SOLAR PROCESS HEAT – SYSTEM DESIGN FOR SELECTED LOW-TEMPERATURE APPLICATIONS IN THE INDUSTRY

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1. Abstract

Industrial process heat accounts for more than 20 % of the final energy consumption of the European Union. This sector is a very promising but also challenging application field for solar thermal technology. In this paper, the potential of solar thermal systems to generate heat for industrial processes is described and the state-of-the-art is discussed. The IEE dissemination project SO-PRO, which works on decreasing the barriers for solar process heat generation is introduced. Interim project achievements and results are presented. In the project, a Design Guide, promoting a holistic planning approach for low-temperature solar process heat was elaborated. The most important conclusions for solar thermal system design for four industrial applications are summarized on the following pages. Complementary to the guide, the usage of design nomograms and their limitations are illustrated in detail. A system design example for a cleaning process is also discussed.

2. Process Heat Demand, Potential for Solar Thermal and Status Quo

2.1 Process heat demand

The final energy consumption of the European Union (13,609 TWh in 2006) can be divided into electricity and transport (51 %), high temperature heat above 250 °C (15 %) and low temperature heat below 250 °C (34 %) (Weiß and Biermayr, 2009). Industrial processes account for 44 % of the overall heat demand (2,934 TWh/a). Almost the whole high temperature heat demand is process heat, since 68 % of the industrial heat demand has to be provided at temperatures above 250 °C (Sanner et al., 2011). Fig. 1 shows that within the low-temperature heat demand below 250 °C (4,640 TWh/a), industrial processes have a share of 19.5 % or 905 TWh/a (Weiß and Biermayr, 2009).

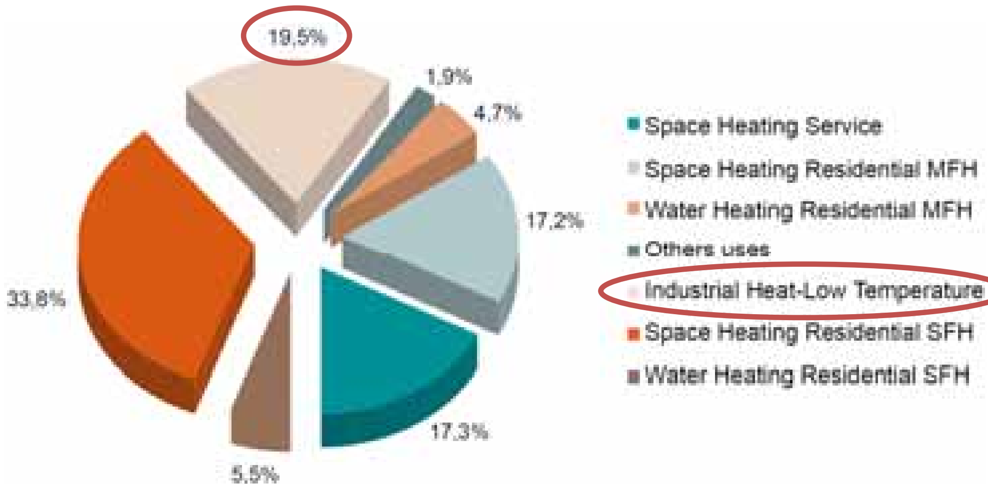

Fig. 1: Distribution of the low-temperature heat demand < 250 °C (4,640 TWh/a) by type of use in the EU (2006). SFH = single family house, MFH = multi family house (Sanner et al., 2011)

2.2 Solar thermal potential for process heat generation

To estimate the potential of generating industrial process heat with solar thermal technologies, it is essential to look at the required temperature levels in detail. Fig 2 shows that in Germany as a typical industrialized country 21 % of the industrial heat demand can be provided at temperatures below 100 °C, 6 % between 100 °C and 150 °C, 4 % between 150 °C and 250 °C and very similar to the European average 69 % above 250 °C (Lauterbach et al., 2011). The share below 100 °C includes hot water and room heating demand.

Several national and international projects proved the high potential of solar thermal systems to generate industrial process heat and identified the most promising and suitable industrial sectors and processes. The most comprehensive studies are POSHIP (Schweiger et al., 2001), PROCESOL II (Aidonis et al., 2002) and PROMISE (Müller et al., 2004). Among others, the industry sectors of food and beverage, textiles, paper, metal treatment, machinery as well as wood and tobacco processing were identified to be promising.

The potential study of the IEA-SHC/SolarPACES Task 33/IV "Solar Heat for Industrial Processes" summarized the main outcomes of the existing potential studies (Vannoni et al., 2008). For Germany, a potential study was elaborated by Lauterbach et al. (2010). In a first step, Lauterbach et al. (2011) identified Germanys promising industrial sectors and summarized their heat demand below 250 °C including the demand for domestic hot water and space heating. The demand above 250 °C was excluded. This way a technical potential of 130 TWh/a was estimated. It was assumed that 60 % of this theoretical potential could not be used due to the priority of energy efficiency measures, the necessity of electrical heat supply (e.g. for plastic products) or restrictions in terms of available roof area. For the remaining potential Lauterbach et al. (2011) suggest an average solar fraction of 30 %. These restrictions result in a potential of approx. 16 TWh/a for Germany, corresponding to 3.3 % of Germanys overall industrial heat demand (or approx. 10 % of the industrial heat demand below 250 °C).

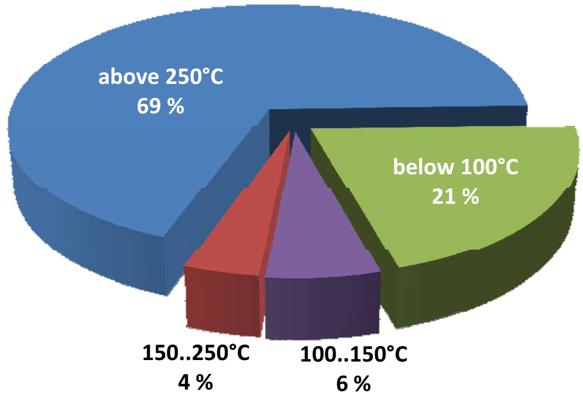

Fig. 2: Industrial heat demand in Germany per temperature range (based on Lauterbach et al., 2011)

For Europe, Vannoni et al. (2008) roughly estimated a potential of 3.8 % of the industrial heat demand. For the 2,934 TWh/a process heat demand in the EU 27 calculated above, the estimated potential would be about 111 TWh/a or approx. 250 Mio. m^2 (solar gains of 450 kWh/(m^2*a) assumed). The order of magnitude of this potential gets obvious when it is compared to the overall installed collector area in the EU 27, which according to Weiß and Mauthner was (2011) about 46 Mio. m^2 in 2009. The solar system gains per m^2 of aperture area of solar process heat installations at beneficiary framework conditions (low temperature level, constant thermal load) can be twice as high as in the residential sector (Hess and Oliva, 2010a). This offers the long-term perspective to cover a part of the industrial heat demand by solar thermal technologies at comparably low heat generation costs. Also against the background of the energy policy targets of the EU and the strategy of the RHC-Platform (Sanner et al., 2011) solar process heat is a necessary and promising renewable energy source.

