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Fast Feasibility Assessment for Solar Thermal Systems in Industry

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Abstract

Industry has a large technical potential for solar thermal systems (STS). One main difficulty of realizing this potential is the considerable engineering costs associated with the individual data acquisition and techno-economic assessment of each facility, as they often have unique load profiles, working temperatures, and solar resource. It is important to reduce this effort and simplify the current, but still necessary, sophisticated feasibility assessment. Therefore, a guideline is developed to support a quick and accurate analysis for the integration of STS in industrial processes.

The concept is based on the preparation and processing of an energy audit to identify the main heat consumers and to assess the integration points. The feasibility assessment of a STS for identified processes is performed by pre-dimensioning the collector field and storage volume, while including a yield assessment for the STS. Therefore different process' load profiles, working temperatures, collector technologies, and solar resources are examined and included as nomograms into the guideline. With this, planners are able to obtain a quick but reliable estimation of the costs and performance of solar thermal systems.

Keywords: Process Heat, Solar Thermal Systems, Feasibility, Integration, Dimensioning

1. Introduction

Although there is a large potential for solar process heat, the market has grown slowly due to the lengthy feasibility assessment. One crucial reason for this is the lack of means for the hydraulic connection to the existing processes and the pre-dimensioning of the collector field and the storage. To promote development in the market, successful pilot projects are needed in a range of suitable sectors. These projects must show that solar thermal is a highly reliable and cost-effective technology to supply heat for industrial needs.

One important reason for slow market development is the still necessary sophisticated feasibility analysis which often impedes such pilot plants. Before starting with the detailed planning of a STS, it is necessary to first know whether or not a company has desire to use solar heat and how it can be integrated into their existing process. Additionally it is essential to choose a suitable solar technology, determine the collector field and storage size, and estimate the annual solar yield. This information is needed to calculate the project and energy costs, normally the most important deciding factor for a STS. The difficulty with this methodology is that it takes significant time and resources to obtain the pertinent data, so most planers do not included STS in their analysis. As such, this additional cost and time hurdle limits the market development for solar thermal systems in the industrial sector.

Therefore within the framework of the project "SolFood – Solar heat for the Food Industry", funded by the German Federal Ministry for Economic Affairs and Energy, a guideline has been developed which allows a faster and more simplified feasibility assessment for solar thermal systems in industry. Additionally, there will be case studies in the food industries to initiate best practice pilot systems. For more information see www.solfood.de.

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2. Feasibility Assessment

Besides the pre-dimensioning and yield assessment, the guideline explains necessary steps to develop a suitable STS. These steps consist of:

- Assessment of some data collected via questionnaire to decide whether or not there is a theoretical potential for the integration of a STS into the existing thermal processes
- Preparation and processing of audits on the production side to identify the relevant heat consumers
- Assessment of heat recovery measures and energy efficiency for intersectoral equipment (compressor, steam generator, chiller…)
- Evaluation and selection of potential integration points for a STS

After this, the hydraulic connection and appropriate collector type can be chosen. Based on these decisions, the guideline describes the approach for the pre-dimensioning of the collector field and the storage. Therefore values for various locations, process temperatures, load profiles and collector types are taken into account to cover most low temperature (< 100 °C) processes in industry.

For the pre-dimension of a solar field, the approach from (VDI 6002) can be adopted from a focus of DHW to the realm of process heat for industry. This approach relies on the dimensioning of a field based on a "good" summer day (VDI 6002), which often yields between 7-8 kWh/m² of solar radiation per day. This design point leads to an economically favorable sized system in which excess heat energy produced in summer is prevented. The heat energy load profile is the main difference between the design phase of a solar thermal system for process heat generation and domestic applications, which varies in both the consumed temperature and daily/weekly/annual load profile. The heat store is dimensioned in accordance to the weekly load profile. Typical annual utilization ratios of selected low-temperature process heat applications are then determined to facilitate the estimation of a system yield, critical for its economic feasibility assessment. In addition a classification of industrial heat consumers is necessary to assess potential integration points for the STS. These aspects are illustrated in detail in the following sections.

3. Classification of Industrial Heat Consumers

Industrial processes contain numerous different heat consumers, all of which have difference thermal and temporal operating parameters. To assess the multitude of potential integration points, a sector-independent classification of industrial heat consumers was developed (Schmitt 2014). This classification is especially helpful to unexperienced developers and technicians which might handle projects in the field of solar process heat.

The developed classification (see picture below) respects all relevant boundary conditions for the integration of a STS into any existing system. It is first divided into two levels, Supply and Process. The supply level is the transport medium of heat energy, directly coming from the main input heat source (i.e. Gas/Oil boiler, Solar, Heat Pump, etc.). The process level is the type of function or use the heat energy from the supply level provides to the industrial equipment, normally through a heat exchanger.

The Supply level is differentiated according to its heat transfer medium, whether it is "Steam" (normally saturated) and "Liquid Heat Transfer Media" (normally pressurized water). This leads to the six potential applications, such as steam generation or increasing return flow temperature. For each of the six applications, integration concepts have been developed and can be further explored (Schmitt 2014).

