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Storage in solar process heat applications

Sebastian Schramm^{a,*}, Prof. Dr.-Ing. Mario Adam^a

^a*Fachhochschule Düsseldorf, Josef-Gockeln-Str. 9, 40474 Düsseldorf, Germany*

Abstract

The subject of this paper is the integration of solar energy into industrial heat supply systems – focusing on the use of solar tanks. Within the framework of the project “Solar Process Heat Standards” funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) load profiles of electroplating processes were measured, a typical load profile was described and simulations were done regarding the dimensioning of the solar tank volume. Depending on the load profile and process temperature, either a large tank volume or a tank-less system leads to the highest solar yields.

Furthermore, a new concept of hydraulic tank integration is presented. It facilitates the quick supply of high solar temperatures which are often demanded for solar process heat applications. State of the art tank integration makes the solar system thermally inert, while simulations and measurements have already proven a considerable advantage of the new alternative.

Moreover four solar process heat applications are analyzed; three belong to the electroplating industry while the fourth uses solar energy for heating water in the food industry (193 – 570 m³). Especially two of the four solar process heat plants presented severe operating errors and a high optimizing potential. One solar plant was improved in order to facilitate the new storage concept. This modification ensures the possibility of shifting between the conventional storage integration and the innovative approach for a comparative evaluation.

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* Corresponding author. Tel.: +49 211 4351464 ; fax: +49 211 4351446

E-mail address: sebastian.schramm@fh-duesseldorf.de

1. Storage integration in the context of electroplating demands

Over the course of several weeks, temperature and power measurements were conducted in five electroplating processes [1]. The data showed characteristically similar load profiles, which can be summarized as follows:

- an early night-time onset of heat consumption,
- the load peak occurs early in the morning,
- the majority of the heat is required during the first half of the day,
- base load during the weekend and during the week in the afternoon and at night.

A characteristic weekly load profile is shown in Fig. 1. A low base load on the weekend and the heating-up of process baths early in the morning is typical of the electroplating industry. The highest peak occurs on Monday morning after the baths have cooled down during the weekend. After the morning peak, the load declines until the afternoon when it drops to base load level. In comparison to the other recorded load profiles, the relation between peak and base load can vary. The base load depends firstly on the temperature of the baths during periods of no production and secondly on whether there are other consumers such as room heating. The temperature of the analyzed electroplating processes varies between 60 and 100°C.

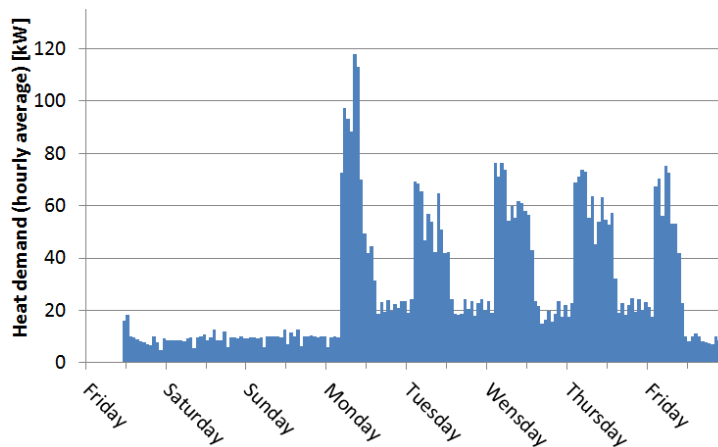


Fig. 1. Load profile of an electroplating process

In the case of electroplating or similar processes, the availability of solar heat and heat demand are not congruent as the majority of the heat is required during the first half of the day, while the solar availability peaks around midday. On the one hand therefore buffer tanks are necessary on the other hand do they prevent that the solar system reaches quickly high temperatures in the morning.

In solar process heat applications, the effective buffer capacity is relatively small due to the insignificant difference between process temperature and maximum storage temperature. In storage design is not the specific volume (l/m^2) that is important but the effective heat capacity (kWh/m^2).