2.3 Status quo and barriers for market deployment

Contrary to the high potential and the ambitious political aims, currently only a few hundred solar process heat systems are installed worldwide. In Europe, the market for solar process heat is very much in its infancy. Remarkable growth rates are observed in China, India and the Middle East (Weiß and Mauthner, 2011). The national and international projects mentioned above identified the main barriers for market deployment, which are mainly financial restrictions (see e.g. Lauterbach et al., 2011), but among others also the priority of energy efficiency measures, the complex system integration and the lack of planning tools and standardized solar thermal system designs. Because of these barriers, solar thermal process heat installations often have a higher effort for planning and installation than such for the domestic sector. Currently, several projects are focused on the reduction of costs for solar process heat by developing new or more effective collectors or components (e.g. Hess et al., 2010b). Also a number of demonstration and monitoring projects are carried out to reduce the technical barriers and to make the systems more efficient (e.g. Hess et al., 2011).

But not only from the solar engineering point of view the planning of solar process heat installations is often complex. To design economical and optimum sized solar thermal systems, energy efficiency measures must always be investigated before planning the solar thermal installation. Reducing the heat consumption of a production site by process optimization and heat recovery measures is essential to determine the remaining heat demand of the industrial processes which shall partly be covered by solar thermal and to know the temperature levels and load profiles at the integration points for the solar heat correctly and reliably for the future. Solar companies and solar planners are usually not experienced in this field of work.

The future plans of a company and the risk of reduced or changed production, resulting in a lower heat demand, higher solar fraction, lower gains and longer stagnation times have to be assessed in advance. Because of the complexity of solar thermal process heat installations, but also due to the non-technical factors mentioned above an experienced and frequent maintenance of solar process heat installations is of major importance and must be ensured for the overall time of system operation.

3. The Project SO-PRO

3.1 Approach and aims of SO-PRO

The Intelligent Energy Europe project SO-PRO (www.solar-process-heat.eu) is a dissemination project bringing together the know-how from experts on industrial processes, solar thermal and regional market development. It started in June 2009 and will end by September 2011. The focus of the project is to overcome some of the non-technical barriers for solar process heat generation, since many of the previous projects in the field identified these barriers as the main reasons for the currently poor market deployment.

SO-PRO aims to trigger the starting-up of markets for solar process heat in 6 European regions (see Fig. 3), among others by targeted awareness raising for industrial decision makers, training of professionals, development of design guides and 12 pilot projects (two per region). The project brings together key actors and target groups by combining perspectives of process planners and know-how of industrial and solar companies and by starting a market development process. In total, the project aims to trigger 60-100 installations within 6 years in Europe. Focusing on the most economical installations with state-of-the-art solar thermal technology, the project mainly addresses low-temperature processes below 100 °C.

Partner	Region
Coordinator: O.Ö. Energiesparverband (ESV)	Upper Austria (Austria)
ESCAN	Regions of Castillas y Madrid (Spain)
Energy Centre Ceské Budejovice (ECCB)	South Bohemia (Czech Republic)
Scientific partner (industrial processes): GERTEC	North Rhine-Westphalia (NRW, Germany)
Sächsische Energieagentur (SAENA)	Saxony (Germany)
Energy agency of Podravje (Energap)	Podravije region (Slovenia)
Scientific partner (solar thermal): Fraunhofer Institute for Solar Energy Systems ISE	(Germany)

Fig. 3: SO-PRO project partners and regions

The project activities already carried out include:

- regional inventories of solar process heat in each participating region
- energy screening of 91 companies
- development and dissemination of checklists and design guides
- regional campaigns, training seminars and conferences
- international conference (Solar Process Heat Conference at the WSED in March 2011)
- stand at the Hanover fair (April 2011)
- international training seminar (in the framework of the Intersolar fair in June 2011)

3.2 Results of the regional inventories

In each of the participating regions, a “Regional Inventory” was carried out and reported. For each region the primary energy prices, the structure of the heat generation and the state of the art in solar thermal were collected. Important market players and stakeholders for solar process heat in every region are listed. Existing solar process heat installations are described and regional support programs for solar process heat installations as well as industry sectors of special interest are mentioned.

The regional partners also carried out “energy screenings” within their region, using the simple and easy to handle checklists developed in SO-PRO (English version at www.solar-process-heat.eu/checklist). The main aims of the energy screenings were to identify potential candidates for solar process heat installations and to get an overview of promising industrial sectors and processes in each region. Based on these screenings, the so called “priority applications” were selected. The regional selection criteria and results as well as all the energy screenings with their lessons learned are documented in “Regional Reports” on the energy screenings and the selection of priority applications. Furthermore, each regional partner elaborated a regional report on “Needs and Requirements of Successful Solar Thermal Contracting”.

The publications

- “Regional Inventory”
- “Regional Report” on the energy screenings and the selection of priority applications
- “Needs and Requirements of Successful Solar Thermal Contracting”

can be downloaded for each region in English and in the respective regional language at www.solar-process-heat.eu/publications/reports.

3.3 Summary of the energy screenings

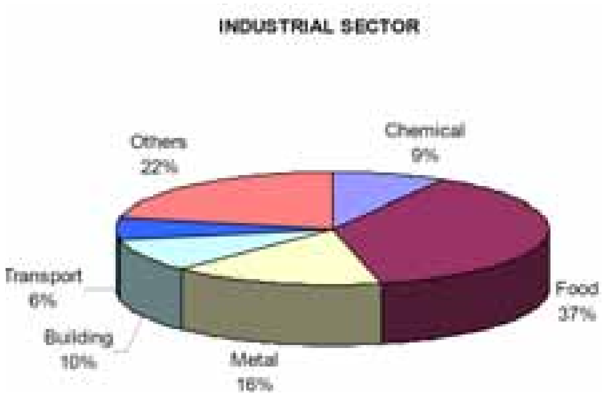

Fig. 4: Overview of the companies screened in all participating regions, distributed by industrial sector (left) and basic processes (right) (Source: “Report on 90 energy screenings”, www.solar-process-heat.eu/publications/reports)

The shares shown in Fig. 4 and within this subsection are all related to the number of companies screened. They do not represent the heat demand of the investigated sectors and processes.