The Process level is differentiated into the three categories of heat consumers "(Pre-) Heating", "Heating & Maintaining Temperature" and "Thermal Separation" to which every process can be assigned to. It is important to note that the heat transfer medium is not so important due to a heat exchanger between the Supply and Process lines, and this helps to determine the integration of a STS into the conventional heating system.. Shared between the three Process categories are five general options for conventional heating: use of internal or external heat exchangers, steam injection, dryers, or evaporators. For example, internal heat exchangers include tube bundles and coils, heating jackets, electric heating elements and direct burners. For each conventional heating method (Figure 1) integration points on the Process level were developed and their concepts can be found in (Schmitt 2014).

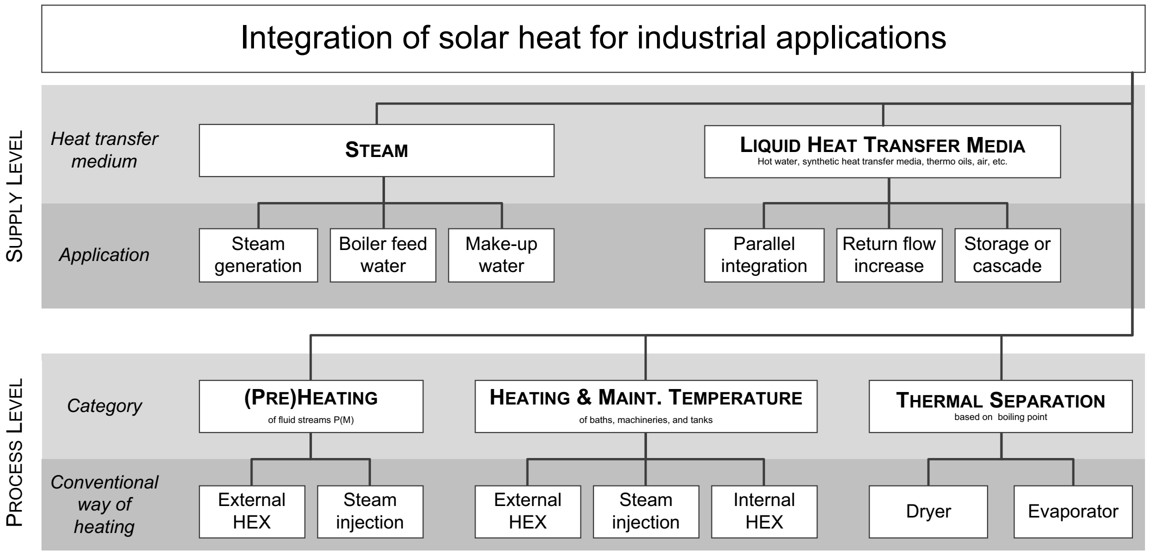


Figure 1 - Classification of industrial heat consumers for the integration of solar heat (Schmitt 2014)

Once a suitable heat consumer on supply or process level is identified, one or more STS integration concepts are given. These options are normally reduced by the boundary conditions on the production site: solar radiation, desired temperature, industrial equipment, mode of operation. If more than one integration point is possible, all need to be compared in detail by using three main criteria: temperature supplied by the solar system, load profile, and complexity of integration.

For each integration concept suggested in the classification, there is a simplified hydraulic flow chart to visualize integration, where the STS integration point into the existing process or into the existing heat supply system is shown. The figure below shows the PL_S_LP integration concept, which signifies that: The integration is on process level (PL), which will heat a suitable tube bundle heat exchanger to generate steam (_S), which is supplied by the STS on a low pressure level (_LP). Therefore, solar heat can be used directly to heat this process to reduce the energy demand of the conventional system, which is through direct steam injection from an oil/gas burner (Figure 2).

The shown integration concept with the parallel steam production is a relative simple way to connect a STS to an existing process, but the required temperatures are fairly high. Regardless, the heat energy provided from the sun is normally significantly lower than temperature of the conventionally supply system with e.g. 180 °C.

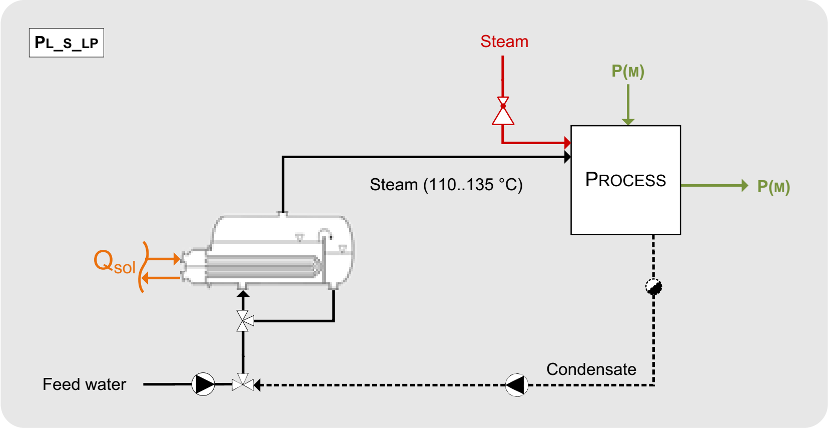


Figure 2- Example of an integration scheme for solar supplied steam on a low pressure level for a process conventionally heated by direct steam injection from fossil fuel burner (Schmitt 2014)

