Solar Heat for Industrial Applications

Design study part II

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Aim of the session (part II)

Basic design of a solar thermal process heat system based on the outcomes of the process optimization session (part I) and following the approach for efficient energy planning in industry:

1. Avoid energy losses (e.g. efficient boilers and process technologies. insulation. etc.)
2. Increase efficiency of the existing system (e.g. exploit heat recovery potential. etc.)
3. Design and implementation of sustainable energy supply technologies to further decrease fossil fuel demand

Outline

Assessment methodology for solar thermal integration

Design study Part I – Process optimization (summary)

- 1.1) Solar thermal integration point
- 1.2) Solar thermal integration concept
- 1.3) Characteristic annual / weekly / daily load profile

Design study Part II – Solar thermal system design

- 2.1) Choice of an appropriate solar thermal collector technology
- 2.2) Collector field placement
- 2.3) Hydraulic diagram solar loop + process loop
- 2.4) Basic engineering of collector loop and loop components
- 2.5) Simulation of the annual solar energy gains
- 2.6) Techno-economic comparison of results

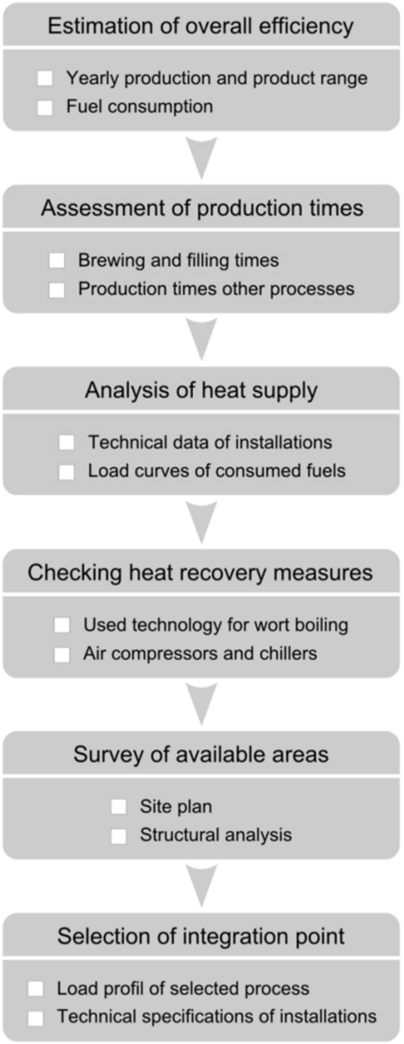
Assessment methodology

- Energy audit on-site (basic data acquisition. company visit)
- Assessment of production times and still-stands (daily. weekly. annually)
- Analysis of heat supply and evaluation of representative load profiles

- **Identifying process optimization and energy efficiency measures**

- Survey of available areas (ground or roof) for solar thermal system installation
- Selection of solar thermal integration point and hydraulic integration concept

- **Detail engineering of the solar thermal system**

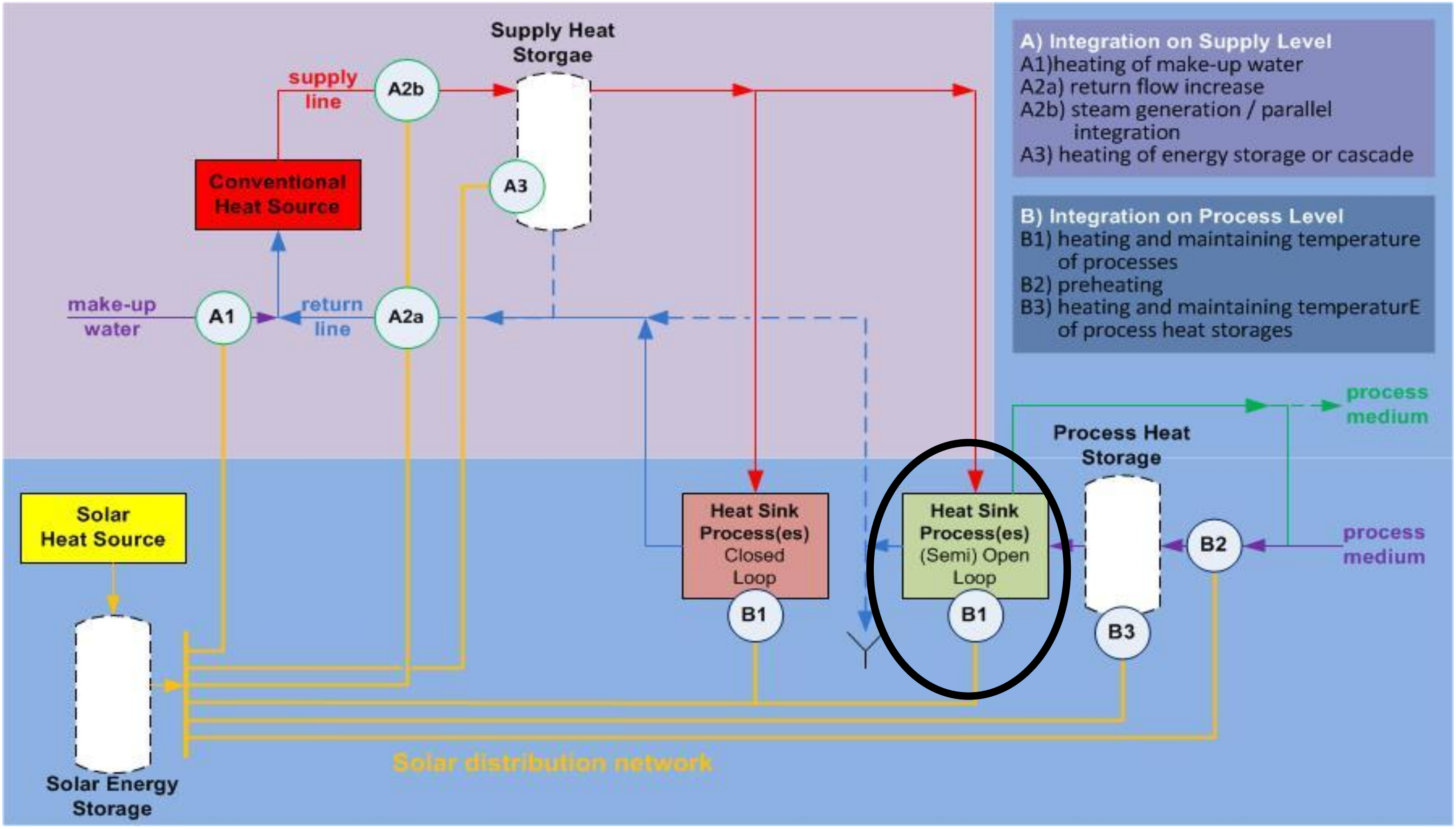


Source: IEA SHC Task 39 / IV 2013 / B. Schmitt

Design study (Part I - results)