In the regions, the energy sources to be potentially replaced by solar thermal were mainly natural gas (55 %) and oil (39 %). District heating (5 %) and electricity (1%) only played a minor role.

The flow temperatures of the screened processes at the potential heat integration points were distributed as follows: 5 % below 30 °C, 38 % between 30 °C and 60 °C, 20 % between 60 °C and 75 °C and 37 % above 75 °C.

The energy costs per kWh varied between 2 and 12 euro cent and were on average 4.7 euro cent per kWh.

Based on the regional inventories and the screenings it was decided to follow a trans-sectoral approach (not limited to specific industrial sectors/branches) and to focus on the four basic processes called “priority applications” explained in the following section on the Design Guide.

4. The SO-PRO Design Guide

4.1 Objectives and content of the Design Guide

The SO-PRO Design Guide (http://www.solar-process-heat.eu/guide) was elaborated in the framework of SO-PRO by Hess and Oliva (2010a) and builds upon the concept of Aidonis et al. (2002). The guide is practice-orientated and aims to provide **"missing links" between solar companies, process planners and industrial energy advisors for four specific industrial applications:**

- **Heating of water for washing or cleaning**
- **Heating of make-up water for open steam networks**
- **Heating of baths or vessels**
- **Convective drying with hot air**

The information given within this section is complementary to the Design Guide. It is intended to illustrate its concept and to explain how the guide can be usefully applied. The exemplary thermal load profiles and solar thermal system concepts are identical with the ones in the Design Guide but also printed to make the document in hand more consistent and to allow a stand-alone use.

To keep the Design Guide short and readable, the document does not go much into detail but provides the most relevant information on solar thermal installations as well as on the typical characteristics of each of the four selected processes. This way it is intended to ensure that solar companies, planners of industrial processes and industrial energy advisers can quickly get the most relevant information of the fields of work which are not their typical daily business.

The guide follows a **"holistic planning approach"** and several consecutive steps are recommended. Preliminary to the installation of a solar thermal system the pre-analysis of the building and the boundary conditions as well as the detailed analysis of the process characteristics and the heat distribution network are mandatory and described in the guide. Possible measures for process optimization and waste heat recovery are recommended.

Some **important terms and values** are introduced:

- <u>Thermal load:</u> heat demand per day or year
- <u>Thermal load profile:</u> daily, weekly and annual variation of the heat demand
- <u>Available temperature level:</u> temperature level at the integration point of the solar heat (i.e. the heat exchanger, low temperatures are favorable)
- <u>Support of open or closed processes:</u> A process is open, if the medium to be heated is not circulated.
- <u>Directly or indirectly heated processes:</u> Heat supply to a process via heat exchanger is indirect. The supply is direct, when the heat carrier is consumed by the process.
- <u>Integration on process or supply level:</u> On the process level the solar heat is supporting a process; on the supply level the solar thermal system is supporting a hot water or steam network for heat distribution.

The major part of the design guide contains exemplary thermal load profiles, solar thermal system concepts and simulated system design nomograms for each of the four selected processes. This part of the guide is mainly intended for training purposes. By means of the exemplary load profiles typical process characteristics are explained. These are likely to be observed by planners during the preliminary analysis of an industrial plant with similar processes. The exemplary system concepts for each of the four priority applications are simplified and intended to illustrate possible solutions for solar thermal heat integration. They are adapted to the exemplary thermal load profiles and other framework conditions of the processes considered.

The most relevant information on the exemplary load profiles and the solar thermal system concepts are shortly discussed in the following. For more detailed information please refer to the Design Guide. The usage of the exemplary design nomograms is explained in the subsections 4.6 and 4.7.

4.2 Heating of water for washing or cleaning

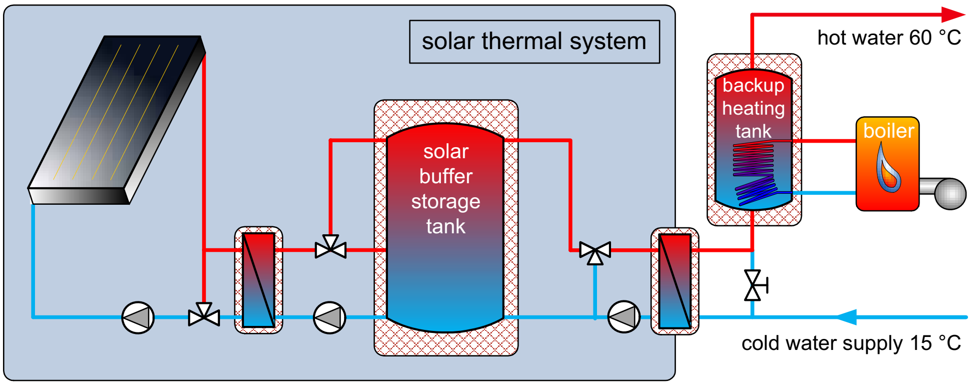

Fig. 5: Exemplary system concept for solar pre-heating of water for industrial use

The system of Fig. 5 is very similar to a conventional large solar thermal installation. The solar loop can be heated up by a bypass before the charging pump is activated. Stratified charging can be realized by different solutions; Fig. 5 exemplary indicates a three-way-valve. The stratified storage can for example be discharged by a so called “fresh-water station”, meaning a heat exchanger with pump and three-way valve maintaining a temperature of 60 °C (or below) at the outlet of the heat exchanger by an own independent control mechanism. The system supports an open cleaning process and shows a very favorable temperature level of 15 °C at the heat integration point. The cleaning water is cooled down and contaminated after use, so that heat recovery is often not possible. Since occasionally high quantities of water with a constant temperature of 60 °C are needed, a backup heating tank is suggested.