The advantages of a solar tank, namely to buffer solar energy until heat is required, need to be compared to the benefits of tank-less systems. Such systems have the following advantages:

- simple hydraulic integration and automatic control of the solar heat infeed
- less thermal mass / a quick supply of high temperatures
- no heat loss by the storage
- less investment cost

Simulation results

In order to quantify the energetic advantage of solar systems with tanks, simulations with differently sized (and without) tanks as well as different load profiles were done with the simulation tool Matlab[®]/Simulink[®]/CARNOT. The collector field is dimensioned so that during the production there is no surplus solar heat even in best solar conditions. Four different common weekly load profiles were simulated (Fig. 2):

- constant heat demand
- heat demand from 6 am to 2 pm
- heat demand from 6 am to 2 pm, six days a week
- heat demand from 6 am to 2 pm, five days a week

Heat demand from 6 am to 2 pm is rather disadvantageous for solar plants – since significant solar radiation occurs only after 2 pm – while it is beneficial for the use of buffer tanks. Heat demand on six or five days a week corresponds to operational reality given there is no production on Sundays and Saturdays respectively.

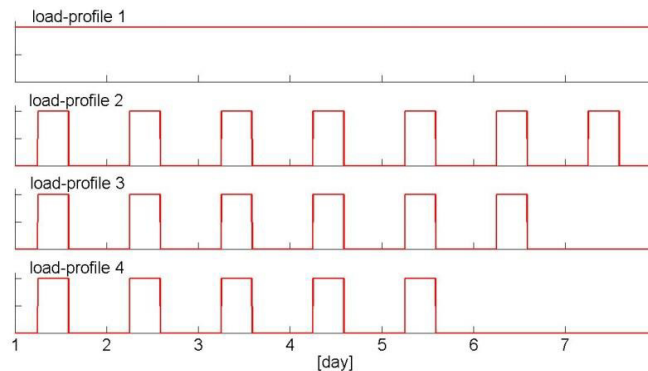


Fig. 2. Load profiles for simulation

The simulated collector inlet temperatures ranged between 60 and 80°C, the heat loss coefficient of the tank was varied between 0,4 and 1,4 W/m²K and the collector yield stretched between 150 and 1500 m² with a constant tank volume (implies a specific tank volume between 10 and 100 l/m²). The choice of parameters results from following aspects:

- The **collector inlet temperatures** are based on the common flowback temperatures in closed heat supply circuits usually found in electroplating (in contrast to fresh water heating). The inlet temperature influences operating temperature and the collectors' efficiency as well as heat losses and the tanks' effective heat capacity.
- The lowest value of the **heat loss coefficient** corresponds to one single, well insulated tank (20 cm, $\lambda=0,045$ W/mK); an optimum which in reality is hardly achievable. Its highest value corresponds to a normally insulated compound (10 cm, $\lambda=0,045$ W/mK) comprising five small tanks (exhibiting a correspondingly larger surface area) as often found at existing solar process heat plants. Any heat losses by means of the distribution system were not considered in the simulation.
- The range of the **tank volume** is rather wide since due to the system conditions both no or very large tank volumes are anticipated as optimum. Owing to the simulation tool, the parameter range was realized by varying the collector field while keeping the tank volume constant. The consumer load was adapted to fit the collector size.

The simulation results demonstrate that the solar surplus yield caused by the use of a tank strongly depends on the varied boundary conditions. Fig. 3 shows firstly solar yields of a system without a tank and secondly the yield bandwidth produced by tanks in different dimensions and with different qualities of insulation for the varied temperatures and load profiles.

