Comparison of thermal losses due to heating-up of system components in two solar process heat plants with parabolic trough collectors

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Abstract

Two solar process heat plants with liquid heat transfer parabolic trough collectors (PTC, 627 m² and 115 m² aperture) at Swiss dairies have been experimentally investigated in detail. They provide solar thermal heat for a hot water network of 102 °C and a steam network of 135 °C - 150 °C, respectively. Detailed yearly, monthly and daily evaluation with regard to usable solar gains Q_{use} and solar energy necessary for heating–up system components to required temperature T_{set} is presented. Thermal heat capacities of the primary circuit have been analyzed and the change in inner energy ΔU has been calculated and cumulated for periods with no usable heat output below $T_{set.}$ Over the year, the ratio of not usable solar energy required to heat-up the system to overall solar gains in the collectors ($\Delta U/(Q_{use+}\Delta U)$) varies between 14-18 % and 20-22 %, respectively. During winter months ΔU can even exceed Q_{use}. These capacitive losses can be reduced by lower heat capacities or an improved thermal insulation. With intermediate storages, inner energy contained in the hot system could be stored for re-heating after an idle period.

Keywords: solar process heat, parabolic trough collector, concentrating solar thermal, thermal heat capacity, thermal losses, heating-up.

1. Introduction

Nearly 70% of final energy consumption in European industry is required for process heat. Part of this energy could be provided by thermal collectors in order to reduce fossil fuel consumption and CO_2 emissions. Though, to date there is little experience with solar process heat plants (SPHP), especially at temperatures between 100 °C and 250 °C, where thermal losses of system components during stand-still periods play a major role compared to low temperature applications. After periods of non-operation, solar energy is required to heat up the components to operating temperature before solar heat can be delivered to the processes.

The work focuses on experimental analysis of two solar process heat plants with parabolic trough collectors quantifying daily and monthly inner energy ΔU required to heat-up heat transfer fluid and piping system and comparing it to useful solar energy gains Q_{use}. Both plants analyzed provide solar heat for dairies and are located in northwest (Saignelégier) and southeast (Bever) of Switzerland. They operate at different collector temperatures (120 °C/190 °C) and differ in size (627 m^2/115 m^2), integration concept (hot water/steam) and type of heat transfer medium (water-glycol/thermal-oil).

A methodology based on the system configuration in Saignelégier has been developed in order to experimentally quantify the required solar thermal energy during transient heat-up periods of the plant (Möllenkamp et al., 2016). In this work, the methodology has been adapted to the plant configuration of Bever and results of both plants are compared and discussed.

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Fig. 1: SPHP in Saignelégier, 1000 m above sea level, 627 m² (aperture) PTC collectors with axis orientation NS with 18° deviation counterclockwise

Fig. 2: SPHP in Bever, 1700 m above sea level, 115 m² (aperture) PTC-collectors, axis orientation NS with 19° deviation clockwise

2. Description of analyzed solar process heat plants

Saignelégier

The SPHP in Saignelégier produces thermal energy for a (cheese) dairy operated by Emmi. The collector field comprises of 17 parabolic trough collectors (PTC) PolyTrough 1800 by NEP Solar (SPF 2017) connected in parallel. It is mounted on the roof of a production hall and its orientation follows the roof geometry (north-south with 18 ° deviation counterclockwise). The total aperture area amounts to 627 m^2 and the row distance alternates between 2.98 und 3.84 m. As heat transfer fluid, a 25 vol.% water-glycol mixture with $c_{p(0\text{-}120\ °C)}$=3.9-4.2 kJ/kg/K is used. The primary circuit consists of solar field and return/supply pipes and delivers useful solar heat Q_{use} to the hot water network operated at 102 °C (secondary circuit) via a heat exchanger if a set point of T_{set} = 117 °C is exceeded (Fig. 3 and Fig. 4). Useful solar energy is either stored in a 15 m^3 water storage, used for pre-heating water in two oil-burners or directly delivered to the processes of the dairy (cleaning or thermal treatments of dairy products). Fluid temperatures are measured at inlet and outlet of the collector field and the heat exchanger. Minute mean values of highly resolved (up to 1 secs) measurements are used for the analysis.

