Designing Solar Thermal Systems for Selected Industrial Applications

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Fraunhofer Institute for
Solar Energy Systems ISE

International Training Seminar
Solar Process Heat (So-Pro)
Intersolar Europe, 9 June 2011

www.ise.fraunhofer.de

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Agenda

- Background and motivation
- The SO-PRO Design Guide
  - Structure and application of the guide
  - Important terms and values
  - Holistic planning approach
- Example: System design for a washing process
  - Pre-dimensioning with rules of thumb
  - Making use of simulated nomograms
- Explanation of the other system designs and processes
- Exercises: Teamwork and discussion of results
- Summary

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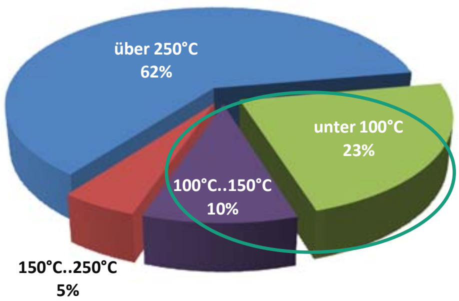
Industrial process heat: demand and potential

- Industrial process heat accounts for more than 20 % of the final energy demand (in Germany, similar for EU 25)
- A significant share of 33 % is needed at temperatures below 150 °C

Huge potential:

- Germany: ca. 16 TWh (3,1 % of industrial heat demand) = 36 Mio. m² (450 kWh / (m²*a)) [1]
- EU 25: ca. 70 TWh = 155 Mio. m² [1] (overall installed collector area in EU 27, 2009: ca. 46 Mio. m² [2])



Demand per temperature range (Germany) [1]

[1] C. Lauterbach et al. 2010: Potential of Solar Process Heat in Germany. Uni Kassel
[2] W. Weiß et al., 2011: Solar Heat Worldwide Report 2009. AEE INTEC

Reality and obstacles

- In 2010 only about 200 solar process heat systems (ca. 42 MW_{th} or 60.000 m^2) in operation were reported worldwide (incl. space heating) [3].
- But solar thermal process heat shows remarkable growth rates especially in China, India, Middle East and Austria [2].

Source: Sotec Solar, Germany

Obstacles:

- Financial restrictions (payback < 5 years)
- Complex system integration, high planning effort, lack of standardized solutions, "missing links" between industrial process planners, energy consultants and solar companies
- Priority of energy efficiency measures

[3] W. Weiß, 2010: Speech at Intersolar Conference Solar Process Heat. IEA Task 33/IV and research of AEE INTEC

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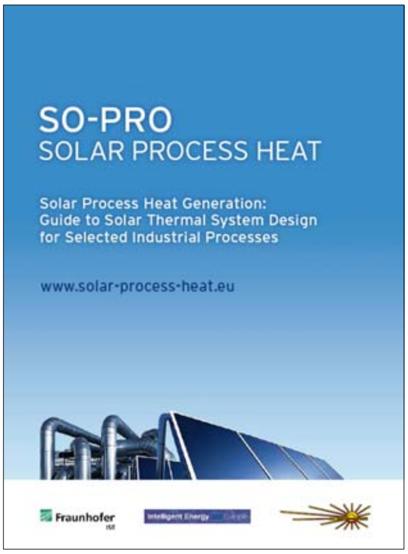
SO-PRO Design Guide [4]

- Objective: provide „missing links“ between process planners, energy consultants and solar companies
- Design principles for four selected applications:
  - Heating of hot water for washing or cleaning
  - Heating of make-up water for open steam networks
  - Heating of baths or vessels
  - Convective drying with hot air
- Holistic planning approach with consecutive steps



[4] S. Heß et al. 2010:
www.solar-process-heat.eu/guide

Important terms and values

- Heat demand:
  - Thermal load: demand per day or year
  - Load profile:
    daily, weekly and annual variation of the heat demand
  - Available temperature level: temperature level at the heat integration point
    (low temperatures are often favorable)

Source: Fraunhofer ISE

- Support of open or closed processes:
  A process is open, if the medium to be heated is not circulated.
- Directly or indirectly heated processes:
  Heat supply to the process via heat exchanger is indirect.
  The supply is direct, when the heat carrier is consumed by the process.
- Integration on process- or supply level:
  On the process level the solar heat is supporting a process, on the supply level the ST-system is supporting a hot water or steam network.

Holistic planning approach – consecutive steps

- Pre-analysis: building and boundary conditions
  - Checklists, phone calls (www.solar-process-heat.eu/checklist)
  - What is / could be the motivation of the company ?
- Analysis of process characteristics and heat distribution network
  - Site visit with technician, sketch of the building
  - Temperature levels, condition of heat distribution network
  - Open / closed processes, direct / indirect heat integration, heat integration at process level or supply level (heat distribution network)
  - Process-schemes, load profiles, installation of measuring equipment
- Process optimization and energy efficiency measures [5]
  - Processes state-of-the-art? Future plans?
  - Heat exchanger optimization (pinch analysis)

Expert-system for an INtelligent Supply of Thermal Energy in Industry

➡ Consider these issues before designing a solar thermal system!