4. Sizing of Collector Field and Storage

A few critical pieces of information are needed in order to conduct a quick pre-dimensioning assessment for feasibility, which consist of both an estimate of the *heat energy supply (solar energy)* and *heat energy load (industrial process)*. Heat energy supply depends on the location of the facility and collector type/orientation. Heat energy load depends on the industrial process temperature and integration point, and energy load profile/duration.

Location: The location of potential solar thermal facility dictates the annual heat yield of such facility, as it can be logically assumed that more energy can be generated in a sunnier location. The presented pre-dimensioning method includes representative climates in Europe which cover the bulk of possibilities throughout the world. In order to use this method, an estimate of the annual GHI (Global Horizontal Irradiation (kWh/m²a)), or radiation on a tilted surface (tilt angle = latitude - 15°) or H_t, should be obtained for the location of interest. Assuming that this value is between the values in the chart below, an interpolation can be made to better estimate the solar field, storage size, and annual yield.

Table 1- Locations and related parameters used for the sizing of the collector field and storage

Location	**Latitude**	**Global irradiation** [kWh/(m²a)]	**H_t** [kWh/(m²a)]	**July days > 7 kWh/(m²d)** [-]	**$H_{t\_day\_avg}$** [kWh/(m²d)]
Copenhagen	55.7	988	1191	9	7.61
Wuerzburg	49.8	1094	1264	11	7.54
Toulouse	43.6	1351	1552	14	7.81
Madrid	40.5	1660	1887	20	7.76

Table 1 shows annual global horizontal and tilted irradiation as well as the number of days with more than 7 kWh/(m²d) and the average daily irradiation for those days on a tilted surface for Copenhagen, Denmark (a moderate, northern European climate), Würzburg ,Germany (warm, central European climate), Toulouse, France (moderate southern European climate), and Madrid, Spain (Mediterranean, continental climate).These "good" summer days are used for the collector field design in the following.

Load Profile: The process heat load profile is important to understand as the collector field and storage must be sized accordingly. Load profiles are split into three section, Daily, Weekly, and Seasonal. A full list of different types can be found in (Lauterbach 2014). The relevant load profiles are shown in (Figure 3).

Daily profiles occur over 24 hours, with typical profiles like Daytime (8h -18h operation), Constant (24h operation), and Cleaning (peak evening load), and their respective profiles are shown below. The weekly profile is important for the dimensioning of the collector field and especially the heat store. Further, the achievable annual system yield is influenced by the weekly profile as well. Most relevant/important examples of typical weekly profiles are Constant and 5 day peak. The annual load profile is important for the determination of typical annual system yields for different process heat applications. Six profiles were created, with most common being Constant, Summer Peak, and Space Heating.