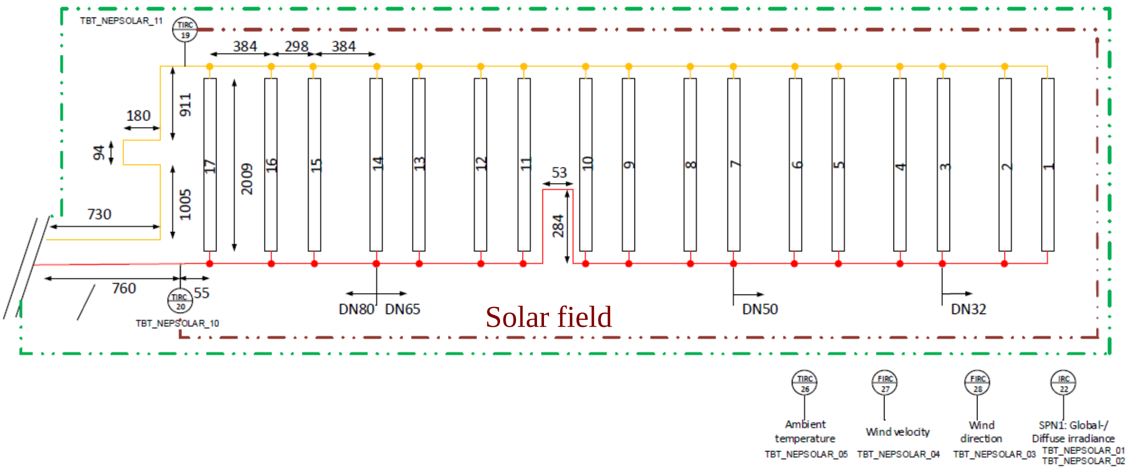

Fig. 3: Hydraulic Scheme of solar field in Saignelégier

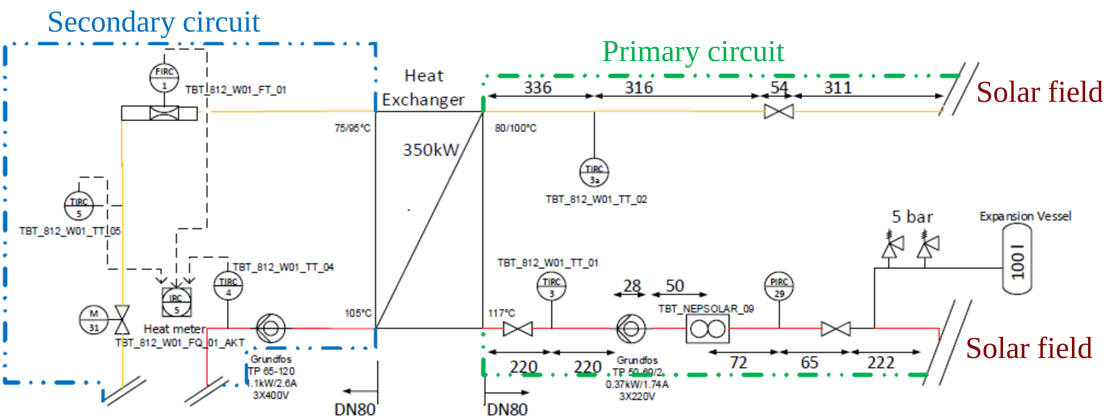

Fig. 4: Hydraulic scheme of SPHP in Saignelégier (solar field not included)

Bever

The second plant is located in Bever and produces thermal energy for a (cheese) dairy operated by Lesa. The collector field comprises of 4 collector rows with a length of 25 m each. Two rows are connected in series and the arising subfields connected in parallel. The solar field consists of parabolic trough collectors PolyTrough 1200 by NEP Solar and is mounted on the rooftop of a production hall. The axis orientation is north-south with 18.8 ° deviation clockwise. The total aperture area is 115 m^2 with and a row distance of 2.45 m (outer rows) and 3.42 m (in the middle). Here, thermal oil is used as heat transfer fluid with $c_{p(0\text{-}190\ °C)}$ = 2-2.7 kJ/kg/K. The solar heat is delivered to a steam network via steam generator. In Fig. 5, the SPHP again is divided into solar field, primary circuit (solar field plus return/supply pipes) and secondary circuit (steam network).Temperatures of the fluid are measured at inlet and outlet of the collector field and evaporator. Instantaneous measurement data with a frequency of one minute was available.