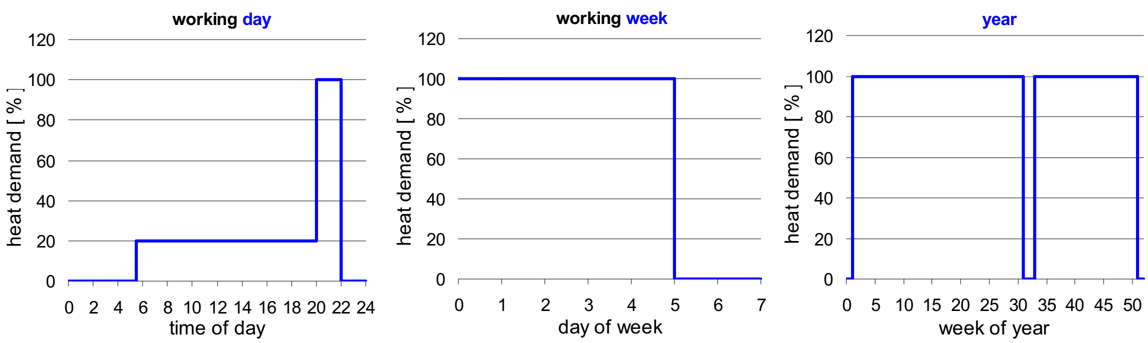

Fig. 6: Example for the discontinuous load profile of the cleaning water demand in a medium-sized company

The exemplary thermal load profile in Fig. 6 shows the cleaning water demand of a medium-sized company, working two shifts (5:30 am to 10 pm). There is no heat demand at weekends and for two weeks in August and around the turn of the year, since the company is closed down at these times of the year. The daily load profile shows a high demand within the last two working hours, since the whole production equipment is cleaned manually at this time. An example for a design nomogram indicating the high potential of such applications for solar thermal heat integration is explained in the subsections 4.6 and 4.7.

4.3 Heating of make-up water for open steam networks

The solar pre-heating of make-up water (Fig. 7) is a very promising application for many industrial sectors, since the solar gains can be high because of the low temperatures of the make-up water (depending on the possibilities for heat recovery). Solar make-up water pre-heating usually is only applicable to (partly) open steam networks. In a partly open steam network, the steam generated by the steam boiler is consumed indirectly and directly by the industrial processes. The steam consumed directly is removed from the steam network, so that new demineralized water, the so called make-up water, has to be added to the feed water tank. This water has to be degassed before it enters the steam boiler. This can be done in several ways, in our example it is done thermally by steam from the boiler itself. With solar thermal heating of the make-up water up to a maximum temperature of 90 °C, this energy for degassing can be significantly reduced.

The system concept is also very similar to conventional large systems. The heat integration can often be realized easily without a separate control mechanism. This can be understood from the load profile in Fig. 8. The fill level control of the feed water tank opens the make-up water inlet for certain intervals per day (e.g. for 30 min). The mass-flow is quite constant at these times, so that the heat exchanger at the integration point (discharging side of the solar buffer storage) can be dimensioned according to this. Whenever a make-up water mass flow is detected, the discharging pump of the buffer storage is activated and depending on the pipe length between storage and heat exchanger the make-up water mass flow can be heated up after a short time. No bypass on the discharging side of the buffer storage is needed since usually the maximum storage temperature at low-temperature solar thermal systems does not exceed 90 °C.

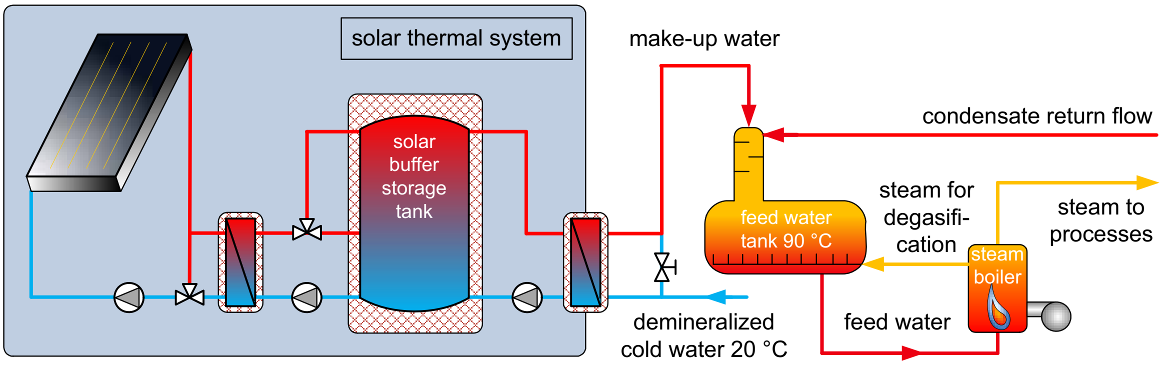

Fig. 7: Exemplary system concept for pre-heating the make-up water of a steam process

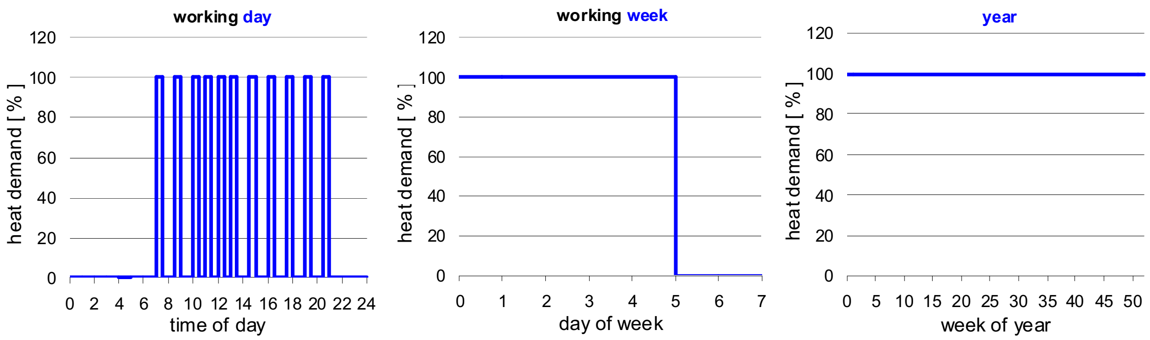

Fig. 8: Example for the make-up water consumption profile of a partly open steam network in a small laundry

Heat recovery is a very important issue at this application. In companies with steam networks often processes with very different temperature levels occur, so that heat recovery is usually possible. By applying these measures the available temperature at the integration point (cold water temperature after waste heat recovery) can rise significantly and the solar gains can decrease.