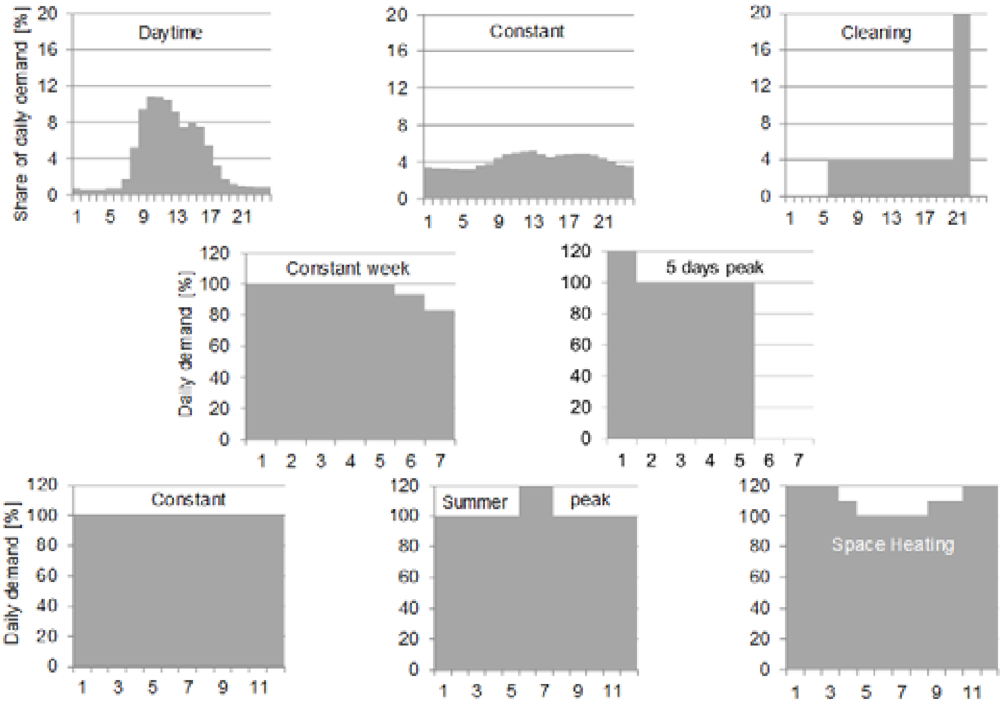


Figure 3- Daily, weekly and annual Load Profiles

Desired temperature level: The temperature level of an industrial process obviously has a strong influence on the design of the overall solar heat system and the dimensioning of the collector field, as its efficiency depends strongly on the provided temperature. Various temperature levels have to be considered although the pre-dimensioning exercise is focused on process temperatures below 100 °C (Table 2).

These values were selected as they represent temperatures found in all three common process heat applications, pre-heating of fluid streams, heating of baths/vessels/stores, and thermal separation processes. If a process does not align with the temperature list above, one can pre-dimension a system for the two most closely aligned temperature ranges and interpolate.

Table 2- Temperature ranges used for the pre-dimensioning exercise

Temperature [°C]	
Return	**Flow (max.)**
15	60/80
30	60/80
40	70/90
50	80
60	90
70	90
80	95

Sizing of collector field

The approach of VDI 6002 (VDI, 2004) to dimension the collector field for summer days with good irradiation shall be utilized for process heat applications. Both design approaches, the VDI 6002 and the one proposed here, avoid gaining excess energy generation during peak load and therefore lead to an economical STS. To determine the collector field size with minimal excess energy generation, a design point is chosen for which the solar fraction on a typical summer day is just below 100 %. Referring to domestic hot water systems, the utilization ratio on a good summer day is approximately 50 %. This leads to an amount of 4 kWh/(m^2_{ap}d) that can be delivered to the heat consumer (hot water preparation). However, varying boundary conditions in Industry such as process temperature and load profile can lead to different utilization ratios. Therefore, a detailed simulation study was carried out to generate design values for the dimensioning of collector area. Several scenarios, which vary the location, desired temperature range, collector type, and the daily, weekly and annual load profiles, were considered to obtain realistic values for the available load corresponding to a given process.

To determine a design point for the collector field size, a specific heat energy load per square meter (kWh/m^2) on the X axis (Figure 6) is selected on a good summer day which will cover just below 100% of said load (i.e. solar fraction/coverage rate) on the Y axis. Figure 6 shows an example of the solar fraction and the utilization ratio on a good summer day (left) and over the year (right) for two processes with different process temperatures (orange line: 15-60 °C and black line: 40-70 °C, a flat-plate collector, the daily load profile "daytime "in Würzburg). Other temperature ranges, load profiles, locations, and collector type combinations can be found in (Lauterbach 2014). Depending on the supply and return temperatures a process has (i.e. 15-60 °C or 40-70 °C), different values for the specific heat energy load at which the solar heat energy can supply at nearly 100% is determined. The value for this specific heat energy load, which leads to a solar coverage rate of just under 100%, can be used as design value (q_{design}) for the collector field.

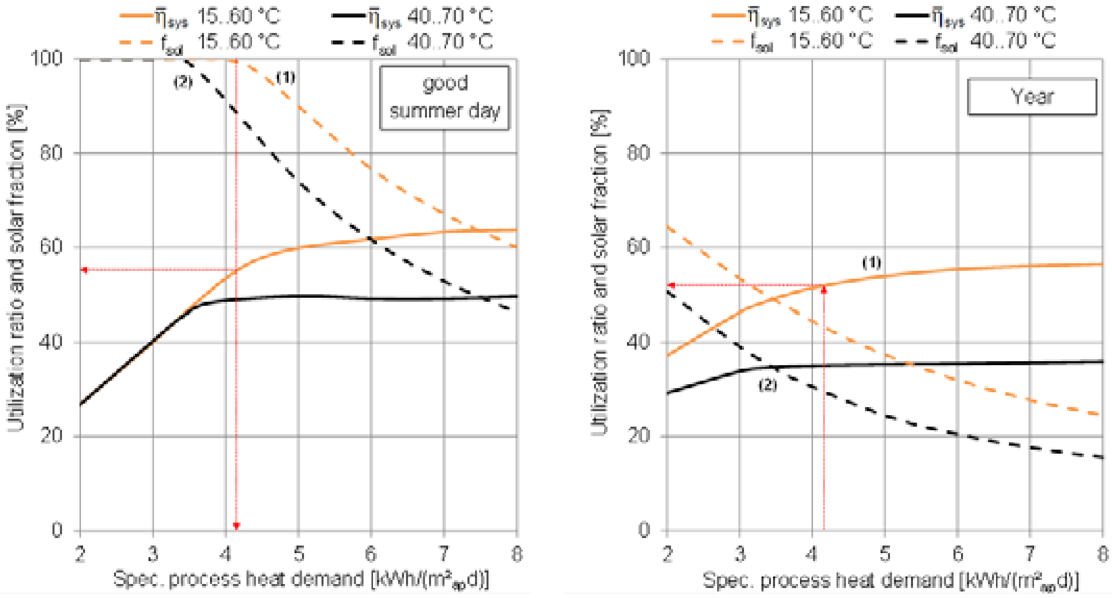


Figure 4- Daily (left) and annual (right) simulation results of the utilization ratio and solar fraction for Würzburg with a flat plate collector and daytime load profile