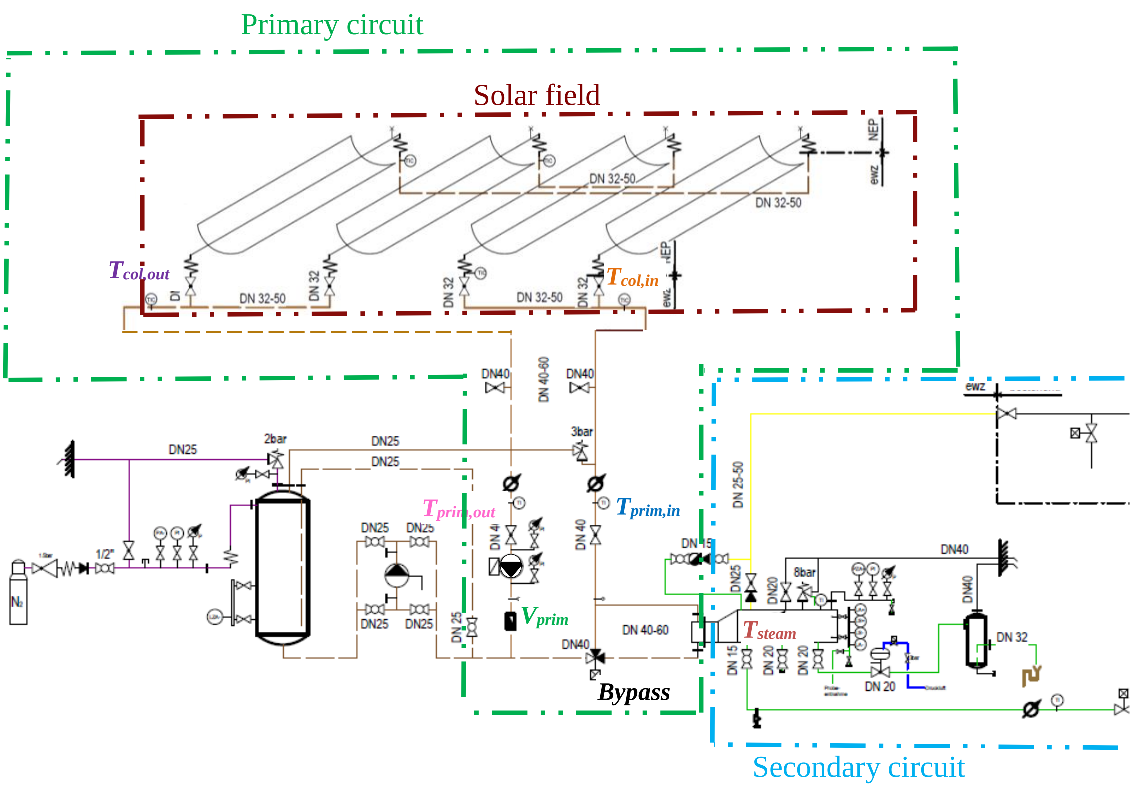

Fig. 5: Hydraulic scheme of SPHP in Bever

In Bever, the presence of a steam generator complicates the evaluation of Q_{use} due to no available information about incoming (feed water) and outgoing (steam) mass flowrates of the steam generator nor from pressure or temperature in the steam network. The steam generator contains 210 l water and is about half filled. Fig. 6 shows a typical operating day for the Bever plant and clarifies the operation modes. If the outlet temperature of the collector field T_{prim_out} exceeds the temperature in the steam generator T_{steam}, the bypass to the internal heat exchanger of the steam generator opens (i.e. at 9:50) and solar energy is used for heating up and evaporating the water in the steam generator. If the steam pressure in the steam generator exceeds the pressure in the steam network plus a certain unknown hysteresis-pressure (e.g. at 11:10 and 12:50), a valve opens their connection and useful solar heat is, driven by pressure forces, delivered to the processes until the pressure in the steam generator has decreased down to the pressure in the steam network (3.1 – 4.8 bar, varying during the day, see Fig. 6). Consequently, a steam temperature of 135 – 150 °C is required to feed useful energy into the steam network calculating T_{steam} from vapor pressure curve. Additionally, the primary circuit has to deliver the necessary temperature difference over the heat exchanger (25 K during operation, see Fig. 6). This leads to a minimal T_{prim_out} of 160 – 175°C (depending on varying steam net pressure) before usable solar heat can be transferred to the process. Though, set temperature for the pump control of the collector field is $T_{col,out}$=190 °C, which can also be seen in Fig. 6.

The dashed lines in Fig. 6 mark two heating up periods converting solar energy in enlargement of inner energy ΔU without providing Q_{use}.