4.4 Heating of baths or vessels

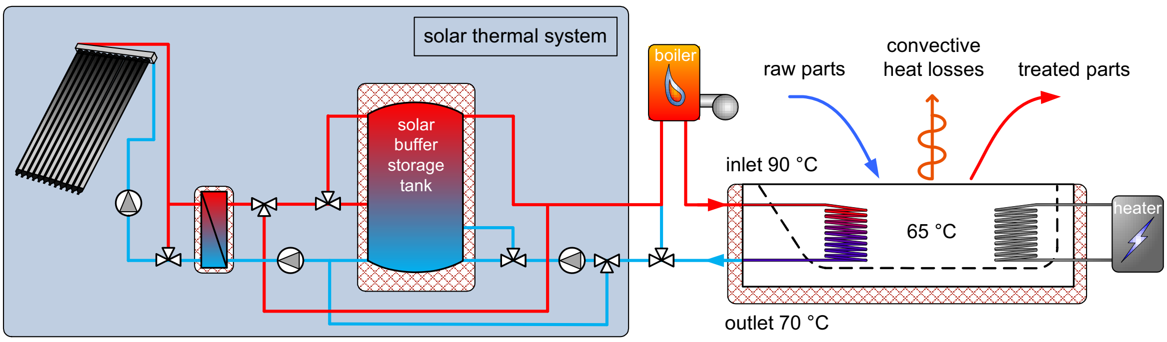

Fig. 9: Exemplary system concept for the solar heating of an industrial bath. Direct heating of the bath is possible by bypassing the storage. The electrical heater is mainly used for temperature control.

At quasi closed-loop processes like the heating of baths the solar gains are usually significantly lower than for the two open processes mentioned before. Thus, the economics highly depend on the temperature of the medium in the vessel or bath which has to be kept at a certain temperature level. Additionally, the solar thermal system concepts are more complex and also complex technical issues regarding the boiler and the heat exchangers of e.g. a galvanic bath have to be considered.

From the system concept of Fig. 9 it gets obvious that for a constant bath temperature of 65 °C the lowest possible return-flow temperature to the buffer storage is 70 °C. This significantly reduces the solar gains compared to the examples of subsection 4.2 and 4.3. The stratified inlet of the return flow from the bath to the storage must be ensured to prevent the buffer storage from being heated up by the bath at times when the buffer is not charged completely (i.e. the temperatures on the bottom are below 70 °C). Due to the high temperature level, the option of bypassing the storage in times with sufficient solar gains should be checked. To realize this option, a very accurate and reliable control mechanism for the charging pump has to be ensured, depending on the bath's requirements with respect to temperature stability etc. When the existing heat exchangers of the bath shall be used it has to be checked if the boiler can modulate in the required range. Otherwise the boiler has to be bypassed in case of solar heating.

Also for the heating of baths and vessels, the possibility of heat recovery from baths with higher temperatures should always be checked. Regular refill is very favorable, since it decreases the temperature level in the solar thermal system. Small buffer storage volumes can be applied when the baths itself can act as a buffer for solar heat (depending on the temperature variation allowed e.g. in a galvanic process).

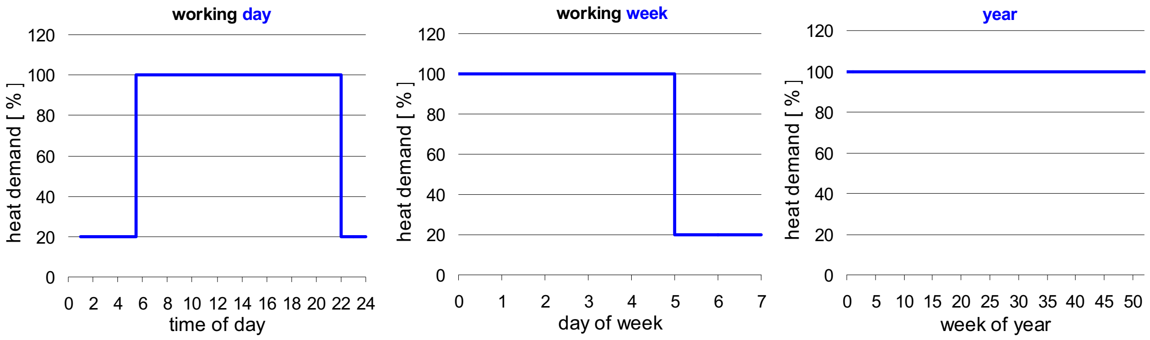

Fig. 10: Example for the continuous heat demand of a galvanic bath in a smaller company

In the galvanic bath analyzed in Fig. 10, cold raw parts are treated and heated up by the bath. This heat demand forms the major part of the thermal load. But the load profile also indicates that the bath itself has certain temperature losses due to convection (if the bath is not covered) and conduction. This means that when e.g. the electrolyte has to be kept above a certain temperature level all the time, there is also a certain heat demand when the company is not producing. A heat demand at weekends can be favorable for the solar thermal system, since the solar gains can be used to compensate the heat losses. This way sometimes electricity for heating can be saved or the boiler can be prevented from working at inefficient part-load.

4.5 Convective drying with hot air

Convective drying is a promising process, since usually ambient air is heated up (open process) and no buffer storage is required. Air collector fields can be used for pre-heating the air. A constant heat demand is favorable. Control mechanisms to maintain certain air temperatures are explained in the design guide. Depending on the pressure losses, the heat exchanger could also be bypassed when the solar irradiation is sufficient (not indicated in Fig. 11).

Electricity consumption is a relevant issue for air collectors, because their efficiency decreases with decreasing mass flows.

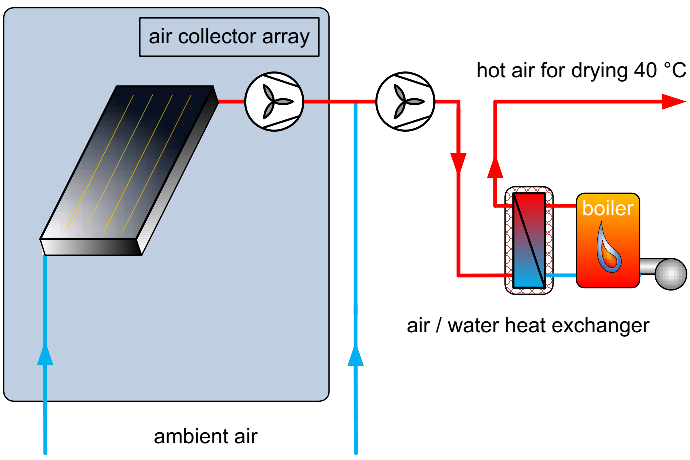

Fig. 11: Exemplary system concept of an open drying process.