1.1) Solar thermal integration point

- Possible integration points for solar process heat applications

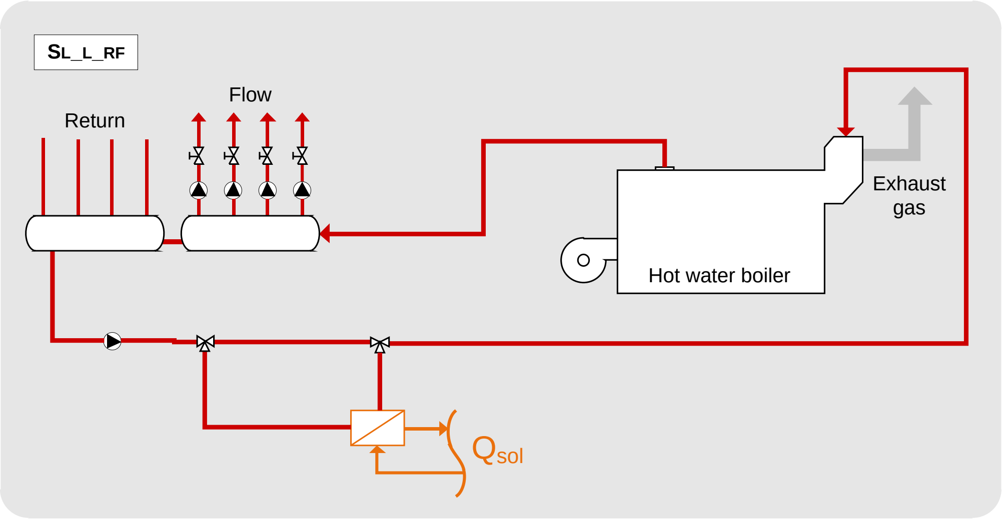


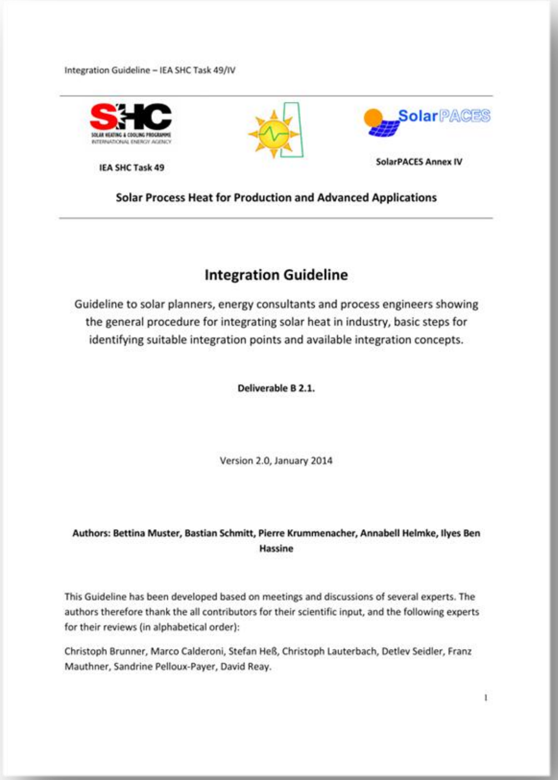
Source: IEA SHC Task 39 / IV 2013

Design study (Part I - results)

1.2) Solar thermal integration concept

- IEA-SHC Task 49 / Annex IV integration guideline
  - Soon available here: http://task49.iea-shc.org/




Integration Guideline – IEA SHC Task 49/IV

IEA SHC Task 49

SolarPACES Annex IV

Solar Process Heat for Production and Advanced Applications

Integration Guideline

Guideline to solar planners, energy consultants and process engineers showing the general procedure for integrating solar heat in industry, basic steps for identifying suitable integration points and available integration concepts.

Deliverable B 2.1.

Version 2.0, January 2014

Authors: Bettina Muster, Bastian Schmitt, Pierre Krummenacher, Annabell Helmke, Ilyes Ben Hassine

This Guideline has been developed based on meetings and discussions of several experts. The authors therefore thank the all contributors for their scientific input, and the following experts for their reviews (in alphabetical order):

Christoph Brunner, Marco Calderoni, Stefan Heß, Christoph Lauterbach, Detlev Seidler, Franz Mauthner, Sandrine Pelloux-Payer, David Reay.

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Design study (Part I - results)

1.2) Solar thermal integration concept

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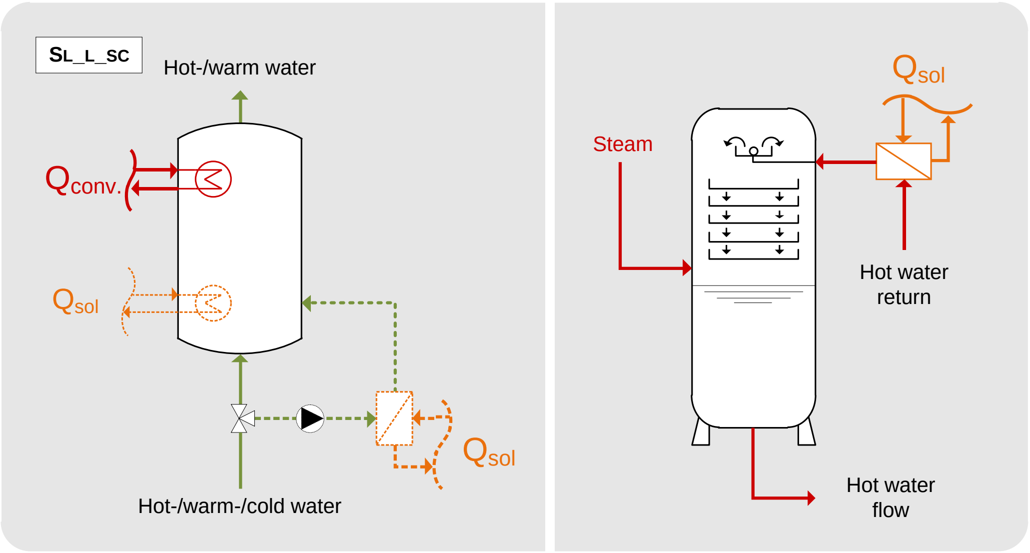

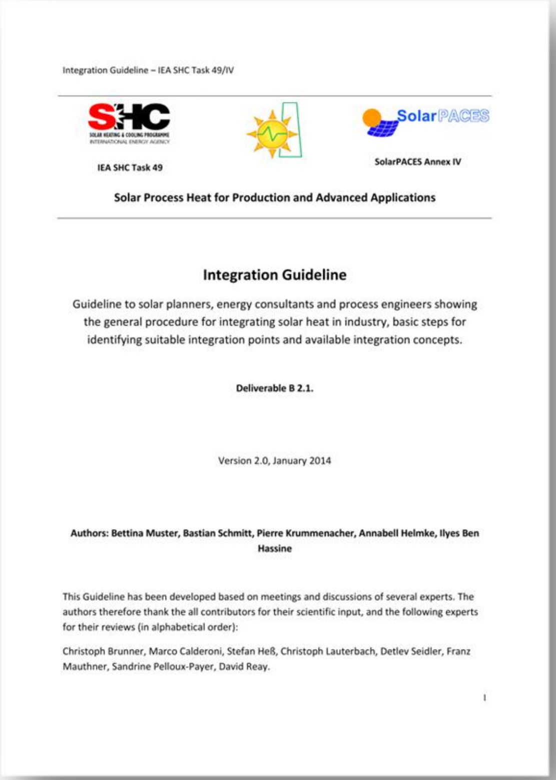
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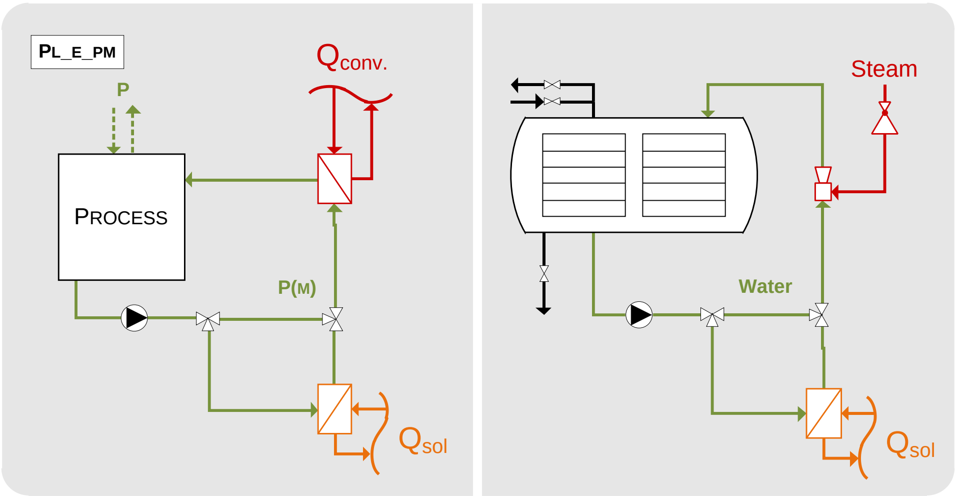