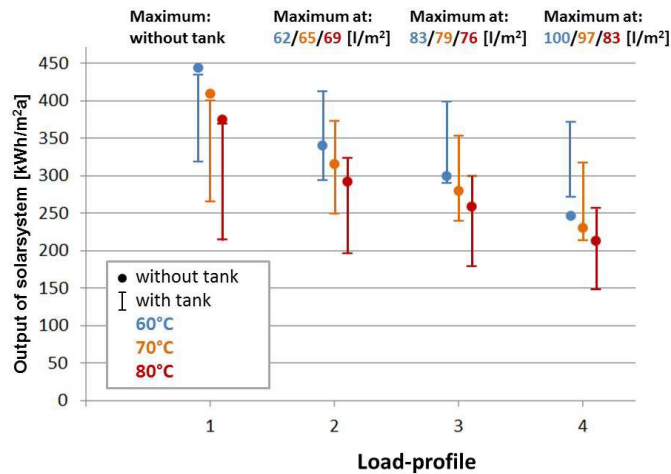


Fig. 3. Simulation results

If there is a constant heat demand (load profile 1), the use of a solar tank reduces the solar yield in any case. As for load profile 1, the maximum attainable solar yield ranges from 375 to 445 kWh/m²/year depending on process temperature. In the case of production breaks (load profiles 2 to 4), tanks may generate both surplus yields and deficit yields within the framework of varied parameters. Maximum attainable solar yields decline in the case of load profile 4 from 260 to 370 kWh/m²/year.

The surplus yields attainable through the use of tanks rise with an increase in production breaks (load profile 2 to 4) and with declining process temperatures. At high process temperatures there are only small differences. For instance, with a process temperature at 80°C, the surplus yield increases in maximum only from 31 kWh/m²/year to 44 kWh/m²/year in comparison to a tank-less system (load profiles 2 to 4, red). However, at a process temperature of 60°C, there is a far greater increase from 72 kWh/m²/year to 124 kWh/m²/year (blue). The requirements for a maximum yield are a good quality tank insulation and a tank volume that matches the collector size, the process temperature and the load profile itself. In the case of load profile 2, the properly dimensioned tank volume and effective heat capacity for low to high process temperatures are 62 to 69 l/m² and 2,9 to 1,6 kWh/m² respectively, while for load profile 4 the values range from 100 to 83 l/m² and from 4,7 to 1,9 kWh/m². For low process temperatures the optimum tank volume and storage capacity increase with the length of the production breaks more noticeably - for 80°C they rise only from 69 to 83 l/m² and from 1,6 to 1,9 kWh/m² respectively while for 60°C the values increase from 62 to 100 l/m² and from 2,9 to 4,7 kWh/m².

Deficit yields are caused by the use of tanks with too large tank volumes and/or bad quality tank insulation. Exceptions are long production breaks and low process temperatures (load profile 4 in blue); here even adverse tank parameters (within the range of varied parameters) lead to higher solar yields.

2. Solar buffer with a dynamically embedded volume

A novelty of the present research lies in the potential of solar systems with tanks to quickly reach high process temperatures.

Currently, state-of-the-art the solar outlets embed hot fluid into different levels of the tank according to temperature. The return flow from the tank to the solar plant is always taken from its lower, cooler part, which benefits the collector efficiency. It is reasonable to use solar energy for low temperatures e.g. for heating fresh water or residential heating. It follows that if the process requires high temperatures, the concept of heat storage bears significant disadvantages. The whole storage volume is involved in the charging process with the result that necessary temperature levels are reached slowly and that only little or no solar energy can be made available for the process heat utilization.

As described above, a main requirement of solar process heat systems, for instance in the electroplating industry, is to reach high temperatures fast and supply them constantly. For this purpose, an innovative storage concept [2] uses a three-way temperature mixer in the flowback to the collector field (see Fig. 5). The mixer's two inlet sides are attached to the tank's upper and lower part. The mixer's outlet leads to the solar heat exchanger. This way, in the case of a cold tank the only part that is actively heated is its upper part. As soon as the required temperature is reached, the valve connection on the tank's lower part opens and a partial volume flow leads through the whole tank. The mixer thereby secures an increase in heated tank volume only after the upper part of the storage volume has been heated to set temperature.