4.6 Application and limitations of design nomograms

In the following, the usage of the system design nomograms shown in the Design Guide is briefly explained. **The nomograms result from system simulations for one individual industrial plant. They can be a useful tool for planners to determine how high the solar thermal system gains and the solar fraction can be for an investigated process, what would be a reasonable ratio between process heat demand and collector area and which storage volume should be applied.** They also can be **applied for training purposes** like it is done in the Design Guide.

Only **two parameters were varied** in the system simulations to generate the nomogram of Fig. 12:

- ratio between the thermal load and the installed collector aperture area (utilisation ratio)
- specific storage volume, i.e. the storage volume per m^2 of aperture area

All the other individual framework conditions like the location of the industrial production site, the load profile and temperature of the supported process, the solar thermal system design, the type and slope of the collector etc. are constant during the simulation. To generate the nomogram of Fig. 12, seven different utilisation ratios were simulated for four specific storage volumes with the software TRNSYS 16. This means that 28 annual energy gain simulations were carried out to generate the curves shown.

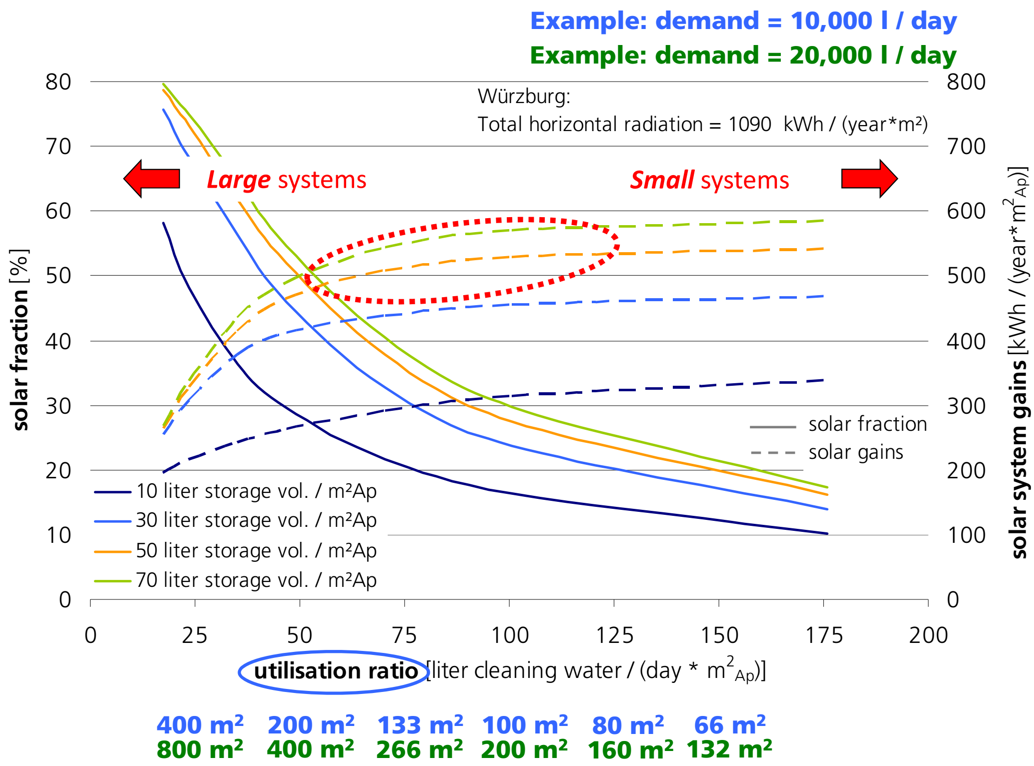

Fig. 12: Example of a solar thermal system design nomogram for a washing process in a small company (valid for the system of Fig. 5 and the thermal load profile of Fig. 6, temperature lift 15 °C to 60 °C, single covered flat-plate with slope 35°)

When, like in Fig. 12, specific values like the utilisation ratio are used, the nomograms are completely scalable. This means that the system design gets independent form the absolute quantity of the thermal load, since the ratio between thermal load and collector area (utilisation ratio) is shown. When „reading“ the nomogram, the thermal load (cleaning water demand per average day) is constant. If for example the simulated process in Würzburg, Germany had a demand of 10,000 l cleaning water per average day of the year, the utilisation ratio of 100 would correspond to 100 m^2 of aperture area. If the demand was 20,000 l the utilisation ratio of 100 would be 200 m^2 aperture area.

In Fig. 12 for each of the four specific storage volumes the development of the solar fraction is indicated for different utilisation ratios with continuous lines. The solar fraction is of course only referring to the thermal load of the processes connected to the solar thermal system. On the left side of the diagram, rather large solar thermal installations compared to the load can be found (high solar fraction), the right side shows rather small installations (low solar fraction). Oppositional to the solar fraction, the development of the usually more important solar thermal system gains is indicated with dashed lines. In smaller systems the solar gains are higher, because the solar heat can always be used by the process. The large systems offer a higher solar fraction, but the gains per m^2 are lower since the temperature in the collectors and the buffer storage is higher, which increases the losses. It gets obvious that specific storage volumes of 10 or 30 l/m^2 of aperture area are far too small for this application. A reasonable area for system design is indicated with the dashed red lines.

The application of nomograms to design "real life" installations is limited. From the explanations above it gets obvious that for every application, load profile, available temperature level, location and solar thermal system concept the planner has to create individual design nomograms by own system simulations. Of course, if the framework conditions are similar to the nomograms shown in the Design Guide, the planner gets a backup for his own simulations and the finally selected collector area and storage volume. But design and planning also contains many aspects, which cannot be evaluated by nomograms. One of these issues is e.g. stagnation. Only the decreasing solar system gains are visible in the nomogram, but it cannot be determined which parts of the reductions are assigned to higher working temperatures and which part is lost due to stagnation times when the pump is not working. Stagnation times can only be assessed from system simulations directly and the technical handling or avoiding of stagnation needs experienced planning.