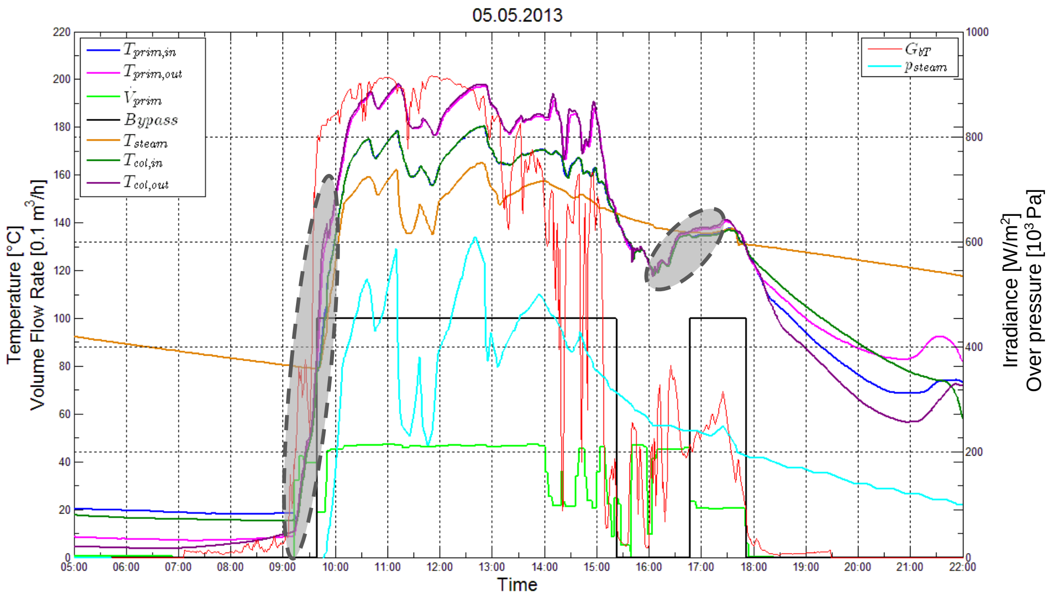

Fig. 6: Exemplary measurement data for the 5th of May 2013 at the SPHP in Bever showing inlet and outlet temperatures of the primary circuit ($T_{prim,in}$ and $T_{prim,out}$), volume flowrates in the primary circuit (V_{prim}), bypass signals (in %), steam temperatures (T_{steam}) and collector field inlet and outlet temperatures ($T_{col,in}$ and $T_{col,out}$) as well as direct normal irradiance on the aperture area (G_{bT}) and steam over pressure in the steam generator (p_{steam}).

Comparison of effective thermal capacity

The aperture area specific total thermal capacity C_{eff} [kWh/(Km^2)] of the primary circuit for Saignelegier comprises only of different fluid filled pipe sections (connecting tubes inside and outside the building and collector pipes), see Fig. 5. C_{eff} has been calculated from dimensions, density and specific heat capacities of heat transfer medium and pipe materials. The major part of C_{eff} (80 %) of the primary circuit in the Saignelégier plant is given by the pipes outside connecting the 17 collector rows, see left diagram in Fig. 7.

In contrast, only 50% of C_{eff} of the piping system in Bever (diagram a) Fig. 7, green segments) results from collector connecting pipes due to less collector rows (4), longer collector pipes (5 m longer) and serial connection. Besides the capacity of 198 l thermal oil with $c_{p(0\text{-}190\,°C)}$ = *2-2.7* kJ/kg/K, additionally the thermal capacity of 210 l water with $c_p = 4.2$ kJ/kg/K in the steam generator (see diagram in Fig. 7, blue section) has to be considered being responsible for two third of the total C_{eff}. Note, that generally the metallic materials of system components like piping, heat exchangers and steam generator account for only about 10% of the total heat capacity, which is mainly determined by the contained fluid.

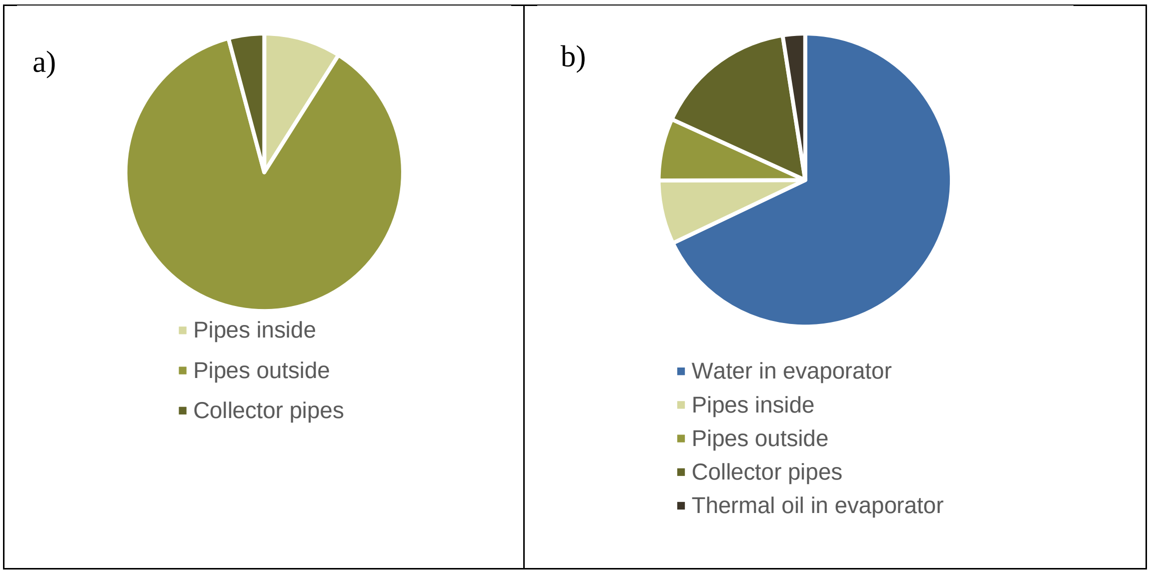

Fig. 7: Distribution of effective thermal capacity C_{eff} in primary circuit of SPHP in a) Saignelégier and b) Bever.