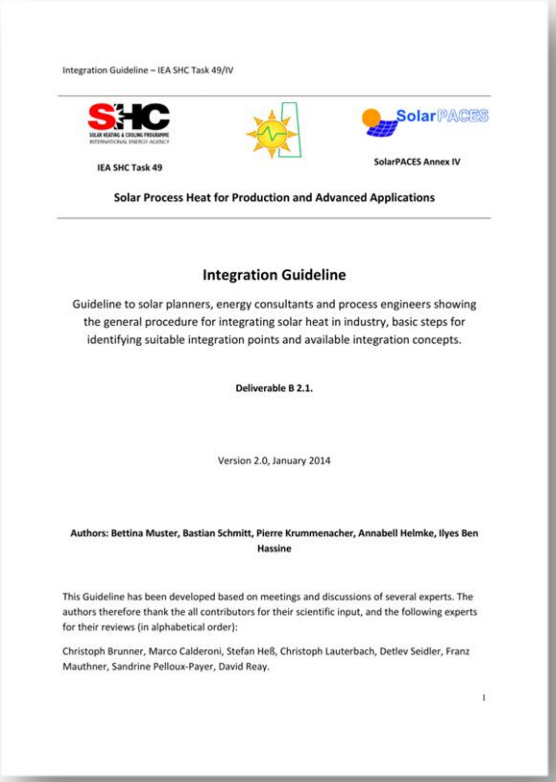
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Design study (Part I)

1.2) Solar thermal integration concept

- Task 1.1: Characterize solar process heat integration point and integration concept
- Task 1.2: Draw basic hydraulic process integration scheme
  - Calculate heat exchanger capacity
  - Calculate piping dimensions

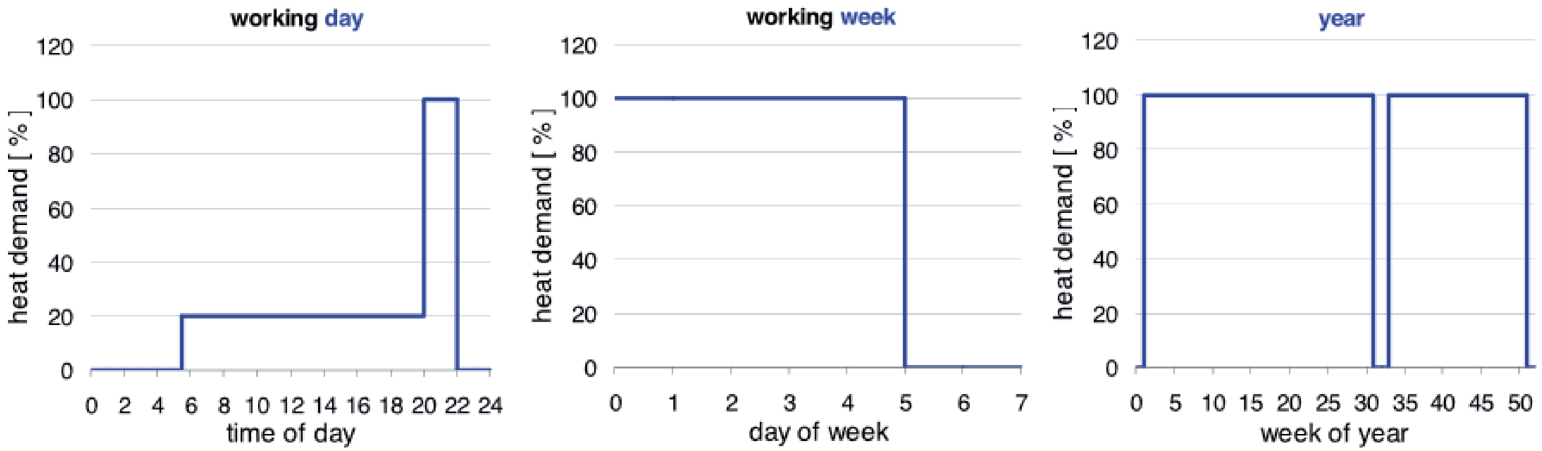
Group work

Design study (Part I - results)

1.3) Characteristic load profile on an hourly basis

– Daily load profile: dimensioning of collector field and heat storage. simulation of solar thermal system yield
– Weekly load profile: dimensioning of heat storage and simulation of solar thermal system yield
– Annual load profile: simulation of solar thermal system yield

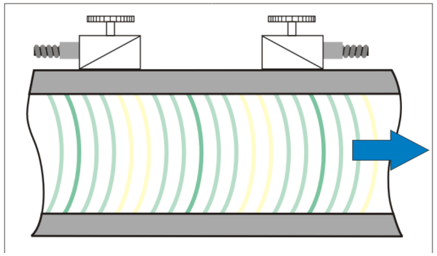
- EXAMPLE: : non-continuous demand(e.g. cleaning water demand)



Design study (Part I - results)

1.3) Characteristic load profile

- If no data on the thermal heat demand available representative measurements should be taken
- E.g.: Ultrasonic Flow Measurement of Liquids



Calculation of Volumetric Flow Rate

$\dot{V} = k_{Re} \cdot A \cdot k_a \cdot \Delta t/(2 \cdot t_{fl})$

where

$\dot{V}$	-	volumetric flow rate
k_{Re}	-	fluid mechanics calibration factor
A	-	cross-sectional pipe area
k_a	-	acoustical calibration factor
Δt	-	transit time difference
t_{fl}	-	transit time in the medium