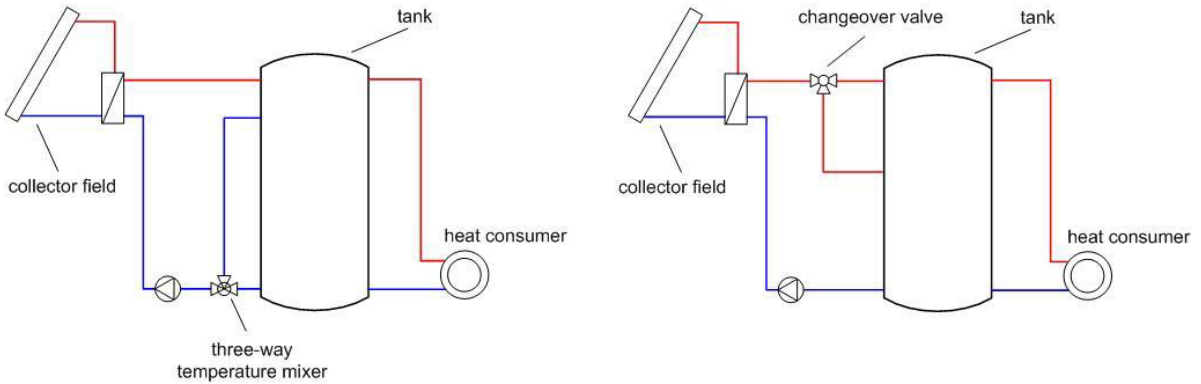


Fig. 5. Storage concepts, concept with dynamic volume (left), state of the art (right)

First measurements in a pilot project as well as simulations prove the dynamic system behaviour of the described storage concept. Fig. 4 shows simulation results of a tank charging process by solar energy through the use of both concepts. The graph presents ten temperature layers as well as the collector inlet and outlet. (The heat extraction by a consumer at temperatures of about 70°C is not depicted.) The concept with the dynamic volume (Fig. 4 bottom) quickly reaches temperatures above 70°C in the upper part of the tank. The mixer has an outlet set temperature (inlet solar heat exchanger) of 65°C and starts to open the port at the bottom tank at circa 11:30 am, so that the solar backflow temperature ceases to increase while the lower part of the tank begins to heat up. The second diagram (top) in Fig. 4 shows the temperature curves of a state of the art tank. The whole tank volume is heated up steadily but reaches 70°C somewhat late (around 1 pm), even though the buffer temperature was hotter in the morning according to the simulation over several days.

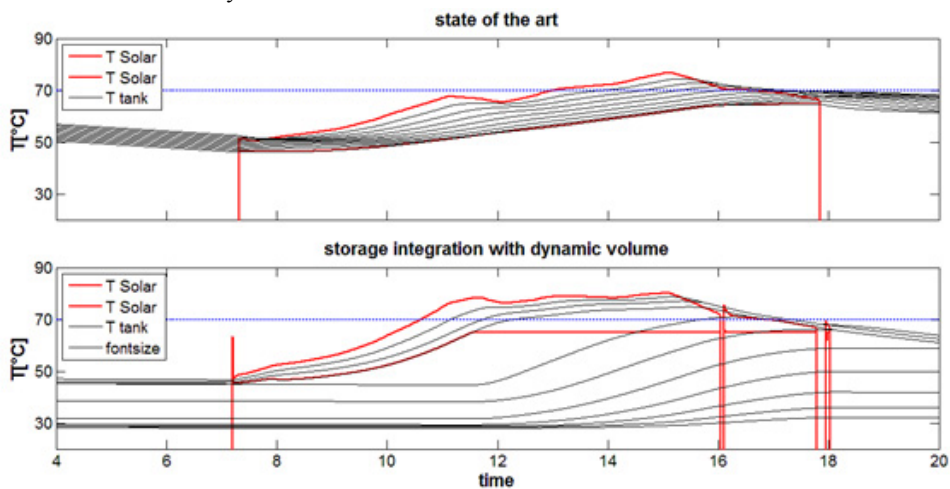


Fig. 4. Collector and tank temperatures, simulation results

To compare different storage integration concepts, a solar process heat application was simulated with a 300 m² collector field, production times from 7 am to 3 pm (five days a week, proportion of peak to base load of 3:1) and a heat demand of circa 8000 kWh/week. Solar energy is used to raise the flowback temperature of the boiler. In simulation periods of two weeks during spring, the tank volume and the process temperatures were varied – between 50 and 100 l/m²_{col} and between 60 and 80°C respectively – on five levels according to the methodology Design of Experiments [3]. With increasing tank volume and increasing process temperatures, the advantage of the concept with a dynamic volume is considerable (Fig. 6). For a tank volume of 50 l/m²_{col} and process temperature of 60°C the surplus yield amounts to 5% and with 100 l/m²_{col} and 80°C close to 25%. The average solar radiation in the simulation period is 4,6 kWh/m²day.