[5] C. Brunner et al. 2010: IEE-Project Einstein: www.iee-einstein.org

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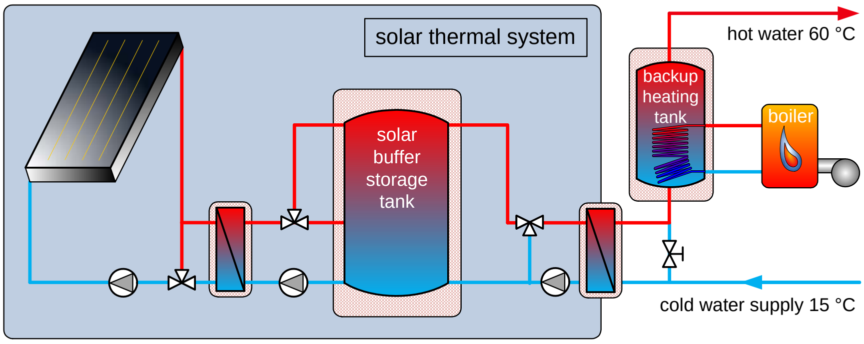
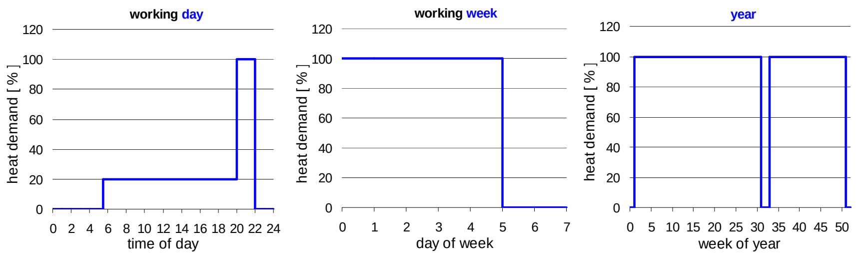
a) Heating of water for washing or cleaning



Exemplary system concept for pre-heating of hot water

Thermal load profile



Example for the discontinuous load profile of the hot water demand for cleaning of production equipment in a medium-sized company.

- Two shifts (5:30 am to 10 pm)
- High demand within the last two hours
- No work at weekends, company holidays in summer and around the turn of the year

Example: thermal load and annual heat demand

- For a measured demand of 10 m³ hot water per working day the heat demand $Q_{working\ day}$ can be calculated (simplified):

$$Q_{Working\ day} = m_{Working\ day} \cdot \overline{c}_p \cdot \Delta T \approx (10{,}000\ kg \cdot 4.18 \frac{kJ}{kg \cdot K} \cdot 45\ K) / 3600 \frac{kJ}{kWh} = 522.5\ kWh$$

- The load profile shows, that between 05:30 and 20:00 the hot water demand is about 408 l / h. Within the last two hours it is 2040 l / h.

- Weekends and company holidays (235 working days out ot 365) lead to a mean daily demand of 6,44 m³ 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?

Pre-dimensioning (rules of thumb for Central Europe)

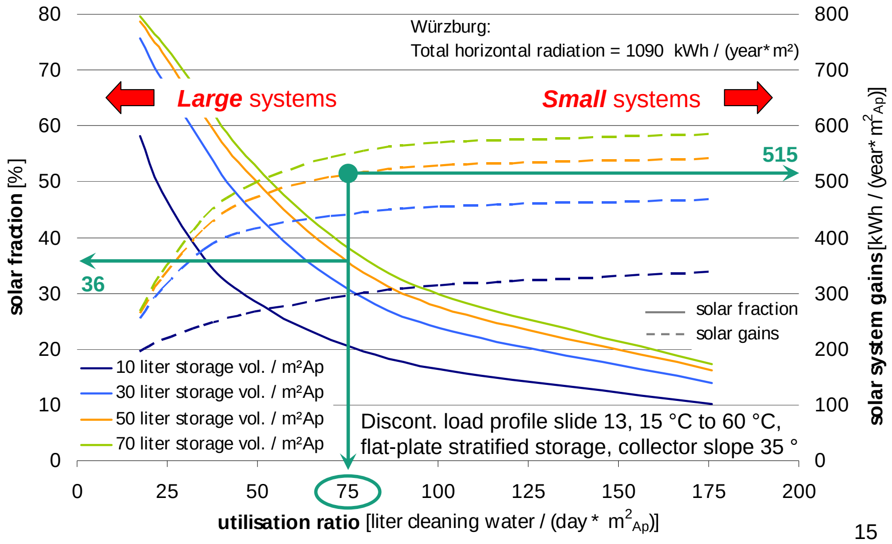
- Aperture area A_{Ap}:
  - Method a): Roof area available as collector aperture area multiplied by estimated solar gains of 500 kWh / (year * m^2_{Ap})
  - Method b): Annual thermal energy demand of the processes to be supported by solar multiplied by a solar fraction of 40 %, divided by 500 kWh / (year * m^2_{Ap})

$$A_{Ap} = (Q_{Year} \cdot 0.4) / 500 \frac{kWh}{m^2_{Ap}} = (122.8\ MWh \cdot 0.4) / 500 \frac{kWh}{m^2_{Ap}} \approx 100\ m^2_{Ap}$$