The total thermal capacities C_{eff} (related to the aperture area) for both plants are similar, see Table 1, though the collector fields are differently large by a factor of 6 in aperture area. Regarding only HTF and pipes, C_{eff} in Bever is three times smaller than in Saignelégier. However, in Bever results even a slightly higher total C_{eff}, additionally considering the water in the steam generator. Hence, compared to Saignelégier, the usable part of solar energy in Bever is expected lower, because principally more heat capacity has to be heated to usable temperature level T_{set}, which in Bever (at least 160 °C) is significantly higher than in Saignelégier (117 °C).

Tab. 1: Aperture-specific effective thermal capacity of pipes and HTF in Saignelégier and Bever as well as C_{eff} of water in the steam generator of Bever and the resulting total heat capacities

	C_{eff} [kWh/m²K]	
	Bever	**Saignelégier**
HTF and pipes	0.94	2.73
Water	2.15	
Total	3.09	2.73

3. Methodology for quantification of usable solar energy Q_{use} and solar energy required to heat-up ΔU

Thermal energy required to heat up system components after stand-still periods is calculated by (see Möllenkamp et al. 2016):

$$\Delta U = \sum_{i=1}^{m} \sum_{j=1}^{n} C_{eff,j} \cdot \left(T_{fl,j}(t_{2,j}^{i}) - T_{fl,j}(t_{1,j}^{i}) \right) \qquad \text{(eq. 1)}$$

with C_{eff} representing the effective thermal capacity of each capacitive section i and m and n the number of section and heating-up periods, respectively. T_{fl} (t_1) represents the mean temperature of the fluid in each section at the beginning of each heating-up period and T_{fl} (t_2) the temperature at the end, respectively.

Usable solar energy Q_{use} is determined by the energy transferred to the secondary circuit by integrating primary circuit power over periods with an operating pump in the secondary circuit:

$$Q_{use} = \int_{t_2}^{t_3} c_p \cdot \rho \cdot \dot{V}_{prim} \cdot \left(T_{prim,out} - T_{prim,in}\right) dt \qquad \textbf{(eq. 2)}$$

With t_2 and t_3 defining beginning and end of each period, respectively.

In Bever, the water filled steam generator represents an additional component which has to be considered for the analysis. As derived more above from typical measuring data (Fig. 6), it is simplifying assumed that solar heat is embedded into the steam network (and therefore represents useful energy) if collector outlet temperatures $T_{prim\_out} > T_{set}$. T_{set} corresponds to the minimum steam pressure in the steam network (3.1 bar) and leads to a threshold of $T_{prim\_out} > 160$ °C for useful solar energy. This means, all solar energy below 160° C is used for heating up collector pipes and steam generator. Due to measuring a maximum steam network pressure of 4.8 bar (corresponding to 150°C steam temperature) the evaluation has also been done for this threshold, whereas real conditions meet in between these two limiting cases.

For the evaluation in Bever it was distinguished between thermal energy required to heat up the collector field, the connection pipes inside and outside the building and the water in the steam generator considering different temperatures for each section. For example, the steam generator cools down to 80 °C during night, while the collector field components are at ambient in the morning and differ slightly inside and outside the building (see Fig. 6).

