Evaluation of Solar Process Heat Systems in Switzerland

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Abstract. Since 2011 several solar thermal installations have been installed in Switzerland for the supply of industrial process heat, from which a selection is monitored by the SPF Institute for Solar Technology. In this article the focus lies on a technical and economical evaluation of three solar process heat plants with concentrating parabolic trough collectors providing heat to Swiss dairies. Each plant is at a different location, has different dimensions and operates at different temperatures, ranging from 117 °C up to 180 °C. This evaluation presents the overall performance of these solar process heat systems and compares them to the expectations and summarizes experiences made during operation in order to help planning and designing of future plants.

INTRODUCTION

One third of the total energy demand in European and other developed countries is consumed by the industrial sector [1]. In order to meet the objectives of the Swiss initiative "*energy strategy 2050*", environmental restrains are placed and the reduction of CO_2 is required, urging industry to enhance their energy efficiency without compromising their competiveness. Besides performing waste heat recovery and process intensification to boost the energy efficiency, the implementation of renewable energy sources is becoming more attractive to reduce CO_2 emission. At least half of the energy consumed by the industrial sector is used to provide heat for processes with temperatures below 300 °C. The scale of energy used for industrial heating represents a unique opportunity for implementing solar process heat technologies at a medium and medium-high temperature level (80 °C-300 °C). According to an estimate of the IEA SHC Task 32, 4% of the total industrial process heat in central Europe could be covered by solar thermal energy. For Switzerland this would amount to around 1 TWh, based on the energy statistics of the Swiss Federal Office of Energy. Since 2011 several solar thermal installations have been installed in Switzerland for the supply of industrial solar heat, from which a selection is monitored by the SPF Institute for Solar Technology. The aim is to technically and economically evaluate the existing plants and learn for future solar process heat plants from experiences made during operation.

The six plants that are evaluated are Pilot and Demonstration plants located at various sites in Switzerland and provide heat for different processes as indicated in Fig. 1. Solar heat provided by vacuum tube collectors in Gränichen is used for heating up enameling baths and in Geneva for sterilization of tools in a hospital. Vacuum flat plate collectors provide heat to a hot water storage at 70 °C or for a bitumen storage at 180 °C, depending on available solar irradiation. Interestingly, three of the plants use concentrating, one-axis tracking parabolic trough collectors, a technology rather used at locations with higher Direct Normal Irradiation (DNI) than in Switzerland. In order to examine the use of these technologies in Central European regions, this article focuses mainly on these three parabolic systems. The concentrating plants provide heat for dairy production in Bever, Saignelégier and Fribourg. The heat transfer medium for the solar system in Bever is thermo-oil, which is heated up to between 150 °C and 180 °C to deliver steam into the steam network. This collector field was the first plant commissioned within this study in 2012 and operates with the highest temperature of all systems. The plant in Saignelégier was installed afterwards with improved parabolic collectors. The solar system in Saignelégier runs with water-glycol as heat transfer medium and delivers constantly 117 °C for the hot water network of the company for cleaning purposes. In Fribourg the solar system can either deliver hot water at 120 °C for cleaning or at 160 °C for cream production, depending on weather condition and production demand. Fribourg was the last parabolic collector plant among these to be installed. It is worth mentioning, that this plant was installed, commissioned and integrated into the existing industrial system completely by the same in-house technicians, who also re-wrote the control system of the collectors to adapt the in-house control system. This differs from the usual practice used for other systems, where the collector field is installed and commissioned by the collector supplier but the system integration is done by a third party.

The Swiss Federal Office for Energy supported this Pilot and Demonstration plants to test and demonstrate solar thermal technology in a rather complex field, such as industrial plants. In Switzerland solar process heat systems, such as these, are still rare, and there is lack of experience. This evaluation aims to answer the following questions: What is the overall performance of the solar process heat systems? Do they perform as estimated in the planning phase? What are the main challenges and how can these be overcome? How are the cost-allocations for these kind of systems and where can cost be optimized?