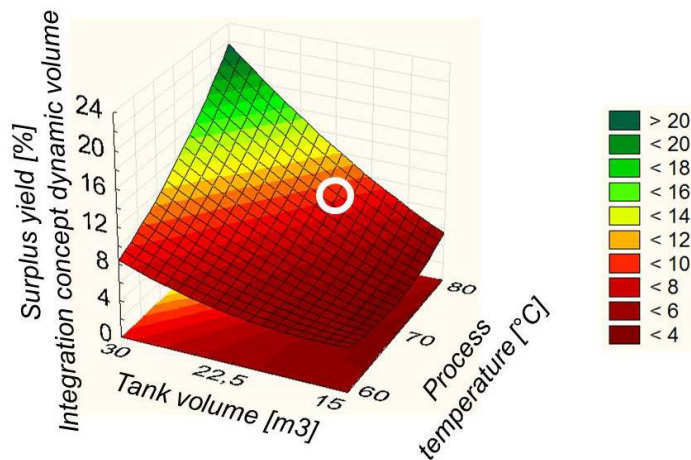


Fig. 6. Surplus yield of system storage with dynamic volume

An annual simulation with a process temperature of 80°C and a tank volume of 22,5 m³ suggests a surplus yield of around 4,5%. For these boundary conditions the benefit is about 10 % in the simulation depicted in Fig. 6.

3. Operating experiences of existing solar process heat plants

Two of the four solar process heat plants (companies Hustert and Viessmann) do not have storage facilities; these have produced satisfying results in terms of operation dependability [4]. Especially with regard to storage integration, the other two plants (companies Steinbach&Vollmann and Merl) exhibited a high degree of unreliability caused by severe errors in planning and installation. For instance, erroneous storage concepts led to a mixing of temperature levels, to a reduction of storage capacity as well as to a transfer of conventionally produced heat into the solar system. These deficits resulted in heat damage which in turn led to plant malfunctions and failures. As a consequence, several heat exchangers, pumps and one partition of a collector field had to be replaced.

In Fig. 7 three severe errors of hydraulic installations are illustrated which were found in one analyzed solar process heat application (Merl):

1. Solar charging of the conventional buffer tank
If a buffer tank for the conventional heating is necessary at all, solar tank and buffer tank should be hydraulically separated. It is not necessary to have a direct connection from solar part to boiler buffer and to heat up the boiler buffer through solar energy (if there is an additional heat-exchanger, see Point 2).
2. Carry-over conventional produced heat into the solar part
If conventionally produced energy is fed into the solar tank, because of consumer backflow it reduces the potential of solar supply. An additional heat-exchanger at the boiler buffer separates the conventional and

solar supply systems. If the consumers need different temperatures, several heat-exchangers can be installed. In the example shown in Fig. 7 the outlets of two consumer heat-exchangers are gathered in one pipe leading to the backup heat-exchanger.

3. Mixing of temperature levels

Consumer backflows with different temperatures should be connected with the tank separately. Otherwise the lowest temperature of the consumer cannot be led to the collectors to improve the efficiency.