As can be seen from Figure 6, the values for q_{design} at 4.1 kWh/(m²d) for process temperatures 15-60 °C and at 3.4 kWh/m²d for 40-70 °C. This means that one m² of collector area (in this case, "good" flat-plate collector) should be installed for every 4.1 and 3.4 kWh of process heat load per day, respectively.

If the typical daily process heat load for one or more points of integration is, for example, 1 MWh, with a supply and return temperature of 70 and 40 °C, respectively, the total net collector area can be calculated as follows:

$$A = \frac{Q_{\text{Process heat, day}}}{q_{\text{design}}} \qquad \text{(eq. 1)}$$

$$A = \frac{1.000\ \text{kWh/d}}{3{,}4\ \text{kWh/(m²*d)}} = 294\ \text{m}^2$$

Figure 6 (right) shows the annual utilization ratio for the specific heat energy load of the process temperatures 15-60 °C and 40-70 °C. At these points 4.1/ 3.4 kWh/(m²d), respectively, the annual utilization ratio no longer increases significantly as the higher specific heat load increases. Thus, the design value (q_{design}) represents a lower limit for an economic interpretation. A higher value would have a smaller collector field, but should have limited, if any, negative impact on the economics; as long as the specific costs of the solar system do not increase (smaller projects often have a greater per unit cost, hence the logic behind “economies of scale”). Smaller values for q_{design} however, lead to lower specific system yields and may worsen the economics. In very favorable process heat applications with high energy yields (very good location, low process temperatures), a smaller q_{design} could be used (larger solar field) which may produce a more economically viable project due to economics of scale and other factors. This must be (through simulations) examined in the context of detailed planning, however.

The estimation of the daily process heat load of a selected integration point is of great importance. Normally, a typical production day in July or August should be chosen to avoid frequent stagnation and thus solar surpluses. It may also be useful to choose a typical production day in spring or autumn for interpretation if the process heat load at these times is typically low, as a number of days occur in April or October with high solar radiation (potential causing stagnation). Furthermore, it may be useful to undersize the solar field (higher q_{design}) with none or with very little thermal storage. This is especially true for high process temperatures since the heat losses can be reduced by minimizing the storage size.

Sensible design values for different process temperatures and collector types in Würzburg and Madrid are shown below in Figure 7 (design values for other locations and load profiles can be found in (Lauterbach 2014)). As indicated, the design values (q_{design}) are in the range of 2.0 to 5.0 kWh/(m²d).

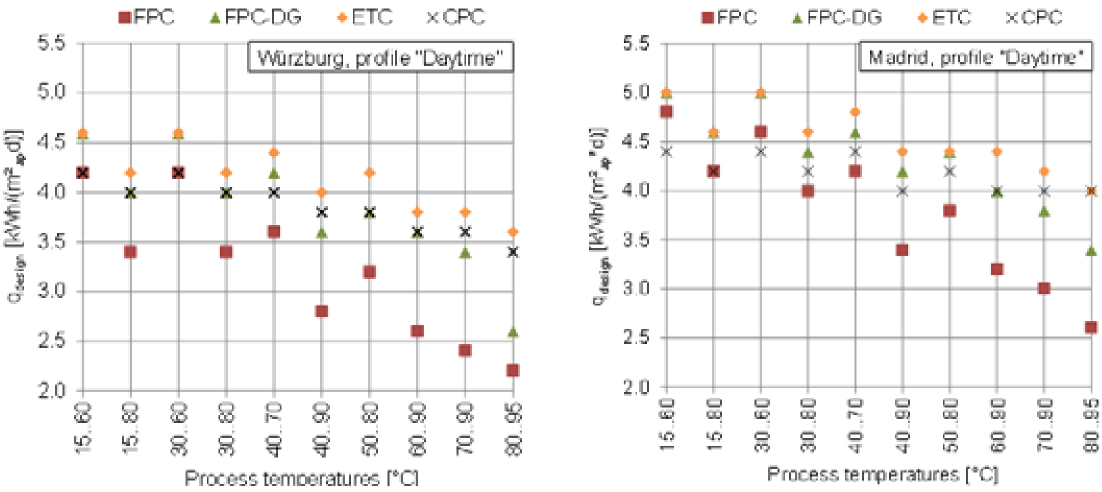


Figure 5- Design values for difference process temperatures and collector types, for Würzburg (left) and Madrid (right)