- Storage volume V_{Sto}:
  - As a first indication, 50 l_{Sto} / m^2_{Ap} can be assumed:

$$V_{Sto} = A_{Ap} \cdot 50 \frac{l}{m^2} = 100\ m^2_{Ap} \cdot 50 \frac{l}{m^2_{Ap}} \approx 5\ m^3$$

Simulated nomograms for system design



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Results for this green design:

- Calculation of the resulting collector aperture area by using the utilization ratio of 75 l hot water per day and m^2_{Ap}:

$$A_{Ap} = (6{,}440 \frac{l\ WW}{day}) / (75 \frac{l\ WW}{day * m^2_{Ap}}) \approx 86\ m^2_{Ap}$$

- The resulting solar system gains are valid for a storage volume of:

$$V_{Sto} = 50 \frac{l}{m^2_{Ap}} * 86\ m^2_{Ap} \approx 4{,}300\ l$$

- Calculation of the annual solar gains of this system by using:
  - specific system gains: $E_{year} = 515 \frac{kWh}{year * m^2_{Ap}} * 86\ m^2_{Ap} \approx 44.3 \frac{MWh}{year}$
  - solar fraction: $E_{year} = 122.8 \frac{MWh}{year} * 36\ \% \approx 44.2 \frac{MWh}{year}$

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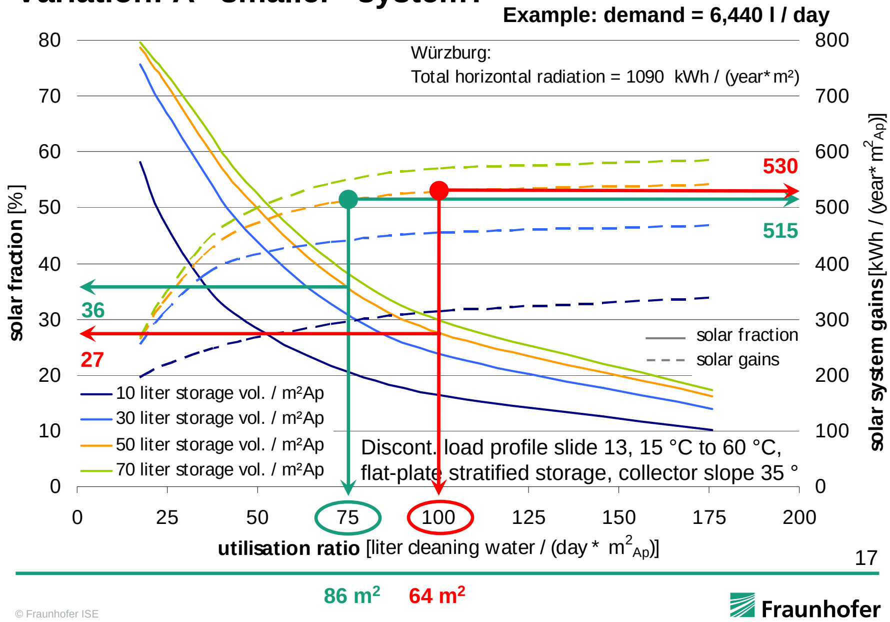
Variation: A “smaller” system?



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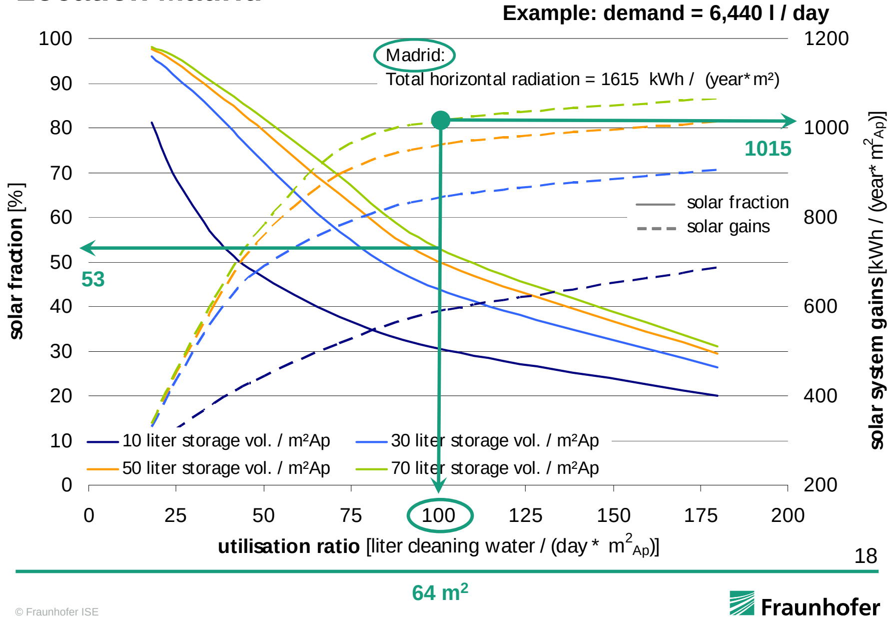
Location Madrid