4.7 Training example: design of a solar thermal system for a washing process

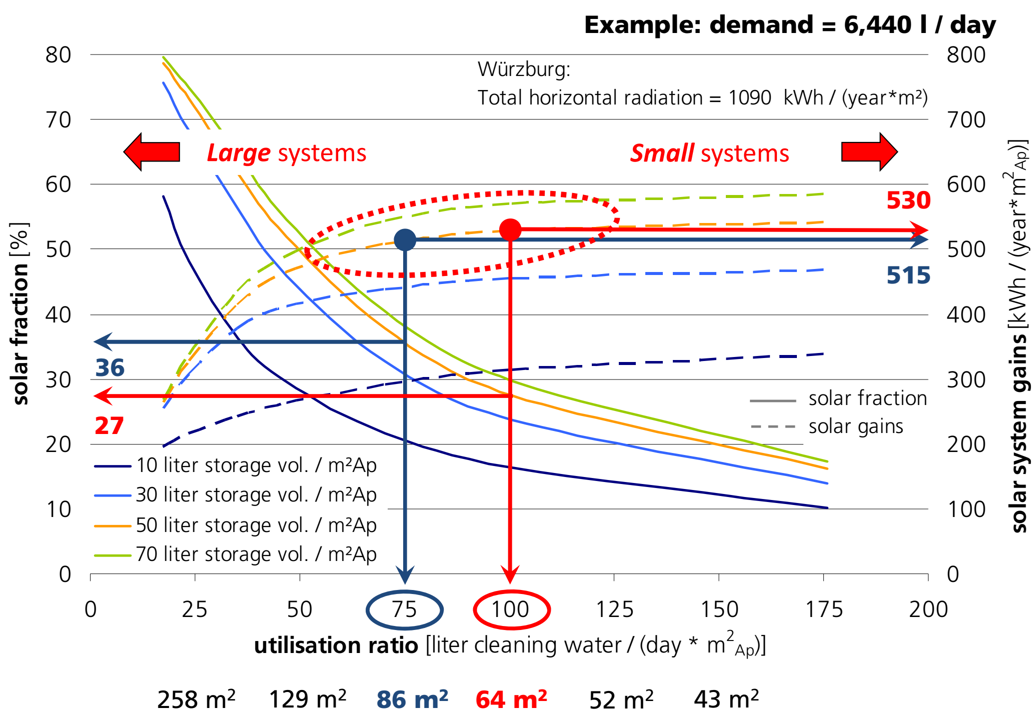

Fig. 13: Example for the solar thermal system design nomogram for a washing process in a small company (valid for the system of Fig. 5 and the thermal load profile of Fig. 6, temperature lift 15 °C to 60 °C, single covered flat-plate with slope 35°)

A company in Würzburg, Germany has a measured cleaning water demand of 10 m^3 per working day. The load profile of this company is shown in Fig. 6. The water has to be heated up from 15 °C to 60 °C. The heat demand per working day can be calculated (simplified):

$$Q_{Working\ day} = m_{Working\ day} \cdot \overline{c_p} \cdot \Delta T \approx (10{,}000\ kg \cdot 4.18 \frac{kJ}{kg \cdot K} \cdot 45\ K) / 3600 \frac{kJ}{kWh} = 522.5\ kWh \quad \text{(eq. 1)}$$

The load profile of Fig. 6 shows, that between 05:30 and 20:00 the hot water demand is about 408 l / h. Within the last two hours of a working day it is 2040 l / h. Weekends and company holidays (235 working days out of 365) lead to a mean daily demand of 6.44 m^3 per day and an annual energy demand of this process of 122.8 MWh_{th} / year.

Which part of this annual demand can be covered by solar thermal in a reasonable way? Which solar gains can be achieved? The numbers indicated in Fig. 13 show two possible designs. If there is enough roof area and financial investment volume available, the design with 86 m^2 should be selected, since the solar fraction is much higher and the solar gains are only slightly lower than for the 64 m^2 design. Even with the missing demand at Saturdays and Sundays and despite the two weeks of company holidays in summer, the solar gains are far above what can be achieved with a domestic hot water system in Würzburg.

For each design point, the collector area A_{Ap} results from the utilisation ratio and the storage volume V_{sto} can be calculated from the specific storage volume of the selected curve:

$$A_{Ap} = (6{,}440 \frac{l\,WW}{day}) / (75 \frac{l\,WW}{day * m_{Ap}^2}) \approx 86\, m_{Ap}^2 \quad \text{(eq. 2)} \qquad V_{Sto} = 50 \frac{l}{m_{Ap}^2} * 86\, m_{Ap}^2 \approx 4{,}300\, l \quad \text{(eq. 3)}$$

The resulting solar gains can be calculated either by using the specific system gains or the solar fraction:

$$E_{year} = 515 \frac{kWh}{year * m_{Ap}^2} * 86\, m_{Ap}^2 \approx 44.3 \frac{MWh}{year} \quad \text{(eq. 4)} \qquad E_{year} = 122.8 \frac{MWh}{year} * 36\,\% \approx 44.2 \frac{MWh}{year} \quad \text{(eq. 5)}$$

In Fig. 14, the location is changed to Madrid (nothing else changed). Here, the gains can be nearly doubled even for a smaller solar thermal system. The necessary specific storage volume is of course higher (even more than 70 l/m$^2_{Ap}$ could be applied), but the reasonable solar fraction can rise up to 60 % in this case.