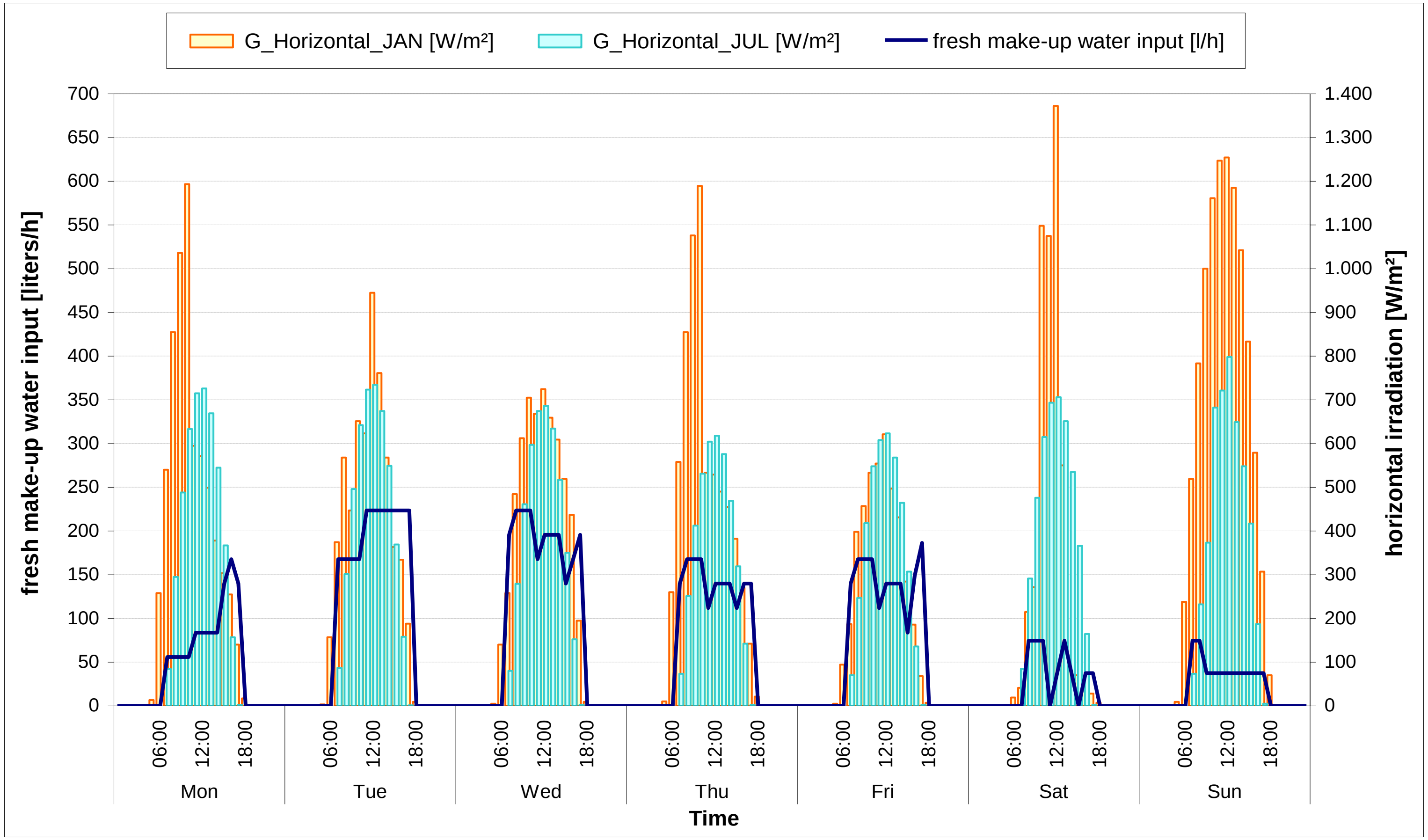
Flow sensor	
range flow velocity	0.01 bis 25 m/s
accuracy (@ v>0.15m/s with standard calibration)	± 1.6% of reading ± 0.01 m/s
Temperature sensor Pt 1000 4-wire	
range temperature	-150° C bis +560° C
accuracy	± 0.01% of reading ± 0.03 K

Technical Specification FLUXUS® F601 (www.flexim.com)

Design study (Part I - results)

1.3) Characteristic load profile

- example: measured make-up water demand for steam boiler at a brewery in Polokwane



Design study (Part I)

1.3) Characteristic load profile

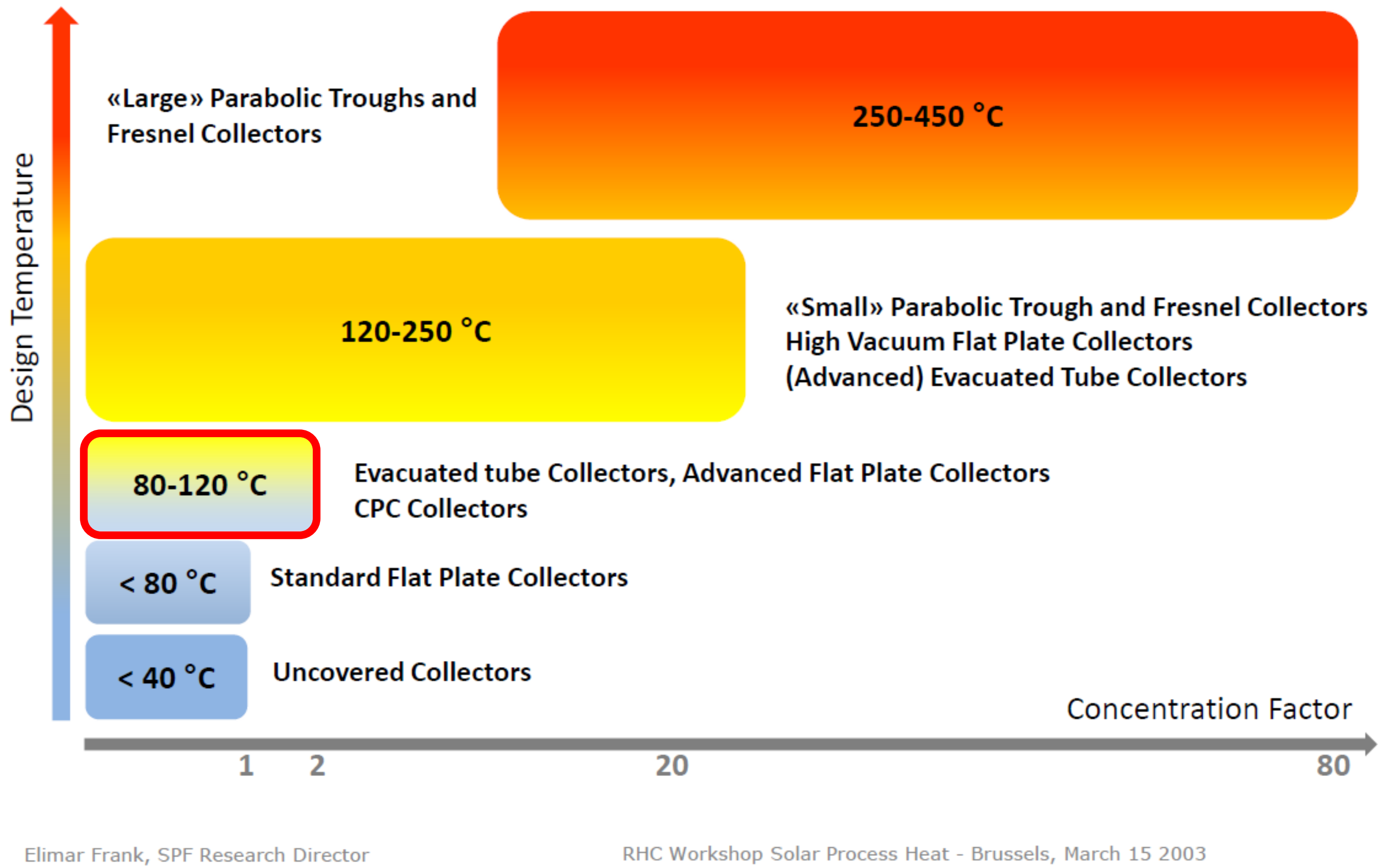
- Task 1.3: Generate annual process load profile on an hourly basis (= 8,760 values)

Group work

Design study (Part II)