4. Q_{use} and ΔU: Results and discussion

Saignelégier

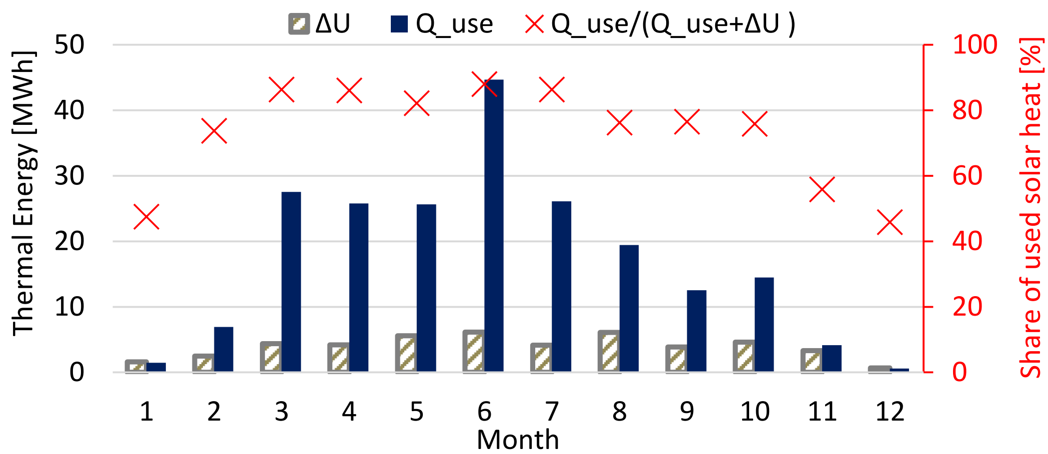

Fig. 8: Solar energy gains required to heat-up system components ΔU, useful solar gains for process heat Q_{use} and share of useful solar heat Q_{use} /(Q_{use} + ΔU) of the SPHP in Saignelégier 2014

According to Fig. 8 between 76 % and 88 % of the total solar gains Q_{tot} with

$$Q_{tot} = Q_{use} + \Delta U \qquad \text{(eq. 3)}$$

has been provided to the hot water network of the dairy between March and October of 2014 in Saignelégier. Here, pipe losses during the operation at $T_{prim\_out} > T_{set}$ have been neglected due to

- having been proven to be totally below 5 % of monthly Q_{tot}, if properly insulated (see Möllenkamp et al., 2016)
- time ratio with $T_{prim\_out} > T_{set}$ is below 20 % during the whole month, reducing part of pipe losses during operation with $T_{prim\_out} > T_{set}$ to less than 1 %

In contrast, the share of useful solar energy decreased down to 46 % in December 2014. This is mainly resulting from less daily direct irradiation on the collector plane and lower ambient temperatures. During the whole year, 18 % (ΔU=47 MWh) of the total thermal solar energy (Q_{tot}=256 MWh) is required for heating-up fluid and pipes of the SPHP in Saignelégier 2014.

In 2015 (see Fig. 9) the annual ratio of required heat for pre-heating is reduced to 14 % (ΔU=37 MWh, Q_{tot}=264 MWh), which is mainly resulting from higher direct irradiation on the aperture area ($H_{bT,2014}$=985 kWh/m² aperture area; $H_{bT,2015}$ =1138 kWh/m² aperture area) and hence higher useful energy gains (Q_{use}=257 MWh). The maximum share of used solar heat is recorded in April 2015 with 93 %. The SPHP was shut down in December 2015 due to snow blocking the tracker. The time of heating-up periods on sunny days in Saignelégier varied between at least 50 min in summer and up to 4.2 hours in winter during 2014 and 2015.

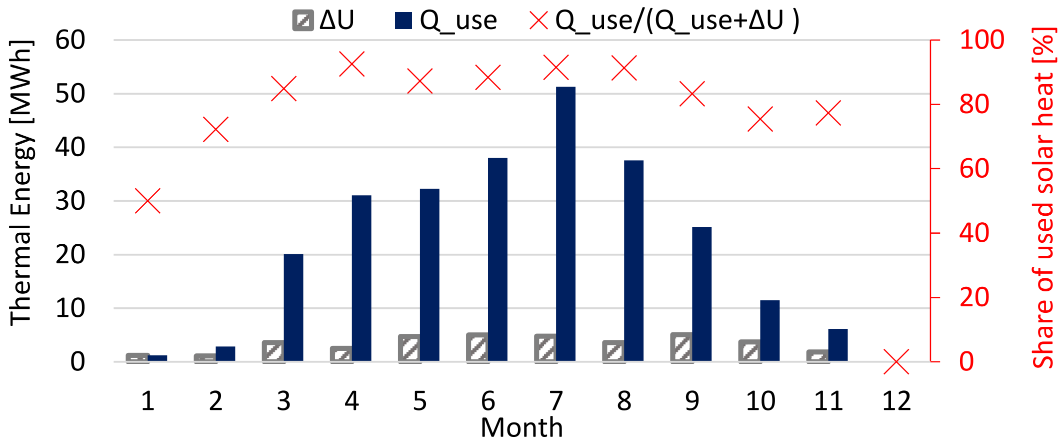

Fig. 9: Solar energy gains required to heat-up system components ΔU, useful solar gains for process Q_{use} and share of useful solar heat Q_{use} /(Q_{use} + ΔU) of the SPHP in Saignelégier 2015

Thermal losses due to heating-up periods could be reduced by implementation of an additional storage, which collects the heat of fluid and pipes at the beginning of each stand-still period and feeds the solar field with hot fluid before the next start of operation.

Bever

The SPHP in Bever was able to provide 55 % - 89 % of the total solar gains to the steam network from March until October of 2013, whereas in January only 18 % of the total solar thermal energy could be used for industrial processes (see Fig. 10). In 2013, 9 MWh of solar energy gains were used for heating-up system components, which represents 20 % of the total yearly solar gains ($Q_{tot,2013}$ = 44 MWh). Here, it can be distinguished between energy to heat-up water in the steam generator (10 % of Q_{tot}) and energy to heat-up thermal-oil and pipes (10 % of Q_{tot}).