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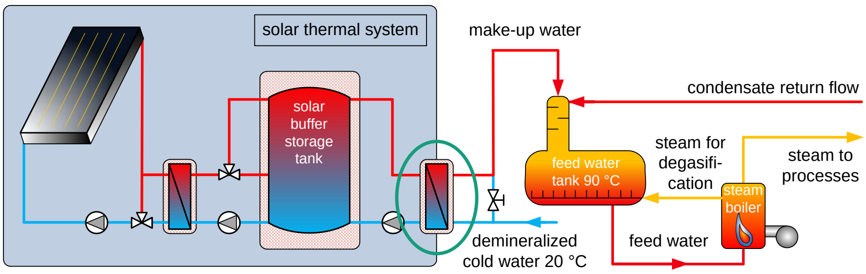
b) Pre-heating of make-up water



Exemplary system concept for pre-heating the make-up water of a steam process

- High solar gains because of low temperature level
- System concept very similar to conventional systems for hot water
- Only applicable to (partly) open steam networks
- Heat recovery has to be analyzed (available temperature can rise)

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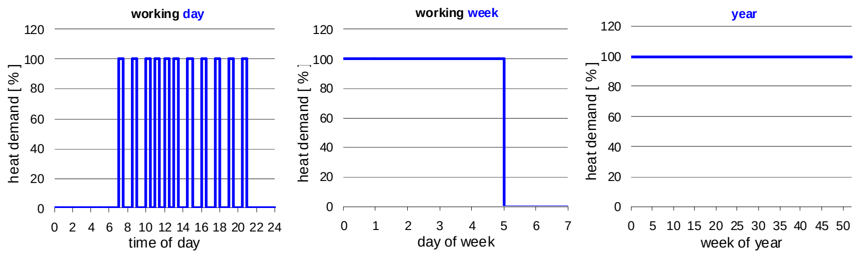
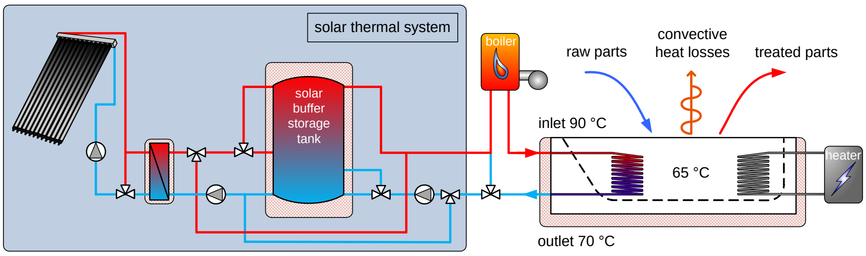
Thermal load profile



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

- Two shifts (5:30 am to 10 pm), weekend, no company holidays
- The fill-level control of the feed-water tank opens for intervals of 30 min

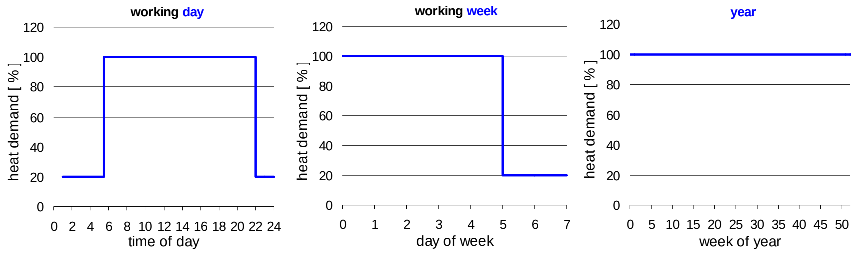
c) Heating of baths and vessels



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

- Closed process: Economics highly depend on the bath temperature
- Heat recovery from baths with higher temperatures checked?
- Regular refill favorable
- Small buffer storage volume possible (bath can act as a storage)

Thermal load profile



Example for the continuous heat demand of an galvanic bath in a smaller company

- Electrolyte has to be kept at a certain temperature all the time
- Heat demand at night and at weekends to compensate heat losses
- No work at weekends, no company holidays