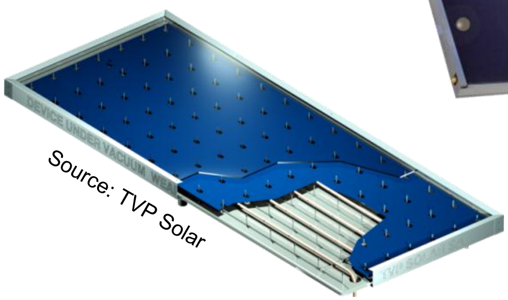
2.1) Solar thermal collector technologies

- Different collectors for different design temperatures

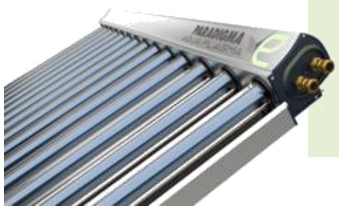


Design study (Part II)

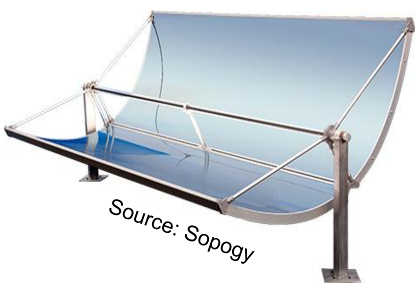
Source: GREENoneTEC



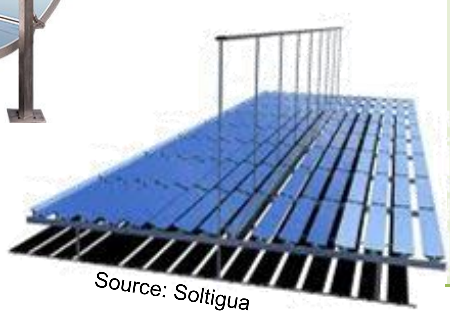
Source: TVP Solar



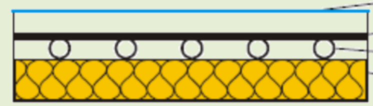
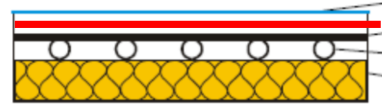
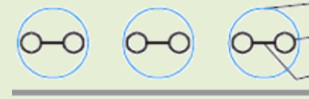
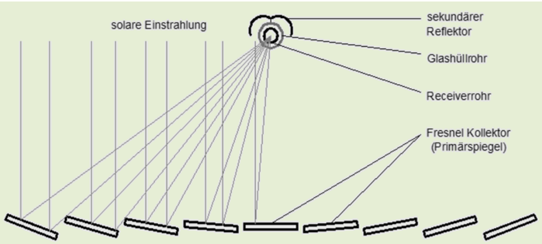
Source: Ritter Solar XL



Source: Sopogy



Source: Soltigua

TYPE	SKETCH (cross-section)	Design temperature
Standard flat plate collectors		**20 – 80 °C**
Advanced flat plate collector (vacuum filled, multiple covers, etc.)		**60 – 120 °C** up to 160 °C
Evacuated tubular collector		**60 – 120 °C** up to 160 °C
Parabolic trough collectors		**120 – 250 °C** up to 400 °C
Fresnel collectors		**120 – 250 °C** up to 400 °C

Design study (Part II)

2.1) Solar thermal collector technologies

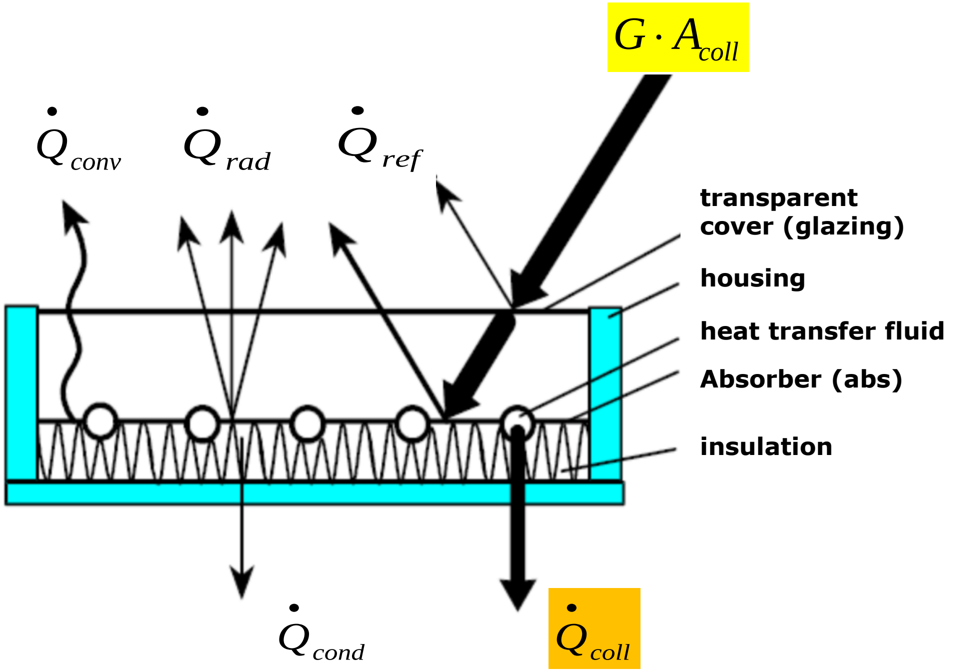
- Solar thermal collector efficiency curve

$$\dot{Q}_{coll} = G \cdot A_{coll} - \dot{Q}_{ref} - \dot{Q}_{rad} - \dot{Q}_{konv} - \dot{Q}_{cond}$$

$$\dot{Q}_{ref} = G \cdot A_{coll} \cdot \left(1 - \tau_{glazing} \cdot \alpha_{abs}\right)$$

$$\dot{Q}_{rad} = A_{coll} \cdot \varepsilon_{abs} \cdot \sigma \cdot \left(T^4_{m,coll} - T_a{}^4\right)$$

$$\dot{Q}_{conv} + \dot{Q}_{cond} = A_{coll} \cdot U_{coll} \cdot \left(T_{m,coll} - T_a\right)$$



Design study (Part II)

2.1) Solar thermal collector technologies

- Solar thermal collector efficiency curve

$$\eta_{coll} = \frac{\dot{Q}_{coll}}{G \cdot A_{coll}} = \tau_{glazing} \cdot \alpha_{abs} - \frac{U_{coll}}{G} \cdot (T_{m,coll} - T_a) - \frac{\varepsilon_{abs} \cdot \sigma}{I_g} \cdot (T^4_{m,coll} - T_a{}^4)$$