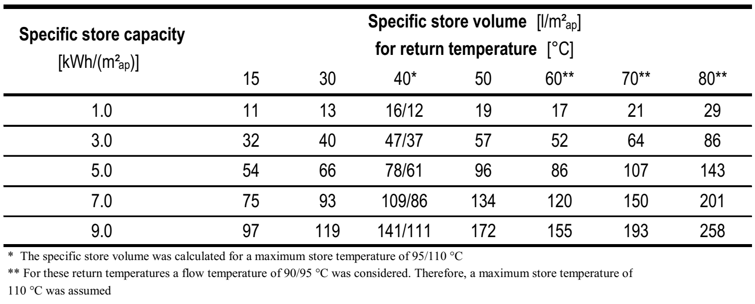
The choice of a suitable collector plays an important role in the planning of a solar process heat system. As stated before there are a handful of different types of collectors suitable for process heat below 100 °C, which consists of standard flat-plate collectors (FPC) and one with a second cover (FPC-DG), vacuum tube collectors (ETC) and compound parabolic concentrator (CPC) collectors. The selection of a collector type and the final plant size can only be done when including information about the annual yield, the specific process heat application, and the cost of the collector. At process temperatures < 50 °C, inexpensive flat plate collectors (FPC) in most cases are best suited. As process temperatures increase (> 80 °C), the efficiency of FPC decreases rapidly, and other, more expensive, collectors (ETC) may soon become the more economical solution, as their efficiency remains higher at said temperatures. FPC may also be used in locations with high radiation and high outdoor temperatures, as long as it has the economic justification.

Sizing of storage volume

Likewise simulations were carried out to gain design values for the dimensioning of the heat storage. The available capacity of the heat storage depends on the process return temperature into the storage and its maximum temperature. The necessary storage volume will increase with a higher return flow temperature as the possible temperature lift in the storage and therefore its' specific capacity are decreasing. For example, if a specific store capacity of 5.0 kWh/(m²d) is desired with a return flow of 80 °C, there would be a need of a specific storage volume of 143 l/m² even if a low pressurized tank with a maximum storage temperature of 110 °C is assumed.

In the preliminary design of the storage, VDI 6002 recommends a size of 50 l/m² for large drinking water systems. However, since the process heat load profiles are much more varied, a wider range of storage capacities must be taken into consideration. The storage capacity of the solar storage tank depends on the process return temperature and the maximum storage temperature.

Table 3- Specific storage capacity based on the fluid return temperature



Specific store capacity [kWh/(m$^2_{ap}$)]	Specific store volume [l/m$^2_{ap}$] for return temperature [°C]						
	15	30	40*	50	60**	70**	80**
1.0	11	13	16/12	19	17	21	29
3.0	32	40	47/37	57	52	64	86
5.0	54	66	78/61	96	86	107	143
7.0	75	93	109/86	134	120	150	201
9.0	97	119	141/111	172	155	193	258

* The specific store volume was calculated for a maximum store temperature of 95/110 °C

** For these return temperatures a flow temperature of 90/95 °C was considered. Therefore, a maximum store temperature of 110 °C was assumed

Table 3 shows the specific storage capacity in l/m² for various specific storage capacities as dependent to the return temperature of the process.

The dimensioning of the collector field and selection of the specific process heat load affects the sizing of the storage. Large-scale collector fields (lower specific load) normally have a higher specific storage capacity than for small-scale collector (higher specific load) which have a lower specific storage capacity. As previously discussed, the typical specific process heat load is in the range of 2-5 kWh/(m²d), with reasonable values for many process temperatures in the range of 4 kWh/(m²d).

Figure 8 shows an example of the change in the annual system yield for various specific capacities and load profiles for a process temperature 15-60 °C and a specific process heat load of 4 kWh/(m²d). As the figure (left) shows, an increase in the specific storage capacity from 5 kWh/m², for the daily load profile "Daily load - Constant week" profile, does not show a significant increase to the annual system yield. However, a reduction of specific storage capacity to 3 kWh/m² leads for the same profile to only a 2% reduction in annual system yield. For the "Daytime - 5 day peak", system yield is reduced by 5%, while an increase of the specific capacity to 7 and 9 kWh / m$^2_{ap}$ results in a higher, but not too significant, increase of the annual yield.