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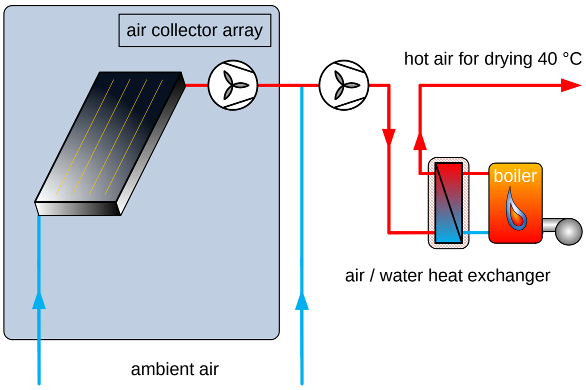
d) Convective drying with hot air



Exemplary system concept of an open drying process. The open air collector system is serially supported by a boiler (solar fan left, conventional fan right)

- No storage necessary
- Continuous heat demand favorable
- Efficiency of air collectors decreases with decreasing mass flow

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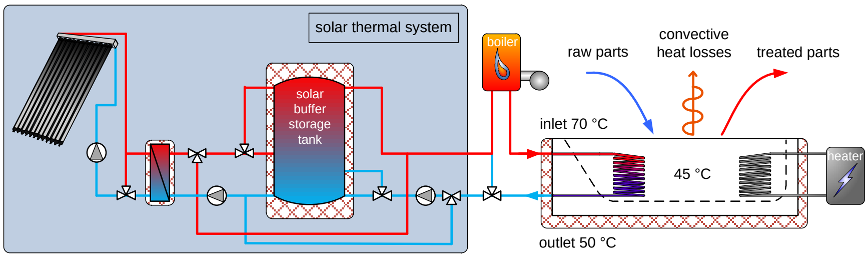
Teamwork: Conception and Design of a solar thermal system supporting an industrial process

- Exercises on the following pages:
  - Design case 1: Solar heating of a galvanic bath
    (closed loop, variation of site, collector type and bath temperature)
  - Design case 2: Pre-heating of feed-water in a laundry
    (discussion of direct / indirect integration of solar heat)
- Procedure:
  - Please form **teams of 2 or 3 persons**
  - **1 pocket calculator** per team is **recommended**
  - Please **do both exercises** and **discuss the results** in your team
    (indicate your design points in the nomograms)
  - **Time: 20 min**
  - Results will be explained and are documented in the handout!

Design case 1: Solar heating of a galvanic bath

A electro-plating company in Würzburg (Germany) is using 250 kWh / d of thermal energy (annual average, weekends/holidays already considered) to heat a bath. This bath must be kept at a temperature of 45 °C all over the year.



System concept for design case 1

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Design case 1: Solar heating of a galvanic bath

- 1) Calculate the annual energy demand of this process and estimate aperture area and storage volume of a ST system covering this demand to 40 % (compare slide 14)

$$Q_{Year} = \Box \frac{kWh}{d} \cdot 365\ d = \Box\ kWh$$

$$A_{Ap} = (Q_{Year} \cdot \Box) / \Box \frac{kWh}{m^2_{Ap}} = (\Box \frac{kWh}{a} \cdot \Box) / \Box \frac{kWh}{a\ m^2_{Ap}} = \Box\ m^2_{Ap}$$

$$V_{Sto} = A_{Ap} \cdot \Box \frac{l}{m^2} = \Box\ m^2_{Ap} \cdot \Box \frac{l}{m^2_{Ap}} \approx \Box\ m^3$$

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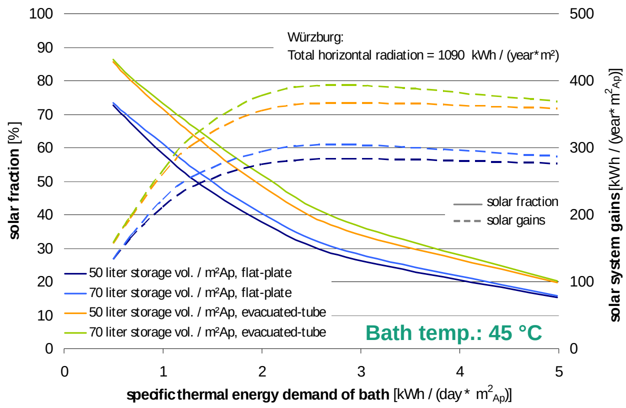
Design case 1: Solar heating of a galvanic bath

- 2) Do a more accurate dimensioning of aperture area and storage volume based on the simulation results in the following nomogram. Apply vacuum tube collectors and 50 l / m2 storage. Which solar fraction should be selected?