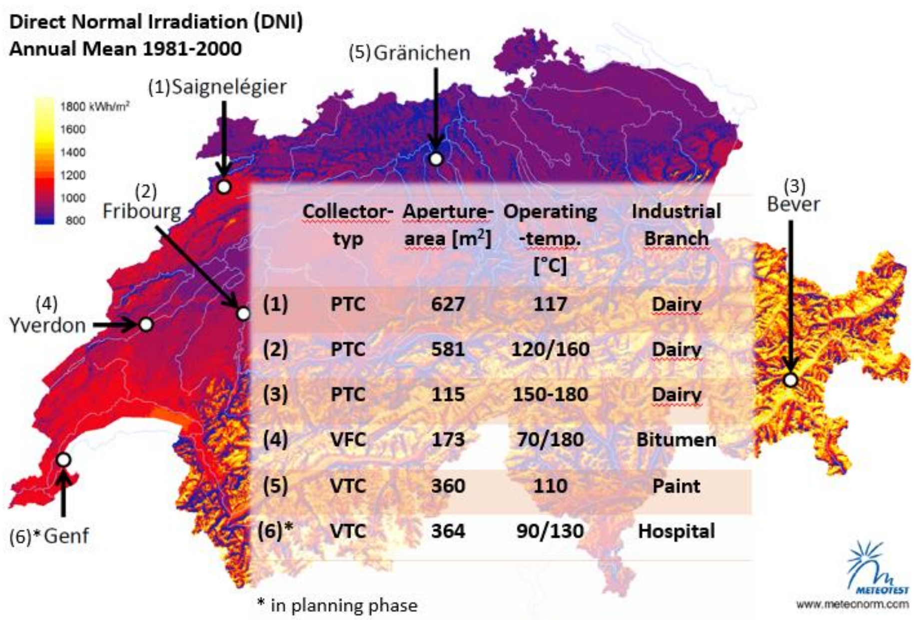

FIGURE 1. Direct Normal Irradiation in Switzerland with the location of the solar process heat plants evaluated within the project. Collector technologies: PTC: Parabolic trough collector, VFC: Vacuum flat plate collector, VTC: Vacuum tube collector.

METHODOLOGY

The solar field systems are monitored over a period of several years, collecting inlet and outlet temperatures, mass flow, pressure and meteo-data in minute time-scale resolution. Based on this data, energy yields are evaluated on a monthly basis and an annual balance is drawn. For the more detailed investigation, the yield and the available radiation are examined on a daily basis. In particular, days during which the plants achieved lower yields despite high incident solar radiation are analyzed in detail to find the cause of the reduction. Problems or mistakes and their solutions are recorded and archived for future projects. Besides the evaluation of energy yields, the economic aspects were also assessed via questionnaires.

For the evaluation of a parabolic trough system it is necessary to accurately measure the Direct Normal Irradiance (DNI), which is the solar energy that can be transformed into heat by concentrating collectors. The most accurate measurement of the DNI is performed by a two axis tracking pyrheliometer, which requires high maintenance and is relatively expensive. Therefore, a more cost-effective, lower maintenance but still reliable device to measure the DNI was placed at the plants evaluated in this study, the Sunshine pyranometer SPN1. Its accuracy is currently tested at the SPF and reported in [2-4].

RESULTS

Daily Performance of Parabolic Systems

Fig. 2 shows Input-Output diagrams for the parabolic collector plants in Bever, Saignelégier and Fribourg. The daily yields of a parabolic trough collector system are plotted as a function of the summed daily direct radiation on the collector area over several years for each plant. For clear representation and better comparison, only the summer period is depictured. The plants are shut down during winter time. In this representation of the data, days showing a low performance of the plants although having high solar irradiation are directly identified by outlying points below the average value. The detailed analysis of these days reveals valuable information about problems occurring during operation under real conditions and have been described in [5,6]. The location in Fribourg has overall lower DNI irradiation than Bever and Saignelégier, which is reflected in the lower values.

