fluctuation of the direct irradiance on the collector plane between 11:00 and 14:00 the operation of the SPHP can be carried on.

Although in the exemplary day shown in Fig 5a the cumulated irradiation is higher (about 16 %), the solar gain of the collector field is significantly lower (1494 kWh corresponding to -26 % compared to the day shown in Fig. 5b). Reasons for this are the heat integration concept and control which are not optimal yet (especially the charging of the storage) in combination with the restriction that the collector output temperature must not exceed 120 °C due to the specifications of some hydraulic parts.

Fig. 4. Operation behavior of the Bever SPHP for a day (July 16, 2012) with good irradiation conditions (Fig. 4a, above) and another day (July 10, 2012) with changing weather conditions (Fig. 4b, below)
3.2. Analysis of daily cumulated solar gain versus daily cumulated direct irradiation

In order to get an overview on the daily output of the collector fields the cumulated daily heat delivery from the collector field has been plotted against the cumulated daily direct irradiance on the aperture area of the collector field (cf. Figs 6 and 7). Again, row shading is not yet considered. For the Bever plant, the daily evaluation of the collector field gains has been described in more detail in Frank et al. (2013) [7]. In this paper, only data for April 2013 is presented and discussed.

In Fig. 6 on the one hand the radiation conditions of a month can be assessed (e.g. the dots at the very left part of the diagram represent days with almost no sunshine). On the other hand, it can be seen how much of the irradiation is transferred to useful heat by the collector field and how this changes with the conditions. As can be seen in Fig. 6 the daily collector field gain reaches up to 500 kWh/d for good conditions already in April (with days that reach a cumulated direct irradiation on the collector plane in the range of 10 kWh/m²d). The highest daily gain that has been observed so far was 550 kWh/d (in July 2012). However, the measurement uncertainty is rather high (see below). In April 2013, a total of 5888 kWh was delivered by the collector field with a monthly collector field efficiency of 39.2%. In the analysis of most of the months in 2012, still some days could be observed where obviously an error...
and/or a missing heat load occurred. Then, the dot representing the day is clearly below the 25 %-line in the diagram. However, in April 2012 no such anomalies can be found. In general, the collector field efficiencies tend to be lower for lower daily irradiation.

The same is plotted for the Saignelegier plant for April 2013 in Fig. 7.

![Fig. 6. Bever SPHP cumulated daily collector field gains versus cumulated daily irradiation on the one-axis tracked collector aperture area (excluding row shading). Here, one dot represents one day and all days of April 2013 are shown, including an estimation of the measurement uncertainty.](image)

![Fig. 7. Saignelegier SPHP cumulated daily collector field gains versus cumulated daily irradiation on the one-axis tracked collector aperture area (excluding row shading). Here, one dot represents one day and all days of April 2013 are shown, including an estimation of the measurement uncertainty.](image)
Again it could be observed that quite a few days occurred with no or little direct irradiation. The daily collector field gain reaches up to approx. 2000 kWh/d for fairly good conditions in April. However, the potential maximum has by far not been reached yet (cf. Fig. 5). Several observations have been made:

- Very slow heat up in winter months with low sun angle due to
  - close collector spacing and
  - collector axis orientation towards sunrise (opposite from the Bever SPHP).
- Excess solar heat at days with constantly high direct irradiation on the collector plane (see also Fig. 5a) when the collectors have to be defocused. Reasons for this are:
  - low buffer storage capacity
  - batch-type processes in production
- Frequent high temperature alarms on single collectors for following reasons:
  - Maximum temperature in the solar circuit is currently limited at 125 °C due to the choice of hydraulic equipment (valves)
  - Setpoint temperature for optimum heat delivery was 120 °C (in the meantime it was reduced to 115 °C), leaving only a 5..10 K range for temperature control of the whole solar loop
  - Unstable return temperature to the field with significant and unexpected return temperature peaks, leading to destabilization of supply temperature and periodical excess temperature.

In April 2013, a total of 12182 kWh was delivered by the collector field with a monthly collector field efficiency of 27.7 %. Almost all daily collector field efficiencies were in the range of the 35 % line or below. Comparing these preliminary results to the Bever plant and considering the observations described above, the Saignelegier plant operation should have a significant potential for improvements despite of the lower direct irradiance at this location compared to Bever.

In Figs. 6 and 7 the measurement uncertainties for the heat delivery calculations have been plotted which have been derived as described in Appendix A.

4. Summary and Conclusions

Measurements from two solar process heat plants in Switzerland have been evaluated, both equipped with similar types of parabolic trough collectors. A description of the plants is given and the performance of the collector fields has been analyzed looking at some days and a monthly evaluation where the energy delivery of the collector field is cumulated for each day. In the first plant (115 m² aperture area at an altitude of 1700 m), the collector field performance (the fraction of daily solar gains from total direct irradiation) reaches values in the range of 45 % already in April (spring time) providing outlet temperatures of about 190 °C. Due to high specific direct irradiation at this site, solar energy delivery higher than 500 kWh/d is reached (up to 4.8 kWh per m² aperture area have been measured).

In the second plant (630 m² at an altitude of 1000 m), the DNI is much lower (1183 kWh/m².a instead of 1881). Although the design temperature of this plant is lower (about 125 °C), the collector field performance did not yet reach higher values than the Bever plant. However, both the daily and the monthly evaluation presented in this paper show that the collector field performance can be high but the integration and control concept of the Saignelegier plant needs to be improved.

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References

Appendix A. Measurement uncertainty

The measurement uncertainties plotted in Figs. 6 and 7 have been derived based on the equation for the energy delivery of the collector field

$$\dot{Q} = \dot{V} \cdot c_p(T_{cf,in}, T_{cf,out}) \cdot \rho(T_{rho}) \cdot \Delta T(T_{cf,in}, T_{cf,out})$$

and an estimation of the uncertainty using

$$\Delta \dot{Q} = \left| \frac{\partial \dot{Q}}{\partial T_{cf,in}} \right| \cdot \Delta T_{cf,in} + \left| \frac{\partial \dot{Q}}{\partial T_{cf,out}} \right| \cdot \Delta T_{cf,out} + \left| \frac{\partial \dot{Q}}{\partial \rho} \right| \cdot \Delta \rho_{rho} + \left| \frac{\partial \dot{Q}}{\partial V} \right| \cdot \Delta \dot{V}$$

The temperature dependent specific heat capacities $c_p$ (in kJ/kgK) and densities $\rho$ (in kg/m$^3$) for Bever (thermal oil) and Saignelégier (water/glycol mixture) have been fitted to be

$$c_{p,Saigne} = 0.00256 \cdot \left( \frac{T_{cf,in} + T_{cf,out}}{2} \right) + 3.86381$$

$$c_{p,Bever} = 0.0036 \cdot \left( \frac{T_{cf,in} + T_{cf,out}}{2} \right) + 2.007$$

$$\rho_{Saigne} = -0.52429 \cdot T_{rho} + 1038.048$$

$$\rho_{Bever} = -0.6749 \cdot T_{rho} + 844$$