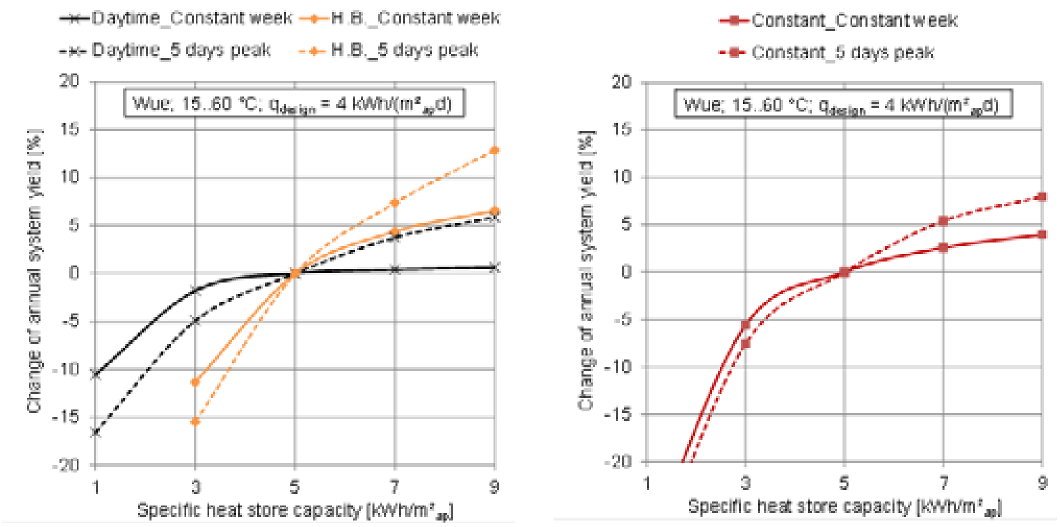


Figure 6- Change of annual system for three configurations, Daytime (left), Heated Bath (left), and Constant (right)

For the daily load profile "Heated Bath (H.B.)," the annual system yield decreases significantly when specific storage capacity also decreases. Also, there is a significant increase (especially when heat is required in only 5 days per week) to the annual system yield when a larger specific storage volume is used. For the daily load profile "constant", Figure 8 (right) shows a reduction of the specific storage capacity reduces the annual system yield more than in the profile "Daytime," but increasing the capacity does not greatly increase the annual yield.

In some cases it may be possible and appropriate to reduce the specific storage capacity to 1 kWh/m². This is true for a constant weekly profile with a specific process heat load of >6 kWh/(m²d), the daily profile "Daytime" at > 10 kWh/(m²d) for a daily profile "Constant," especially at higher process temperatures. Solar systems with such small-sized collector arrays (large available load) can be installed with no (or very little) storage, however leads to a reduced annual system yield, but it does realize a system at lower cost. Another advantage of such a system is a slightly lower system temperatures, in which heat exchangers can be eliminated. The design of such systems require more detailed information about the load profile, which usually are not yet available as part of the planning process. Therefore, they should be designed based on more detailed load profiles via simulation.

For the accurate estimation of a suitable storage capacity, the cost of a larger storage should be assessed versus the increase of annual yield. There is a point where having an increased storage size is beneficial, but eventually becomes oversized and the full volume of the tank is never used. Generally speaking, the sizing of a storage tank can generally be estimated by the daily energy yield during the peak summer day (for 5/6 day work weeks). The specific storage size can quickly be estimated by:

$$V_{stor} = \frac{H_{t\_day\_avg}}{\rho C_{p_{tank}} * \Delta T_{process}} \qquad \textbf{(eq. 2)}$$

This "rule of thumb " is chosen as most manufacturing processes occur during the daytime and not a great amount of storage is needed to shift the heat supply to other times in the same day. Having one day of storage allows for some heat supply shifting, stagnation prevention, and utilization of energy on Monday morning, where energy demands are larger than normal since the facility cools down over the weekend (particularly helpful for heated bath applications). There may be case where oversizing both the collector field and storage may yield in a more economic cost of heat energy (higher annual energy yield and a lower specific project cost due to economies of scale), but this has to be determined by simulation, and is outside the scope of this quick pre-dimensioning assessment exercise.

These annual utilization ratios for various daily and weekly load profiles, process temperatures, collector types and specific storage capacities can be taken from (Lauterbach 2014). Together with the current costs for various storage sizes; one can determined whether an increase or decrease of storage volume would produce a more economically viable project.

5. Yield Assessment

The annual system yield is the most important value for assessing the economic feasibility of an STS besides system cost. This yield is influenced by many factors like temperature level, load profile, collector type, and location. Therefore utilization ratios were developed with respect to these important factors. These ratios can be used to calculate a system yield for various locations as the estimation of a utilization ratio for a location not covered in the guideline is much easier than estimation of an annual system yield.

In (Lauterbach 2014) utilization ratios for various process heating applications in selected locations can be found, which can be used to estimate the yield of solar thermal process heat plants at nearly any other location. This is possible because the estimation of the yield for other locations as shown here is much simpler, since the utilization ratio for different locations is quite similar, and thus the annual yield is mainly a function of the solar radiation available at the location of interest. The system utilization ratio is defined as follows:

$$\eta_{sol} = \frac{Yield^{annual}_{simulated}}{H_t} \qquad \textbf{(eq. 3)}$$

To estimate the annual yield for any given location, the equation can be rearranged.

Here, a slope is assumed for the collector, which corresponds to the latitude of the site, less 15°. Figure 9 shows examples of the utilization rates for different process temperatures, collector types, two different weekly profiles and the daily load profile in Würzburg. Detailed values for additional locations and shapes can be found in (Lauterbach 2014).