There is a trend of increasing collector efficiency from the plants in Bever to Saignelégier and to Fribourg, going from average of 40% up to almost 60% collector efficiency per day. The graph for the plant in Bever shows many days with low performance. Indeed, this plant has been facing several technical issues due to leakage of thermo-oil at the connecting bellows between the constantly moving absorber tube outlet and the collector field piping, resulting in long down-time periods. The plant in Saignelégier on the other hand has shown steady performance. Only in September 2016 it was shut down for repair, also due to leakage in the piping. The plant in Saignelégier shows a plateau at high irradiation values, which is due to an under dimensioning of the storage tank and no alternative heat sink to use the available solar heat. In 2014 13.1 MWh (approx. 6% of the yearly energy yield) was lost due to solar overproduction, which could have been avoided by additional storage volume or adjusted control strategy [5]. The plant in Fribourg shows year by year improvement, starting from 2014 with a daily collector field efficiency of 40% and several days with low performance, mainly due to an overpressure issue resulting in a shutdown of the plant. With growing experience over the years and technical and control improvements, such as the fine-adjustment of pressure threshold settings, the company managed to reach an efficiency of the plant of 60%.

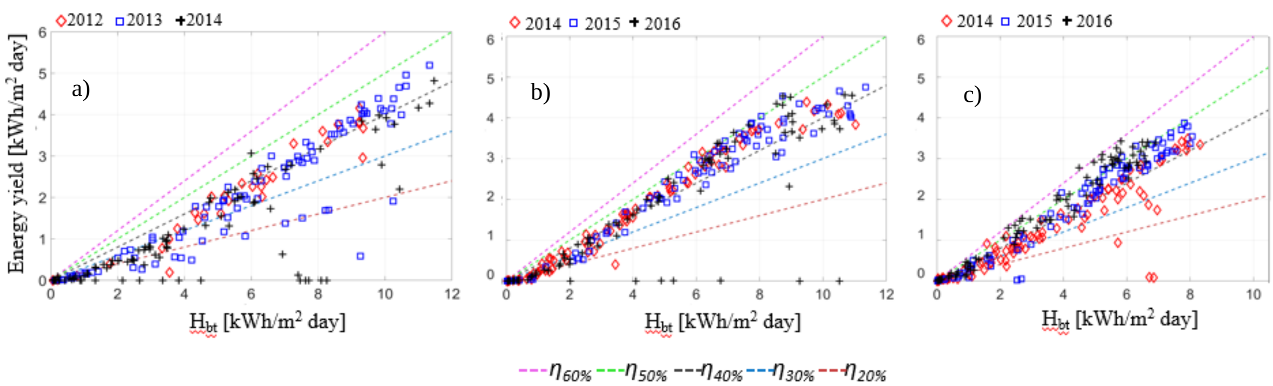

FIGURE 2. Daily efficiency yield (data point) as a function of direct normal irradiation perpendicular to the tracking axis H_{bt} for the solar process heat system in a) Bever, b) Saignelégier and c) Fribourg for different years. The dashed line indicate the theoretical efficiency.

Collector Efficiency vs Collector Field Efficiency

The Input-Output diagrams in Fig. 2 give an average overview of the daily performance of the plants. However, from this representation it is difficult to compare the plant performance due to the different operating temperatures. For a single parabolic trough collector PTC 1800 NEP, as used in the solar heat plants, the efficiency curve at different temperatures at 800 W/m^2 was recorded under ISO 9806 Norm conditions at the SPF Institute for Solar Technology. The efficiency curve is defined by the optical efficiency η_0 and thermal loss coefficients (a_1: linear heat loss, a_2: quadratic heat loss):

$$\eta = \eta_0 - a_1 \frac{T_m^*}{DNI} - a_2 \frac{{T_m^*}^2}{DNI}, \tag{1}$$

with $T^*_m = T_m - T_{amb}$, T_m: medium temperature and T_{amb}: ambient temperature and DNI perpendicular to the collector aperture.