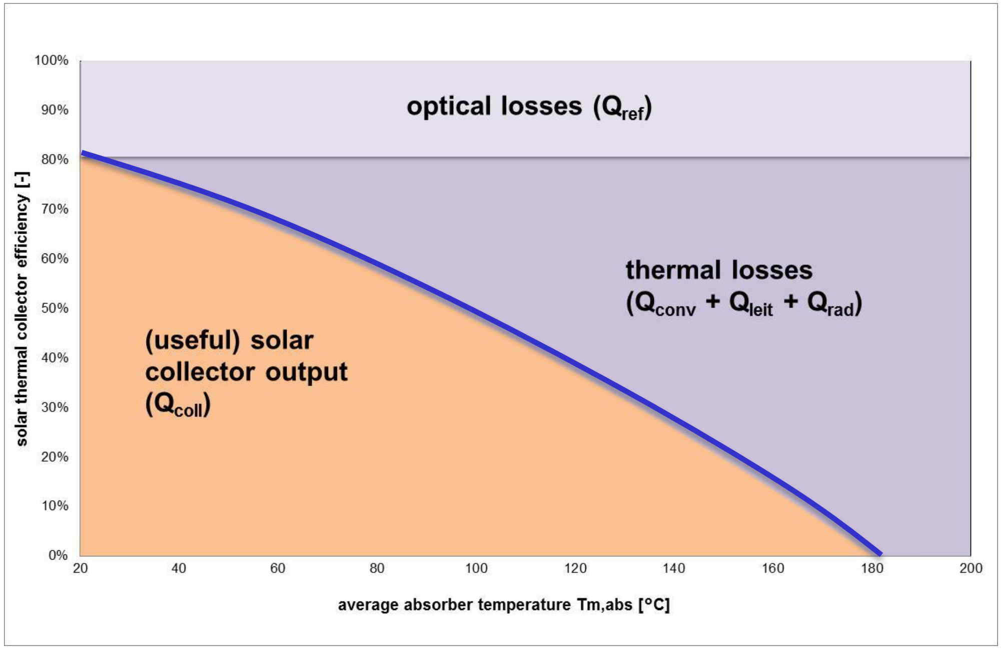
c_0 c_1 c_2

Symbols:

c_0 maximum efficiency (= efficiency at tm = ta) [-]

c_1 linear heat loss coefficient [$W \cdot m^{-2} \cdot K^{-1}$]

c_2 quadratic heat loss coefficient [$W \cdot m^{-2} \cdot K^{-2}$]



Design study (Part II)

2.1) Solar thermal collector technologies

- Solar thermal collector efficiency curve

$$\eta_{coll} = c_0 - c_1 \cdot \frac{T_{m,coll} - T_a}{G} - c_2 \cdot \frac{(T_{m,coll} - T_a)^2}{G}$$

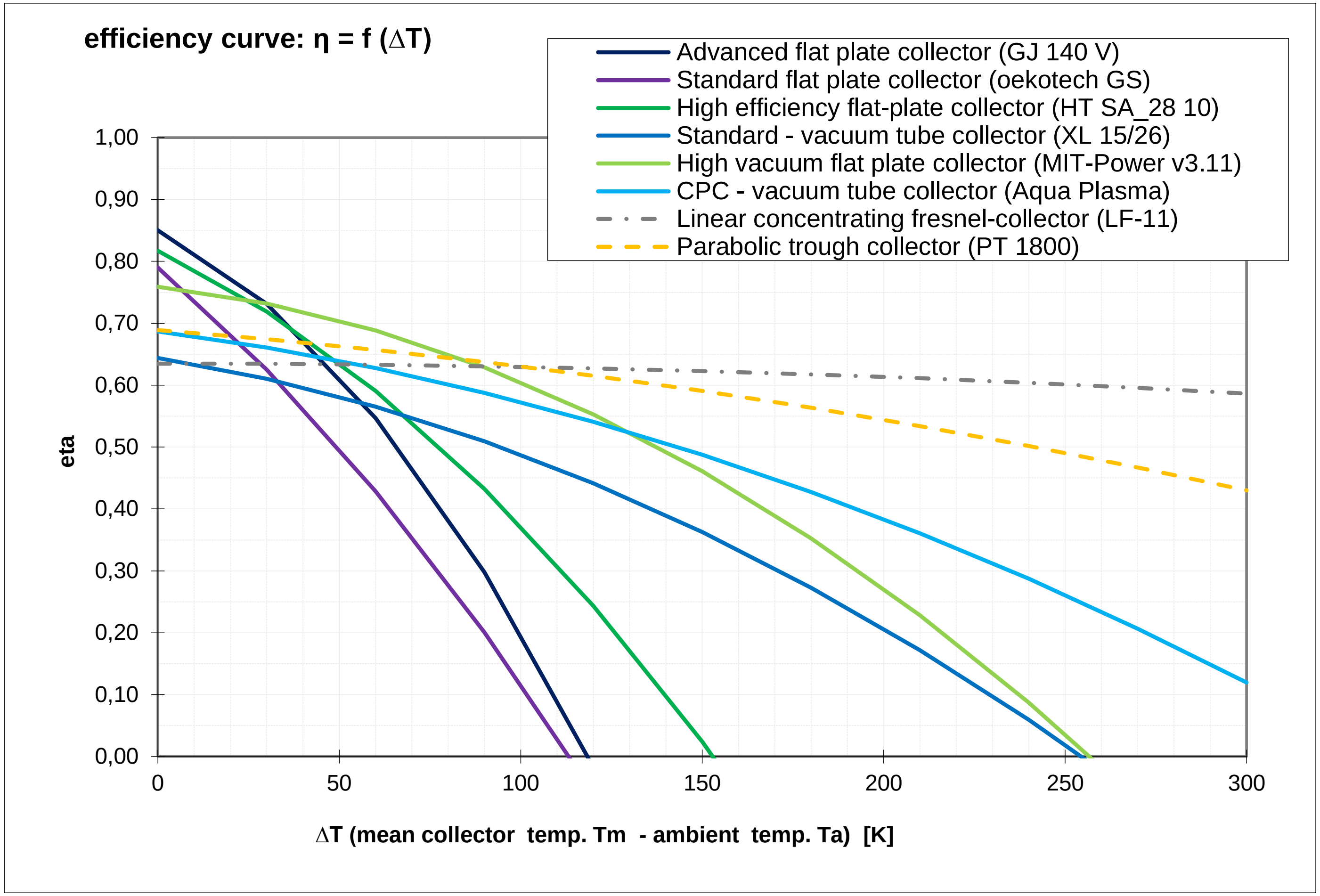
Type of collector			
Source:	c_0	c_1	c_2
Standard flat plate collector (oekotech GS)	**0.79**	**3.979**	**0.014**
Advanced flat plate collector (GJ 140 V)	**0.85**	**2.30**	**0.029**
High efficiency flat-plate collector (HT SA_28 10)	**0.817**	**2.205**	**0.0135**
Standard - vacuum tube collector (XL 15/26)	**0.644**	**0.749**	**0.005**
CPC - high efficiency vacuum tube collector (Aqua Plasma)	**0.687**	**0.613**	**0.003**
High vacuum flat plate collector (MIT-Power v3.11)	**0.76**	**0.51**	**0.007**
Linear concentrating fresnel collector (LF-11)	**0.635**	**0.000**	**0.0004**
Parabolic trough collector (PT 1800)	**0.689**	**0.36**	**0.0011**

- for collector data sheets go to: http://solarkey.dk/

Design study (Part II)

2.1) Solar thermal collector technologies

- Efficiency curves for G=800W/m² and Ta= 20°C



Design study (Part II)

2.1) Solar thermal collector technologies

- Task 2.1: Choose appropriate solar thermal collector technology based on process characteristics
  - Pre-define suitable collector technologies based on the temperature level needed
  - Use efficiency curve template and information from the solar thermal collector data sheet for detailed efficiency curve analysis

Group work

Design study (Part II)

2.2) Collector field placement

- Availability of suitable space for a solar thermal collector field installation is often a bottleneck at industrial sites
  - Get site plans. pictures. Google maps images. GIS data. etc.
  - Discuss with responsible people on site regarding appropriate roof or ground areas
  - In case of roof mounting it is often necessary to ask for a structural analysis of the roof beforehand

- In case there is space available optimum inclination and orientation of the single solar thermal collectors can be determined
- Based on the available space a maximum possible collector field size can be estimated beforehand

Design study (Part II)