$$f_{sol} = \square\,\%$$

$$A_{Ap} = \frac{\square \, \frac{kWh}{d}}{\square \, \frac{kWh}{d \cdot m^2}} = \square \, m^2$$

$$V_{Sto} = \square \, m^2 \cdot \square \, \frac{l}{m^2} = \square \, m^3$$

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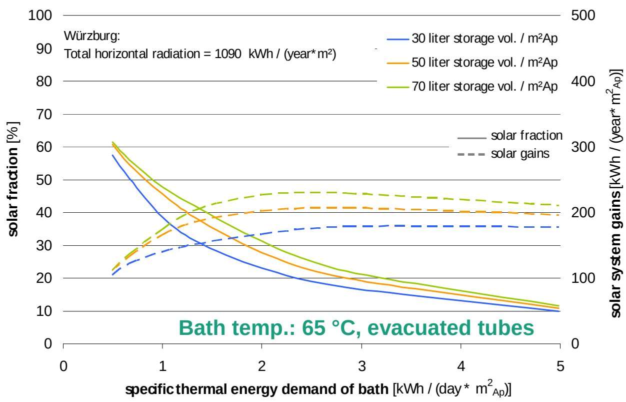
Design case 1: Solar heating of a galvanic bath

- 3) How would you assess the same system with a bath temperature of 65 °C ? What is the main reason for the low solar gains? Look at the system concept on slide 22!

Reason:



$$f_{sol} = \square\,\%$$

$$A_{Ap} = \frac{\square \, \frac{kWh}{d}}{\square \, \frac{kWh}{d \cdot m^2}} = \square \, m^2$$

$$V_{Sto} = \square \, m^2 \cdot \square \, \frac{l}{m^2} = \square \, m^3$$

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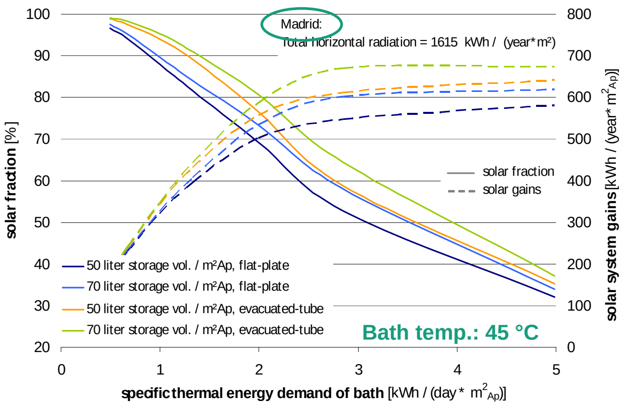
Design case 1: Solar heating of a galvanic bath

- 4) Suppose the company would be located in Madrid.
  How would you design the system for 45 °C there?

Selected collector type: fl



$$f_{sol} = \square \%$$

$$A_{Ap} = \frac{\square \frac{kWh}{d}}{\square \frac{kWh}{d \cdot m^2}} = \square m^2$$

$$V_{Sto} = \square m^2 \cdot \square \frac{l}{m^2} = \square m^3$$

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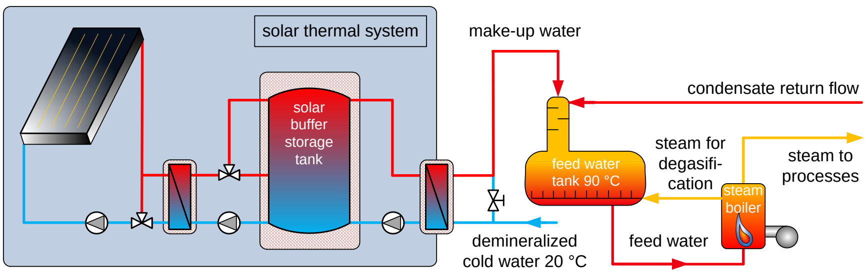
Design case 2: Solar heating of make-up water

A laundry in Würzburg (no holidays, no work at weekends) runs a steam network with several indirect consumers and a big inline washing machine using the steam directly. Thus, the network needs about 15 tons of make-up water per average day.



System concept for design case 2

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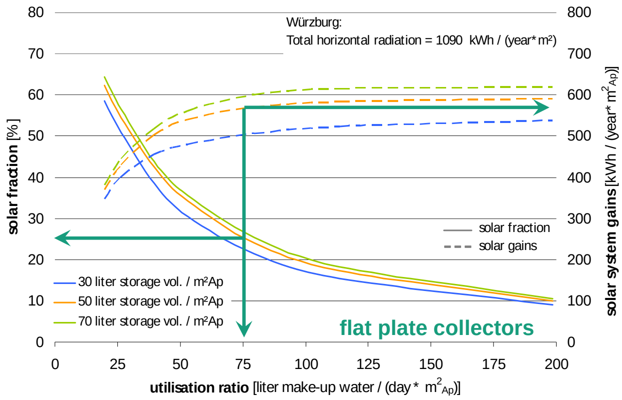
Design case 2: Solar heating of make-up water

- 1) Fill in the characteristic values for a medium-sized solar thermal system supporting this process (see indicated design)



$$f_{sol} = \square \%$$

$$A_{Ap} = \frac{\square \frac{l}{d}}{\square \frac{l}{d \cdot m^2}} = \square\ m^2$$

$$V_{Sto} = \square\ m^2 \cdot \square \frac{l}{m^2} = \square\ m^3$$

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Design case 2: Solar heating of make-up water

- 2) What is the difference in the recommended solar fraction and the solar system gains between make-up water (slide 33, load profile slide 21) and cleaning water (slide 15, load profile slide 12)?

a) Recommended solar fraction:

☐ % for make-up water and ☐ % for cleaning water

b) Solar system gains:

☐ kWh / m² for make-up water and ☐ kWh / m² for cleaning water

- 3) What is the reason for the different solar fraction?