This collector efficiency curve indicates the maximal performance that can be reached by the collector fields, if no additional thermal and optical losses occur. In order to draw a comparison between single collector efficiency and collector field efficiency, the latter is calculated under quasi-steady conditions. Therefore, only data with stable DNI at 800 W/m^2 and stable flow rate is evaluated around solar noon (±15 min), in order to minimize the losses due to the incident angle and field losses, such as row shading and end losses. Figure 3 shows data points for each collector field that fulfill the mentioned conditions. As expected, the collector field efficiency for all plants lies below the collector efficiency curve. However, the values for the collector fields in Bever and Saignelégier overlap well within the error bars with the collector efficiency curve. The difference between the collector field and the collector efficiency in Fribourg is more pronounced. Possible reasons for the lower field efficiency are manifold and could be due to soiling, degradation, bending of the mirrors, optical losses due to small tilted solar incidence and thermal losses (between collector field inlet and outlet measuring points). In case of Fribourg the bending of the 20 m long collector might be the main reason for the deviation. In general this comparison shows that the collector fields achieve almost the same efficiency as a collector measured under control conditions, which indicates that in general the collector field show a satisfactory performance.

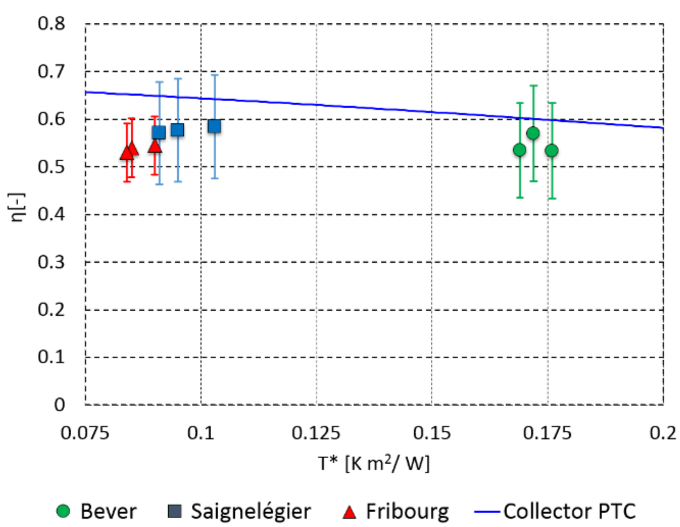

FIGURE 3. Comparison of collector efficiency curve (blue line) for the parabolic trough collector PTC 1800 NEP vs collector field efficiency determined under quasi-stationary conditions for solar fields in Bever, Fribourg and Saignelégier

To summarize the energetic evaluation, an overview of energy yields of the evaluated plants is presented in Table 1. For the sake of completeness, the plants with non-tracking collector technologies are listed as well. The monitoring period indicates in which time-range the solar process heat system was operational and useful data was recorded. The solar irradiation in table 1 is DNI for the parabolic trough collectors and global irradiation for the non-concentrating systems. The annual collector field efficiency describes the ratio between the annual energy yield and the available solar energy on the aperture area.

As can be seen by the shortness of the monitoring period, the plant in Bever has not been fully operational since 2014 due to the leakage issue. Although the plant showed a good performance when operated, the technical challenges dominated and this plant has not met the expected performance of 76 MWh per year. However, the plant has been repaired in the meantime and its operation will continue.

The solar system in Saignelégier shows the highest annual energy yield in 2015 with 418 kWh/m^2, which corresponds to 263 MWh and which matches exactly the estimated energy yield and represents 12% coverage of the entire heat demand of the industrial site. By using solar heat instead of fossil fuel 69 t CO_2 were saved in 2015.

The plant in Fribourg fulfilled the estimation of 197 MWh and exceeded it in 2015 with 221 MWh, which is equivalent to 50 t CO_2 saved. When comparing annual collector field efficiencies, the improvement of performance of this plant is consistent with Fig. 2.