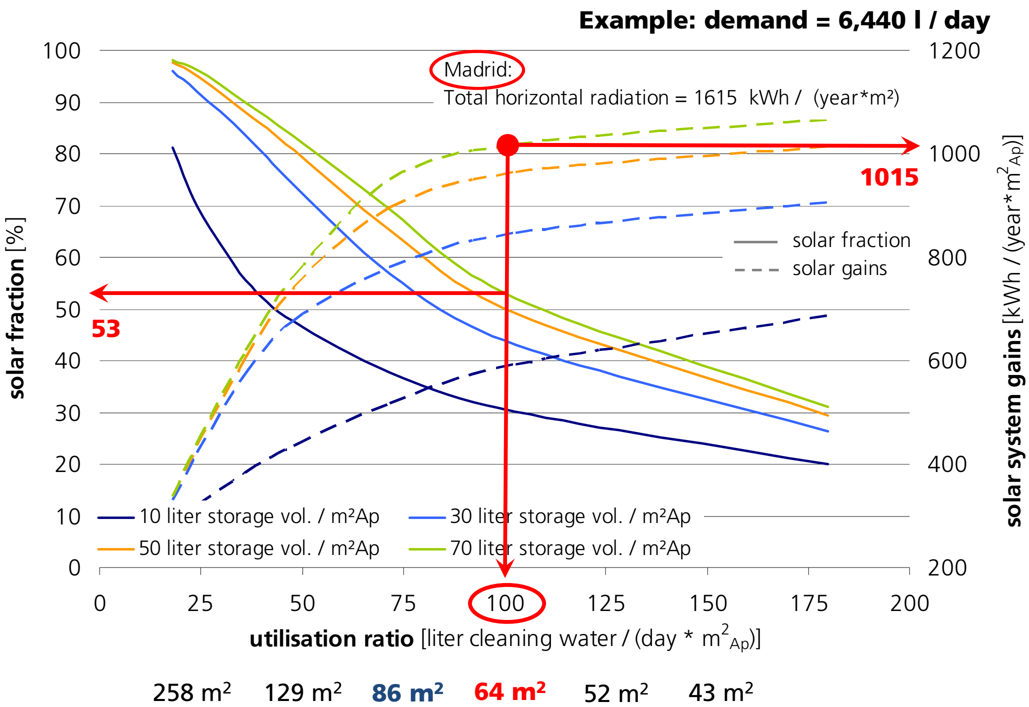

Fig. 14: Example for the solar thermal system design nomogram for a washing process in a small company (valid for the system of Fig. 5 and the thermal load profile of Fig. 6, temperature lift 15 °C to 60 °C, single covered flat-plate with slope 35°). The location changed from Würzburg to Madrid

5. Summary and Outlook

Even below 100 °C the solar generation of industrial process heat is economically and technically challenging. But since about 44 % of the total heat demand of the European Union is caused by industrial processes, this very high potential has to be exploited for solar thermal to achieve our environmental targets.

Technically, industrial processes with a low available temperature level look very promising (heating of cold water or ambient air). The annual energy gains of solar thermal systems supporting these processes can be twice as high as in the domestic sector. Often the integration of solar heat on the process level is more efficient than the support of a hot water or steam network (lower temperatures possible).

Planners should always **stick to the holistic planning approach!** Reliable knowledge of the process parameters (load profile, temperature levels, mass flows etc.) are pre-conditions to plan and design a reliable and economical solar thermal system. Energy efficiency measures (efficient processing and control, use of waste heat, etc.) should always be considered before planning a solar thermal system.

Experience with realized demonstration plants proved that **the "optimal" design is often not defined by technical parameters** like thermal load or available irradiation **but by the motivation of the industrial company**, their future plans and the financial support schemes.

From the today perspective, **public funding of demonstration plants should be increased** to reach a critical mass of installations within the promising industrial sectors and processes. These systems must be planned, monitored and documented by experts to ensure the expected impact of such lighthouse projects. In the mid-term, more **cost-effective collectors and components** for collector loop temperatures far **above 100 °C** are needed and solar companies, planners and installers have to be **trained** to realize also these systems reliably. Some of these issues are addressed in the **new IEA-SHC Task 49**: "Solar Process Heat for Production and Advanced Applications", which will start at the beginning of 2012.

6. References

Aidonis, A., Drosou, V., Mueller T., Staudacher, L., Fernandez-Llebrez, F., Oikonomou, A., Spencer, S., 2002. PROCESOL II - Solar thermal plants in industrial processes. Design and Maintenance Guidelines. Centre for Renewable Energy Sources, Pikermi. URL: www.energytech.at/pdf/procesol_2_english.pdf

Hess, S., Klemke, M., Oliva, A., Di Lauro, P., Hermann, M., Stryi-Hipp, G., Kramp, G., von Bodungen, O, Eisenmann, W., Hanby, V., 2011. Pilotanlage mit RefleC-Kollektoren: Anlagenkonzept und Monitoring-Ergebnisse. 21. OTTI-Symposium Thermische Solarenergie, Bad Staffelstein, 124-129.

Hess, S., Oliva, A., 2010a. Guide to Solar Thermal System Design for Selected Industrial Processes. O.Ö. Energiesparverband, Linz. URL: www.solar-process-heat.eu/guide

Hess, S., Oliva, A., Di Lauro, P., Klemke, M., Hermann, M., Kramp, G., Eisenmann, W., Hanby, V., 2010b. Solar Heat for Industrial Processes: RefleC-Collector Development and System Design. EuroSun 2010, Graz.

Lauterbach, C., Schmitt, B., Jordan, U., Vajen, K., 2011. Solare Prozesswärme in Deutschland - Potential und Markterschließung. Proceedings on CD. 21. OTTI-Symposium Thermische Solarenergie, Bad Staffelstein.

Lauterbach, C., Schmitt, B., Jordan, U., Vajen, K., 2010. Potential for Solar Process Heat in Germany - Suitable Industrial Sectors and Processes. EuroSun 2010, Graz.

Müller, T., Weiß, W., Schnitzer, H., Brunner, C., Begander, U., Themel, O., 2004. PROMISE - Produzieren mit Solarenergie. Bundesministerium für Verkehr, Innovation und Technologie, Wien. URL: http://www.nachhaltigwirtschaften.at/nw_pdf/0401_promise.pdf

Sanner, B., Kalf, R., Land, A., Mutka, K., Papillon, P., Stryi-Hipp, G., Weiss, W., 2011. 2020-2030-2050 - Common Vision for the Renewable Heating & Cooling sector in Europe. European Technology Platform on Renewable Heating and Cooling, Brussels. URL: http://www.rhc-platform.org/cms/fileadmin/Documents/RHC_BROCHURE_140311_web.pdf

Schweiger, H., Mendes, J.F., Schwenk, C., Hennecke, K., Barquero, C.G., Sarvisé, A.M., Carvasho, M.J., 2001. POSHIP – The Potential of Solar Heat for Industrial Processes. AIGUASOL Enginyeria. Barcelona. URL: http://www.solarpaces.org/Library/docs/POSHIP_Final_Report.pdf

Vannoni, C., Battisti, R., Drigo, S., 2008. Potential for Solar Heat in Industrial Processes. CIEMAT, Madrid. URL: www.iea-shc.org/task33/publications

Weiss, W., Biermayr, P., 2009. Potential of Solar Thermal in Europe. European Solar Thermal Industry Federation (ESTIF), Brussels. URL: http://www.aee-intec.at/0uploads/dateien758.pdf

Weiss, W., Mauthner, F., 2011. Solar Heat Worldwide Edition 2011: Markets and Contribution to the Energy Supply 2009. AEE INTEC, Gleisdorf. URL: http://www.aee-intec.at/0uploads/dateien757.pdf