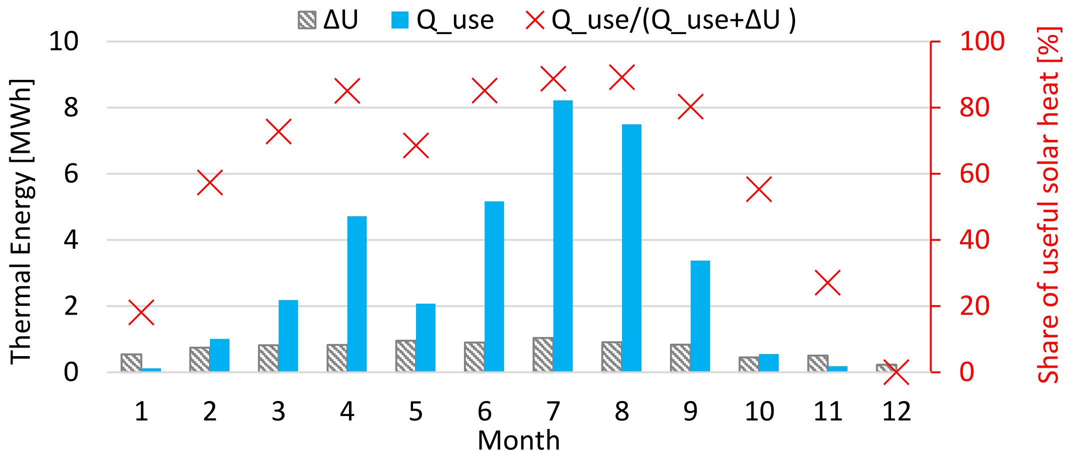

Fig. 10: Solar energy gains required to heat-up system components ΔU, useful solar gains for process heat Q_{use} and share of useful solar heat Q_{use} /(Q_{use} + ΔU) of the SPHP in Bever 2013

For the maximal pressure of 4.8 bar as measured in the steam network a collector field outlet temperature of 175 °C is required to evaporate the water. Under this assumption, a yearly $\Delta U/Q_{tot}$ *=22 %* and hence a higher ratio of solar energy used to heat up the system is experimentally obtained. The real value $\Delta U/ Q_{tot}$ for Bever is between these two extremal cases (20 % for 160 °C and 22 % for 175 °C). Heating-up times in Bever varied between 1.5 and 2 hours.

For the Bever plant, it is recommended to further improve the insulation of the steam generator, before considering an additional storage for saving thermal energy during stand-still periods.

Comparison between the two plants

The evaluation of measurement data shows that the ratio of required solar energy to heat-up the system compared to overall solar gains do not differ much between both plants analyzed ($\Delta U/Q_{tot}$ 14-18 % in Saignelégier and 20-22 % in Bever) even though minimally acquired collector field temperatures in Bever (>160 °C) are much higher than in Saignelégier (117 °C) and thermal capacities per solar aperture area are comparable.

In spite of a similar total effective thermal capacity C_{eff}, it has to be considered that different temperature differences arise for heating up water and thermal-oil in the Bever plant. Due to its better insulation, the steam generator cools down to only 80°C during night, while the primary circuit cools down to ambient, see Fig. 6. Assuming an ambient temperature of 20 °C inside and outside the building, heating-up in the morning once a day consumes

$$\Delta U_{Bever} \approx C_{eff,water} \cdot (130-80)K + C_{eff,HTF+pipes} \cdot (190-20)K = 267\ kWh/m^2$$

$$\Delta U_{Saignelégier} \approx C_{eff,HTF+pipes} \cdot (120-20)K = 273\ kWh/m^2$$

of solar thermal energy in the morning.

Also the high yearly direct irradiation on the tilted aperture area H_{bT} in Bever (1285 kWh/m² yearly, monthly see Fig. 12) favors a lower $\Delta U/Q_{tot}$, which can be seen from Fig. 11 showing monthly H_{bT} for the Saignelegier plant comparing the years 2014 and 2015: The yearly share of used solar heat in Saignelégier increases from 82 % to 86 % if yearly H_{bT} grows from 985 kWh/m² to 1138 kWh/m².

Nevertheless, distribution of direct normal irradiance (DNI) over the day also plays a role. For example, five sunny days and five cloudy days show a higher ratio of usable solar energy compared to ten days with fluctuating DNI but same cumulated DNI.

The exact influence of the parameters discussed on the share of usable solar energy Q_{use} and not usable solar energy required to heat-up ΔU can only be determined by dynamic simulations.