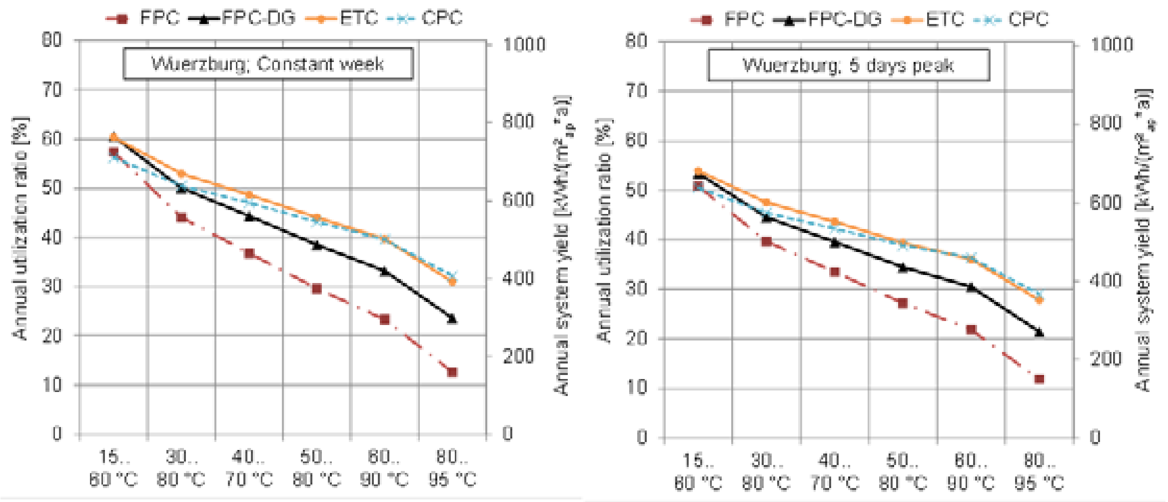


Figure 7- Annual utilization ratio in Würzburg for different temperatures and collector types, for the Constant weekly profile (left) and 5 day peak (right)

In order to estimate the yield variations due to different annual load profiles, the simulation was rerun which resulted in Figure 10. It turns out that a production break of two weeks reduced the yield by about 5% in the summer. If process heat is only needed during six summer months, the annual system yield reduced by about 25% in Würzburg and about 33% in Madrid. An increased demand for heat (with the same collector array size) in summer and heating in winter has little effect on the annual system yield. It should be noted that the collector field can optionally be dimensioned larger to compensate for an increased heat demand in the summer.

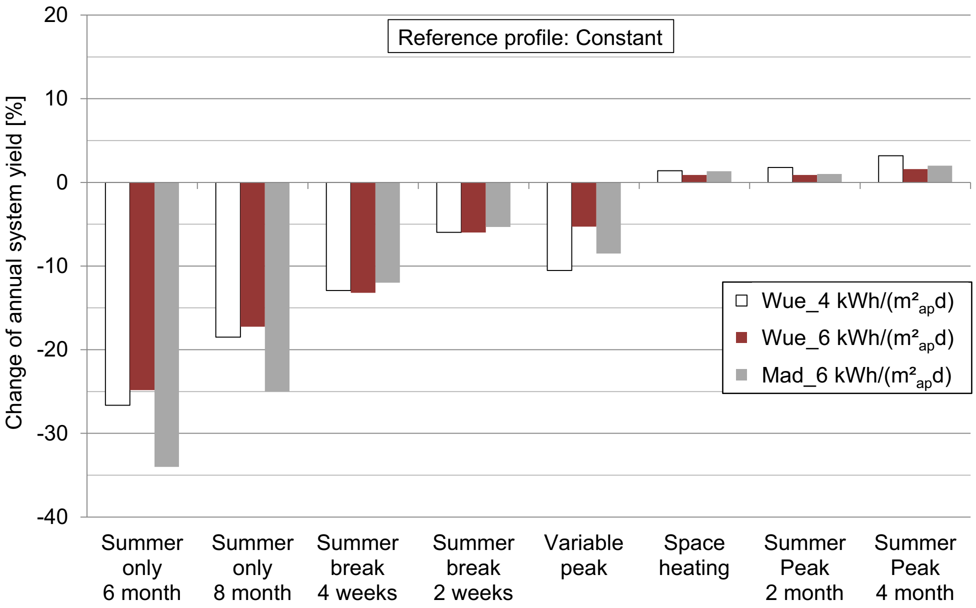


Figure 8- Sensitivity analysis of the annual system yield by varying the annual load profile

6. Outlook

The described guideline for detecting main heat consumers, heat recovery potential, and integration points, for pre-dimensioning the collector field and storage, and calculating thermal yield, can quicken and simplify the feasibility assessment for STS in industrial processes below 100 °C. It is important to validate this approach by using it in industrial case studies so planners may gain confidence in this analysis technique. As such, the validation will be done via case studies in the previously mentioned "SolFood" project in the food sector. If the benefit of the guideline can be demonstrated within the case studies and it gains conceptual and physical understanding within the desired target groups, there is a good chance that planners will take STS for industrial processes into account for future projects.

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