2.2) Collector field placement

– Mounting options for flat and evacuated tube collectors

Ground mounted systems

Collectors with ballast blocks, waterworks, Graz, Austria [SOLID]

Post mounted system, Oberzeiring, Austria [SOLID]

- area utilization ratio: 0.3-0.4 (ground. flat roof) / 0.8 (in roof)

Design study (Part II)

2.2) Collector field placement

– Mounting options for Fresnel or parabolic through collectors


Source: Solera GmbH

- area utilization ratio: 0.3-0.4


Source: Industrial Solar

- area utilization ratio: 0.8-0.9

Design study (Part II)

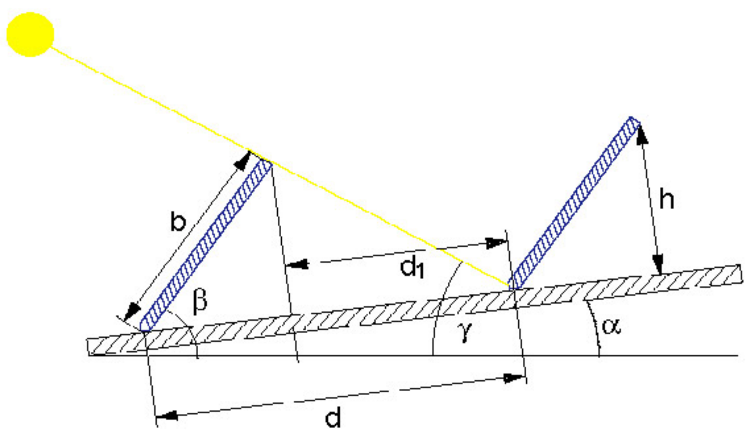
2.2) Collector field placement

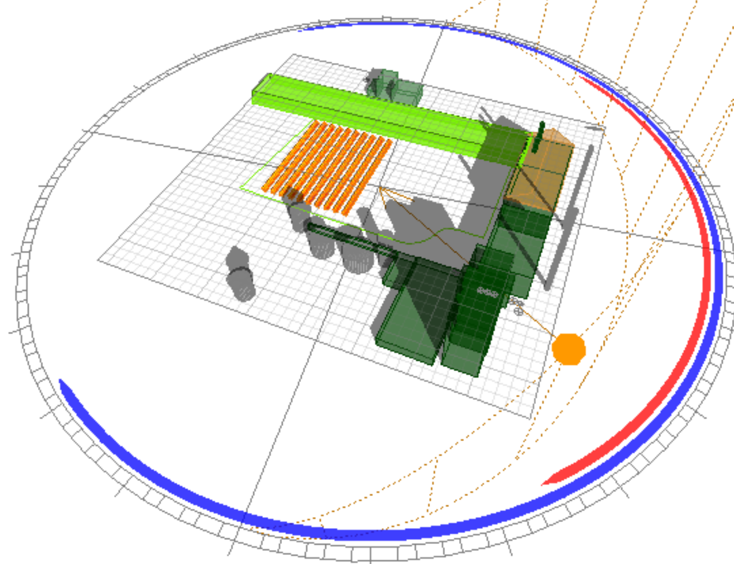
– How to choose the right inclination and orientation of the collectors?

Design study (Part II)

2.2) Collector field placement

- How to choose the right inclination and orientation of the collectors?
  - As a general rule. the collector should be facing the equator. That means in the southern hemisphere facing north and in the northern hemisphere facing south.
  - In addition care should be taken that the collectors are not shaded at any time of the year. either by trees. buildings or other collectors.





Design study (Part II)

2.2) Collector field placement

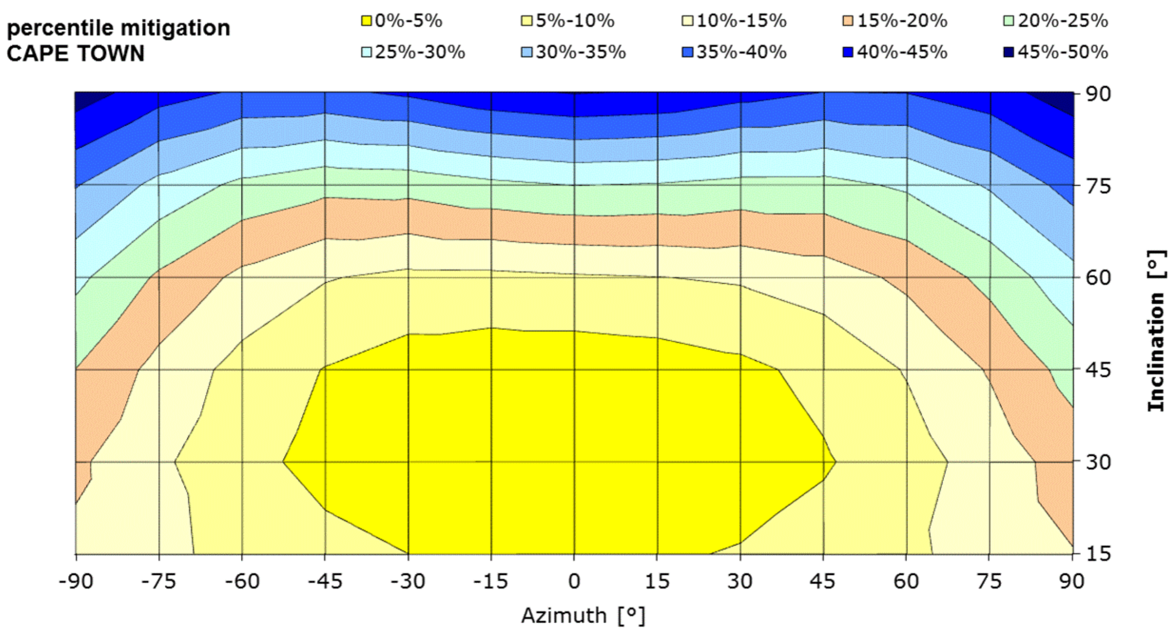
- How to choose the right inclination angle (slope angle of tilt)?
  - The largest yield is obtained when the collector is always orientated perpendicular to the sun. However. the optimal tilt angle for the collectors varies according to the season. as the sun is higher in the sky in summer than in winter.
  - **As a general rule. the optimum angle of tilt is (almost) equal to the degree of latitude of the site. e.g.:**
    - Latitude Cape Town: 33.9° South → opt. tilt angle: 31°
    - Latitude Johannesburg: 26.2° South → opt. tilt angle: 29°

- To determine optimum annual tilt angle use: http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?lang=en&map=africa

Design study (Part II)

2.2) Collector field placement

- Collector orientation can vary **±40°** from equator and from **15° to 45°** in slope with less than a 5% reduction in energy savings for a South African climate (reference: Cape Town).
- **Within this range it is generally easy to compensate with a slightly larger collector area**