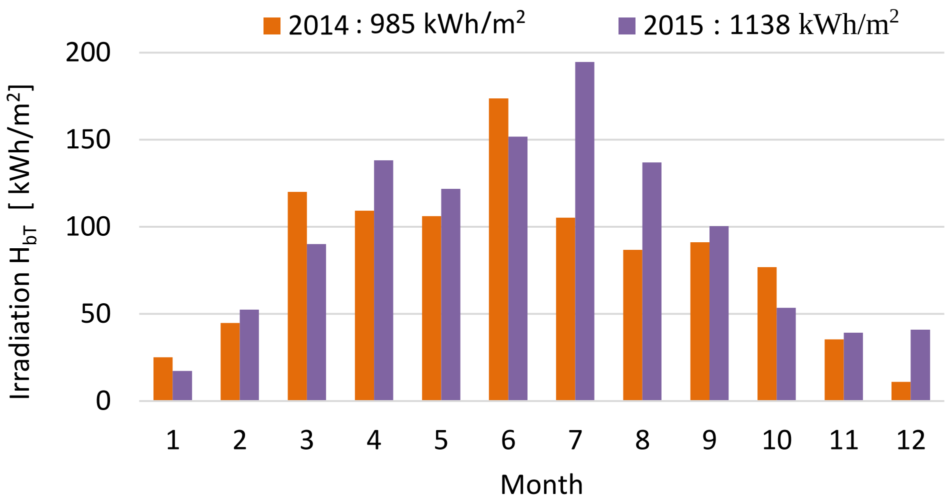

Fig. 11: Monthly direct irradiation on the tilted aperture area of the SPHP in Saignelégier 2014 and 2015

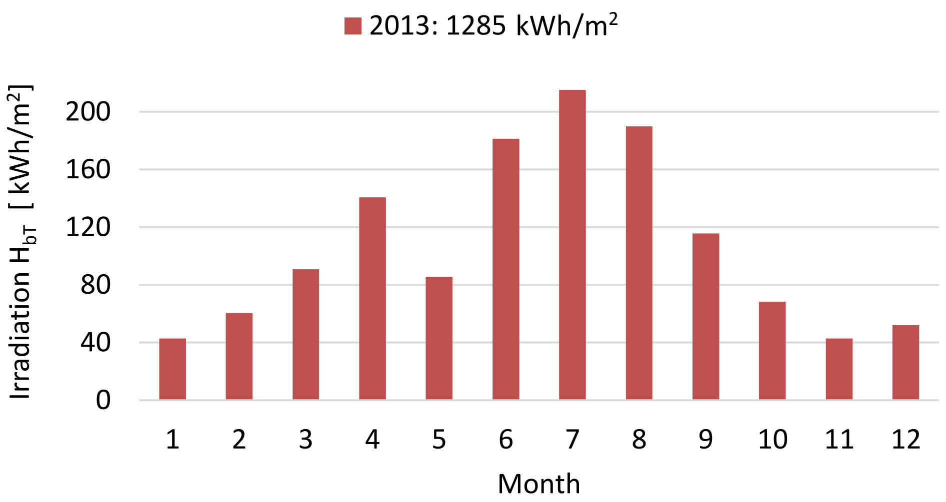

Fig. 12: Monthly direct irradiation on the tilted aperture area of the SPHP in Bever 2013

5. Summary and outlook

For two SPHP in Switzerland with PTC collectors at operating temperatures between 100 °C and 200 °C and collector aperture areas between 115 and 627 m² it could be shown experimentally that 14 to 22 % of potentially usable yearly solar energy, i.e. solar energy transferred to the collector fluid of a SPHP, are lost due to thermal losses in stand still periods which must be balanced by solar heating-up processes. In further studies both plants will be modelled with a dynamic simulation software in order to

- study the exact influence of the different parameters (thermal capacities of components, operating temperatures, integral solar radiation and its distribution, user behaviour) on solar energy required to heat-up ΔU and usable solar energy Q_{use}.
- quantify possible thermal energy savings with the developed optimization methods for each plant, which enlarge Q_{use} reducing ΔU by better thermal insulation and/or saving ΔU at the begin of a stand still period for the next heating up period by means of a thermal storage.

6. References

Möllenkamp, J., Rittmann-Frank, M.H., Caflisch, M., Rommel, M., Häberle, A., Beikircher, T., Schölkopf, W., 2016. Evaluation of thermal losses in parabolic trough collector fields of solar process heat plants in Switzerland. Conference Proceedings of EuroSun 2016, Palma de Mallorca.

SPF Insitute for Solar Technology, 2017. Solar Collector Factsheet NEP Polytrough 1800. URL http://www.spf.ch/fileadmin/daten/reportInterface/kollektoren/factsheets/scf1549en.pdf., accessed 13.10.2017.