☐

- 4) Which are the two main reasons for the different solar system gains?

a) ☐

b) ☐

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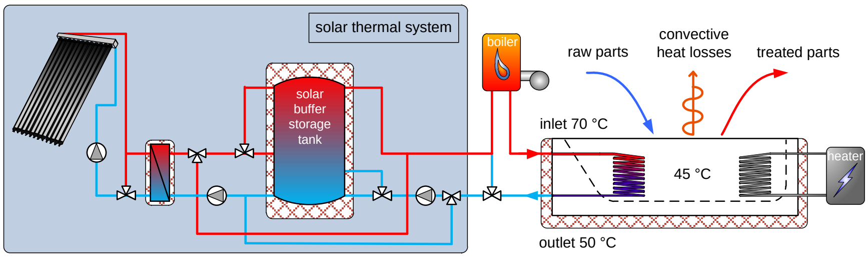
Results for case 1: Solar heating of a galvanic bath

A electro-plating company in Würzburg (Germany) is using 250 kWh / d of thermal energy (annual average, weekends/holidays already considered) to heat a bath. This bath must be kept at a temperature of 45 °C all over the year.



System concept for design case 1

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Results for case 1: Solar heating of a galvanic bath

- 1) Calculate the annual energy demand of this process and estimate aperture area and storage volume of a ST system covering this demand to 40 %

$$Q_{Year} = 250 \frac{kWh}{d} \cdot 365\ d = 91{,}250\ kWh$$

$$A_{Ap} = (Q_{Year} \cdot 0.4) / 500 \frac{kWh}{m^2_{Ap}} = (91{,}250 \frac{kWh}{a} \cdot 0.4) / 500 \frac{kWh}{a\ m^2_{Ap}} = 73\ m^2_{Ap}$$

$$V_{Sto} = A_{Ap} \cdot 50 \frac{l}{m^2} = 73\ m^2_{Ap} \cdot 50 \frac{l}{m^2_{Ap}} \approx 3.65\ m^3$$

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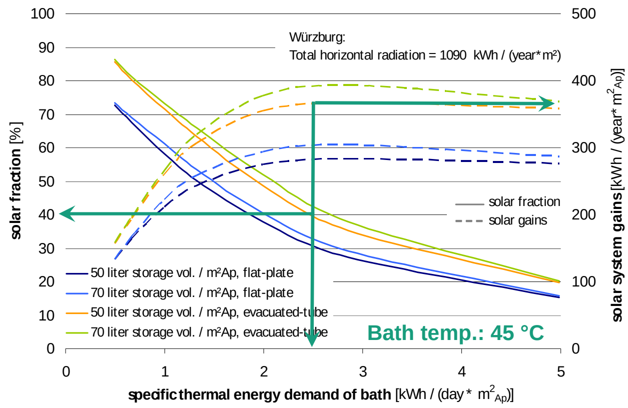
Results for case 1: Solar heating of a galvanic bath

- 2) Do a more accurate dimensioning of aperture area and storage volume based on the simulation results in the following nomogram. Apply vacuum tube collectors and 50 l / m2 storage. Which solar fraction should be selected?



$$f_{sol} = 40\ \%$$

$$A_{Ap} = \frac{250\ \frac{kWh}{d}}{2.5\ \frac{kWh}{d \cdot m^2}} = 100\ m^2$$

$$V_{Sto} = 100\ m^2 \cdot 50\ \frac{l}{m^2} = 5\ m^3$$

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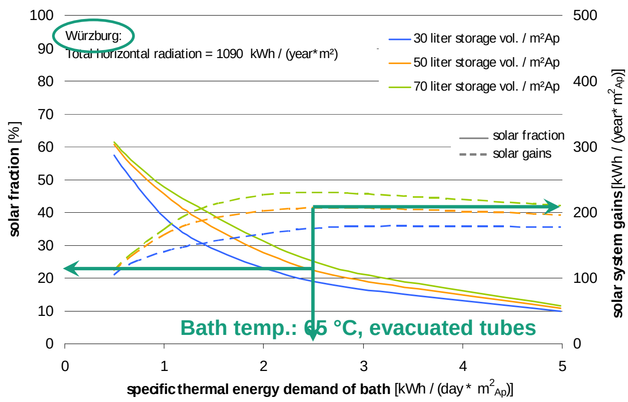
Results for case 1: Solar heating of a galvanic bath

- 3) How would you assess the same system with a bath temperature of 65 °C ? What is the main reason for the low solar gains? Look at the system concept on slide 22!