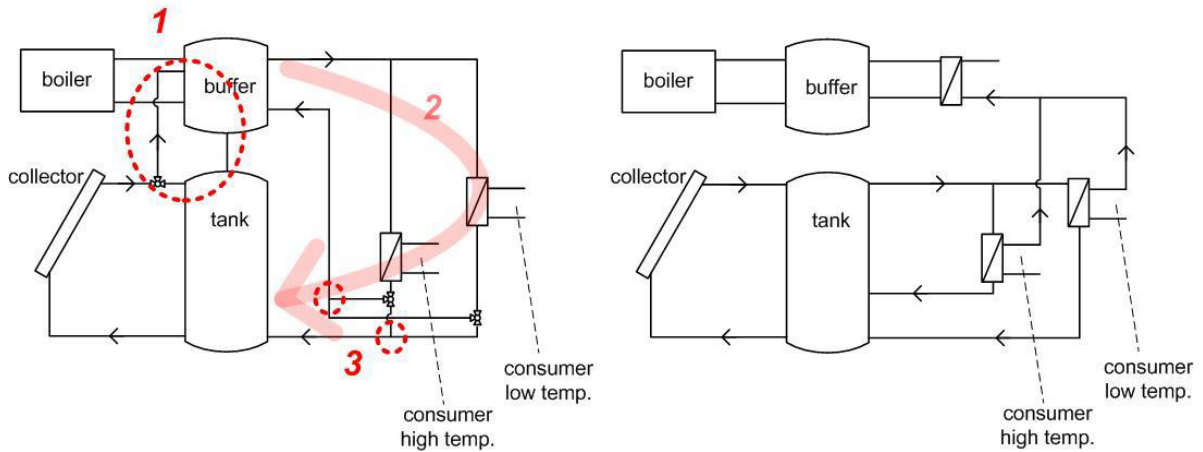


Fig. 7. Scheme heat supply, realized (left), optimized (right)

The other deficient plant (Steinbach&Vollmann) was optimized in view of system integration: the solar tanks no longer operate in parallel but in series circuits. Furthermore, hydraulic and control components were chosen in order to be able to activate both the conventional storage integration and the innovative storage concept (as described above) for a speedy supply of high temperatures. During the summer of 2014, these different storage concepts will be comparatively measured.

Because the solar plants do not have sufficient monitoring, many of these damages and erroneous installations were only discovered by measurements, operation reviews and plant inspections in the framework of the funded project. One reason for this is that failures of a solar process heat plant without function control appear implicitly. A backup heating warrants the heat supply of the process and compensates losses of the solar system. Operating staff neither have the skills and time nor is it their scope of responsibility to supervise the solar plant. The dire necessity of a stationary automatic monitoring is obvious.

Table 1. key information for the analyzed solar plants

Company	Steinbach & Vollmann	Merl	Hustert	Viessmann
Industry	electroplating	food	electroplating	electroplating
Process	bath-, residential heating, hot water	cleaning, flushing of bottles	bath-, residential heating, drying,	degreasing
Collector yield size	80°C	60-70°C	75°C	65-75°C
Collector type	400 m ²	528 m ² (aperture)	220 m ²	193 m ² (aperture)
Solar storage	VRK/CPC	flat plate	VRK/CPC	VRC
Installation date	5 tanks, all 7,5 m ³	11 tanks, all 40 m ³	no tank	no tank
	January 2008	April 2010	July 2011	October 2011

4. Conclusion

The knowledge gained through this project shows that solar process heat has to overcome technical (and economic) hurdles in order to successfully secure itself a place in the industrial heat market as well as to exhaust its potential. The realizations of well-functioning solar process heat plants need to be expedited in order to gain and publicize valuable technical knowledge as well as to standardize system engineering. Scientific support for design and monitoring of new solar process heat applications is advisable. Defective solar process heat applications may have a negative long term effect on market penetration.

It is necessary to pay particular attention to the integration of solar storage. The dimensioning of solar tanks depends intensely on the load profiles and process temperatures. According to system simulations with different boundary conditions and load profiles, maximum solar yields between 250 and 450 kWh/m²/year are reached with buffer volumes between 60 and 100 l/m² (between 1,6 and 4,7 kWh/m² effective storage capacity) or in the case of constant heat demand with a tank-less system. The optimum volume /storage capacity increases with the length of base load and with decreasing process temperatures. In case of high process temperatures, the simulated maximum benefit of a buffer tank is very small; for a process temperature of 80°C it ranges only between 31 and 44 kWh/m²/year depending on base load duration. In this case and in cases of constant heat demand, the complete abandonment of solar tanks may be the most economical solution.

Simulations show that in solar process heat plants with a solar buffer, a new control strategy activating a dynamic tank volume increases solar yields by up to 25%. Especially in periods of low solar radiation, the benefit of this strategy grows with higher process temperatures and larger tank volumes.

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