The estimation of the energy yield of 158 MWh for the collector field in Gränichen was not achieved. However, the data logging of the plants data was not reliable and a total data of 2 months were lost. The plant with the lowest efficiency is the facility in Yverdon. The reasons for the low collector yields are mainly due to unexplored technology (SRB collectors) and problems with system layout and integration, which are explained in detail in [7].

	Monitoring period	Operating temperatur	DNI [kWh/m^2]	Energy yield [kWh/m^2]	Energy yield [MWh]	Annual collector field efficiency
Bever	Aug.- Dec. 2012	190°C	426	128	15	**30%**
	Jan.- Dec.2013		1162	353	41	**30%**
	Jan.- Aug. 2014		833	195	22	**23%**
Saignelégier	2014	117°C	945	344	217	**36%**
	2015		1138	418	263	**37%**
	2016		928	297	187	**32%**
Fribourg	2014	120°C /160°C	928	340	198	**37%**
	2015		976	380	221	**39%**
	2016		843	336	195	**40%**
			Global irradiation [kWh/m2]			
Gränichen	2015	70°C- 90°C	876	340	122	**39%**
	Jan- April 2016		222	90	32	**41%**
Yverdon	Apr.-Dec 2015	80°C /180°C	747	92	16	**12%**
	Jan.-Oct. 2016		1198	83	14	**7%**

TABLE 1. Summary of the results for the monitored solar heat plants in Switzerland. The plant in Geneva is not yet operational.

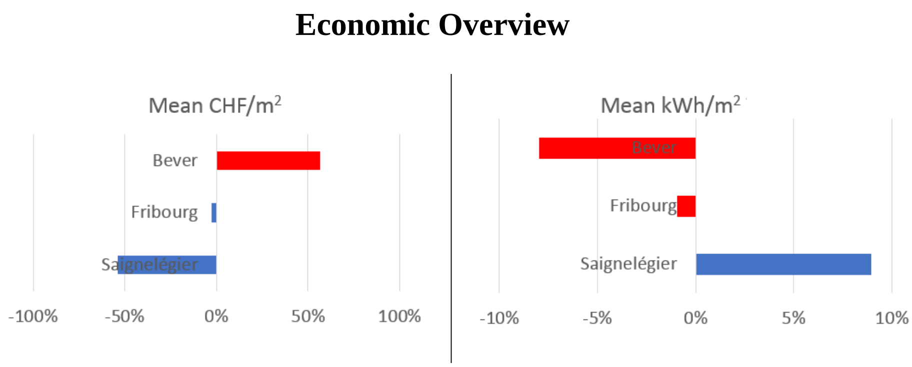

FIGURE 4. Deviation for the three solar process heat plants with parabolic trough collectors from (left) average investment cost value and from (right) the average energy yield of 384 kWh/m^2.

For each solar process heat system in this study the information about total investment cost and cost allocation was acquired via questionnaire. For sake of anonymity, the average investment cost value for the three entire parabolic trough systems (including collector field, planning, system integration etc.) is calculated and the deviation from this is displayed for each individual plant in Fig. 4 (left). In order to couple costs with performance of the individual systems, Fig. 4 (right) displays the difference performance of each field and the mean energy yield per m^2. This representation allows a direct comparison of the economic performance of the plants at one glance.
Figure 5 gives an overview of the splitting of the total investment cost into different categories.
The most expensive system with anyhow the poorest performance, is the plant in Bever, which operates at 180 °C. This system has the highest cost for system integration due to the complexity rising from steam integration and the oil handling. In this results the incurring reparation costs are not even listed, which would lead to even higher cost expenditure. For future systems, it is necessary to find a reliable technical solution to prevent oil leakage, which has reduced the availability of the system immensely.
The collectors in Fribourg were installed on a stand, which increased the roof preparation costs significantly and thus the total investment costs.
The most economic system that shows also the highest energy yield is the plant in Saignelégier. The performance of this plant could even be improved by additional storage volume as mentioned above.