Reason: Available temperature level: 70 °C



$$f_{sol} = 25\ \%$$

$$A_{Ap} = \frac{250\ \frac{kWh}{d}}{2.5\ \frac{kWh}{d \cdot m^2}} = 100\ m^2$$

$$V_{Sto} = 100\ m^2 \cdot 50\ \frac{l}{m^2} = 5\ m^3$$

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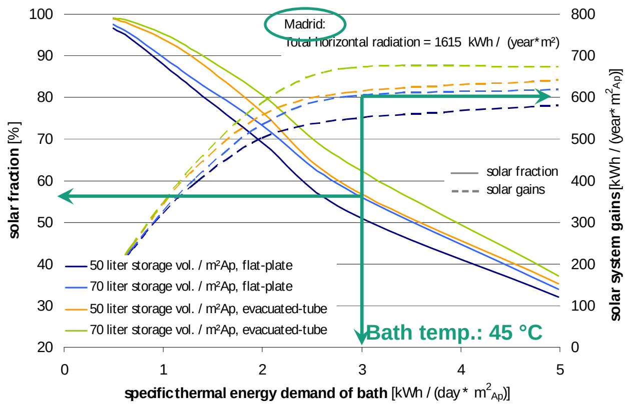
Results for case 1: Solar heating of a galvanic bath

- 4) Suppose the company would be located in Madrid.
  How would you design the system for 45 °C there?

Selected collector type: flat-plate



$$f_{sol} = 56\ \%$$

$$A_{Ap} = \frac{250\ \frac{kWh}{d}}{3\ \frac{kWh}{d \cdot m^2}} = 83\ m^2$$

$$V_{Sto} = 83\ m^2 \cdot 70\ \frac{l}{m^2} = 5.8\ m^3$$

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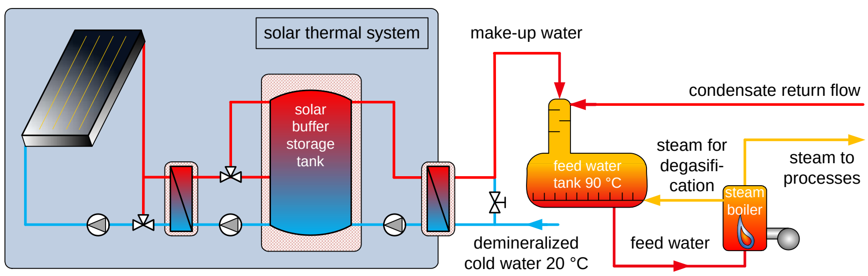
Results for case 2: Solar heating of make-up water

A laundry in Würzburg (no holidays, no work at weekends) runs a steam network with several indirect consumers and a big inline washing machine using the steam directly. Thus, the network needs about 15 tons of make-up water per average day.



System concept for design case 2

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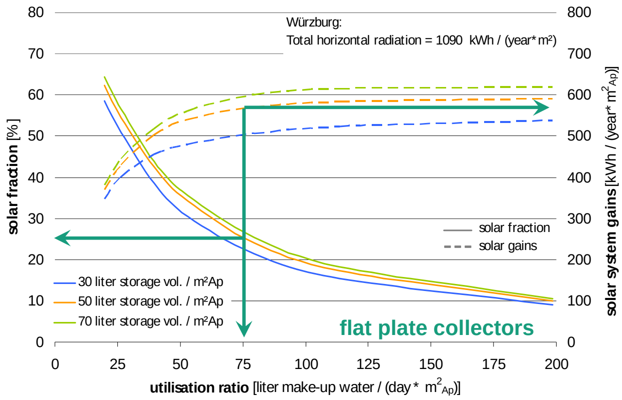
Results for case 2: Solar heating of make-up water

- 1) Fill in the characteristic values for a medium-sized solar thermal system supporting this process (see indicated design)



$$f_{sol} = 25\ \%$$

$$A_{Ap} = \frac{15000\ \frac{l}{d}}{75\ \frac{l}{d \cdot m^2}} = 200\ m^2$$

$$V_{Sto} = 200\ m^2 \cdot 50\ \frac{l}{m^2} = 10\ m^3$$

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Results for case 2: Solar heating of make-up water

- 2) What is the difference in the recommended solar fraction and the solar system gains between make-up water (slide 33, load profile slide 21) and cleaning water (slide 15, load profile slide 12)?

a) Recommended solar fraction:

25 % for make-up water and 36 % for cleaning water

b) Solar system gains:

570 kWh / m² for make-up water and 515 kWh / m² for cleaning water

- 3) What is the reason for the different solar fraction?

The thermal load is defined up to 60 °C for cleaning water, but up to 90 °C for make-up water.

- 4) Which are the two main reasons for the different solar system gains?

a) The load profile for cleaning shows company holidays.

b) Solar gains above 60 °C can not be used for the cleaning water.

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