As previously mentioned, all solar process heat systems in this study are pilot and demonstration plants with a high risk for the investors. Each plant was designed individually, which resulted in high costs. In order to move from this pilot and demonstration phase to commercial systems, solar process heat systems need to become more reliable and economically viable with standardized solutions. Although the average cost for the investigated parabolic trough collectors is approximately 880 CHF/m² (or 780 Euro/m^2) and is not much higher than the more conventional vacuum tube collectors at 705 Euro/m^2 [7], there is still an urge to lower the overall costs in order to become an attractive and competitive technology as an energy source for industrial purposes. Lower cost per m^2 can already be achieved by installing bigger plants, such as the one in Saignelégier, which already only costs almost half as much as the small plant in Bever with its area of 115 m^2.

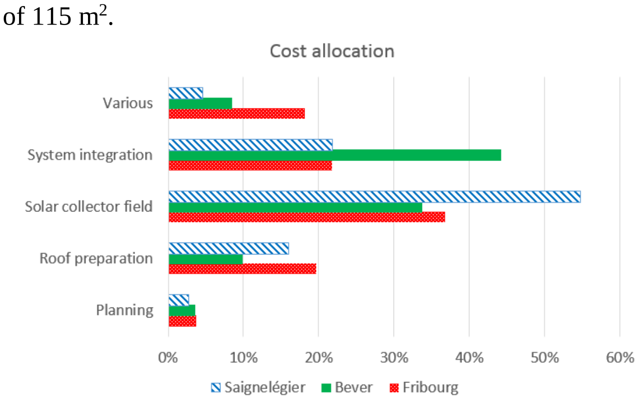

FIGURE 5. Overview of the cost allocation for the three solar process heat systems with parabolic trough collectors.

OUTLOOK AND SUMMARY

This article presents the monitoring results of three solar process heat plants with concentrating parabolic trough collectors providing heat to Swiss dairies. Each plant is at a different location, has different dimensions and operates at different temperatures, from 117 °C up to 180 °C. The smallest plant in Bever has shown most issues in operation, leading to technical challenges and down-time periods due to the high temperature demand of 180 °C. However, the other two plants in Saignelégier and in Fribourg have performed as expected and delivered 264 MWh at 117 °C and a total of 220 MWh at 120 °C and 160 °C, respectively. The plant in Fribourg has shown a constant improvement of the energy yield over the years in operation. This plant was installed, commissioned and integrated into the existing industrial system completely by the same in-house technicians, who since then have operated and maintained the system. The resulting familiarity with the system leads to fewer mistakes, faster failure response and hence less down-times.

In general, the parabolic trough collectors have shown satisfactory performance and fulfilled the expectations of planners and customers. It is clear however, that this technology will only achieve its full potential at locations with higher DNI during the entire year, which then leads to higher annual energy yields. The biggest obstacle for solar process heat systems in general, independent of the collector technology, are the high investment costs, which do not amortize within less than 3 years, as is often required by industrial customers. There is need to cut costs (e.g. by means of standardization and simplification) and to apply new financing methods that lower the risk for the final customers.

1. T. Naegler Int. J. Energy res. 2015; 39:2019-2030, 2015 John Wiley & Sons, Ltd. SOI:10.1002/er
2. M. Battaglia *et al.* Conference Proceedings SolarPaces 2017, Santiago de Chile, Chile
3. M.H. Rittmann-Frank *et al.* Conference Proceedings EuroSun 2016, Palma de Mallorca, Spain
4. J. Möllenkamp *et al.* 27. Symposium Thermische Solarenergie, 10. – 12. Mai 2017 in Bad Staffelstein
5. J. Möllenkamp *et al.* 25. OTTI Symposium Thermische Solarenergie, 6.-8. Mai 2015 in Bad Staffelstein
6. J. Möllenkamp *et al.*Conference Proceedings EuroSun 2016, Palma de Mallorca, Spain
7. D. Ritter *et al.* 27. Symposium Thermische Solarenergie, 10. – 12. Mai 2017 in Bad Staffelstein