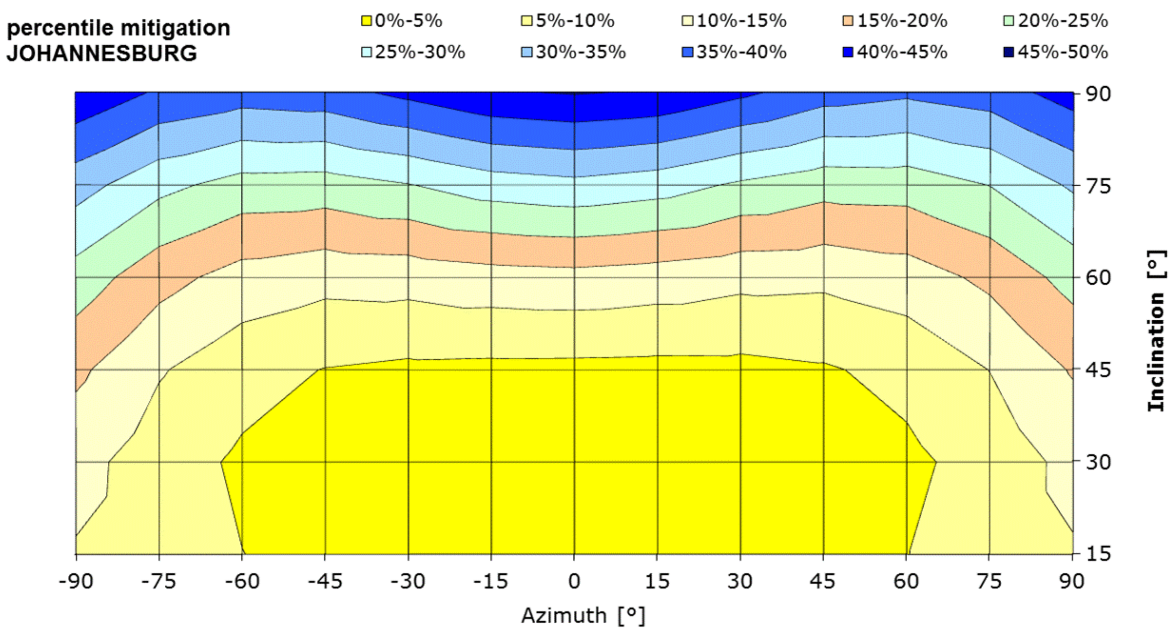


Source: AEE INTEC based on Meteonorm climate data

Design study (Part II)

2.2) Collector field placement

- Collector orientation can vary **±60°** from equator and from **15° to 45°** in slope with less than a 5% reduction in energy savings for a South African climate (reference: Johannesburg).
- **Within this range it is generally easy to compensate with a slightly larger collector area**



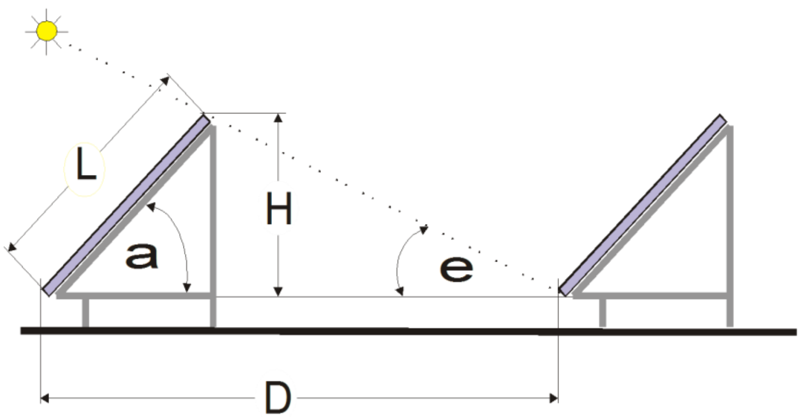
Source: AEE INTEC based on Meteonorm climate data

Design study (Part II)

2.2) Collector field placement

– Minimum row distance to avoid overshadowing

- Variables influencing the distance. D between the collector rows.



$$H = L \cdot \sin \alpha$$

$$D = \frac{L \cdot \sin[180 - (\alpha + \varepsilon)]}{\sin \varepsilon}$$

Symbols:

D	Distance between the rows of collectors [m]
L	Collector length [m]
H	Collector height [m]
α (a)	Collector inclination angle [°]
ε (e)	Incident solar radiation angle **in winter** [°]

Design study (Part II)

2.2) Collector field placement

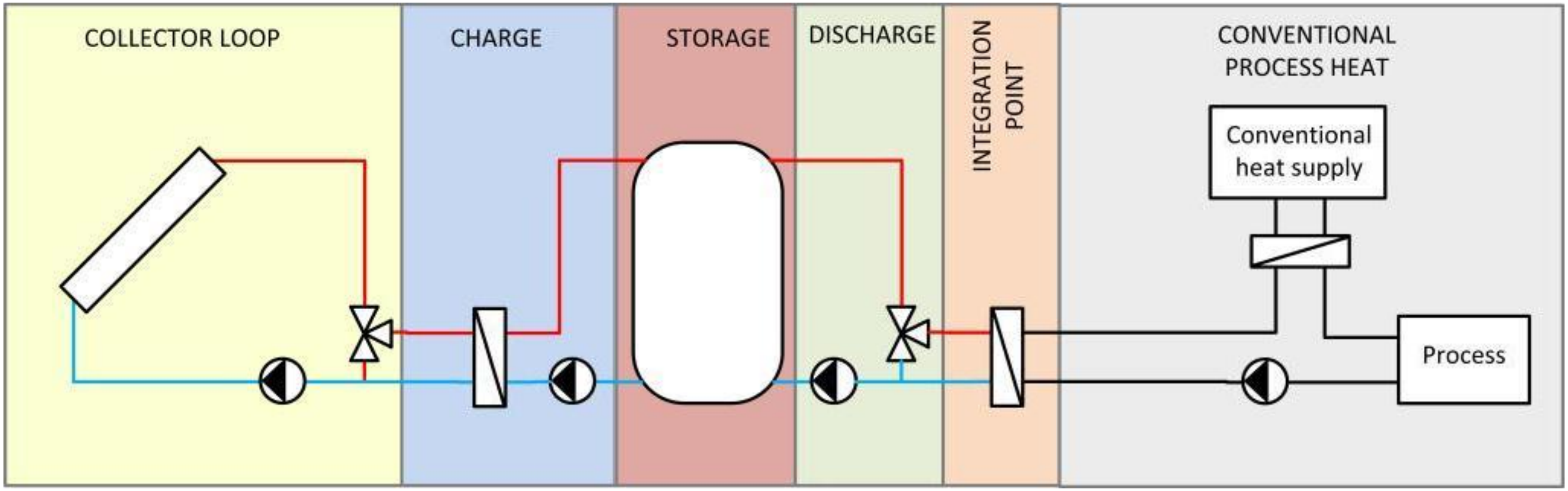
- Task 2.2:
  - What is the **maximum** collector field size for a given ground area?
  - What inclination and azimuth angle do you propose?
  - Make a first draft of the ground mounted collector field (no. of rows, no. of collectors per row)

Group work

Design study (Part II)

2.3) Hydraulic diagram of solar loop + process loop

- Schematic diagram of solar process heat application



Design study (Part II)

2.3) Hydraulic diagram of solar loop + process loop

– Task 2.3: Draw basic hydraulic diagram of solar loop + process loop

Group work

Design study (Part II)

2.4) Basic (detail) engineering of the solar thermal system

- Collector loop (solar primary loop)
  - Size of the solar thermal collector field
  - Dimensioning of solar primary loop pipes and pump
  - Introduction: Expansion and safety devices
  - Introduction: collector field hydraulics
- Charge (solar secondary loop)
  - Dimensioning of solar loop heat exchanger
  - Dimensioning of solar secondary loop pump and pipes
- Dimensioning of the solar energy storage volume
- Discharge (solar process heat supply loop)
  - Dimensioning of solar process heat supply loop heat exchanger
  - Dimensioning of solar process heat supply loop pump and pipes

Design study (Part II)

2.4) Basic (detail) engineering of the solar thermal system

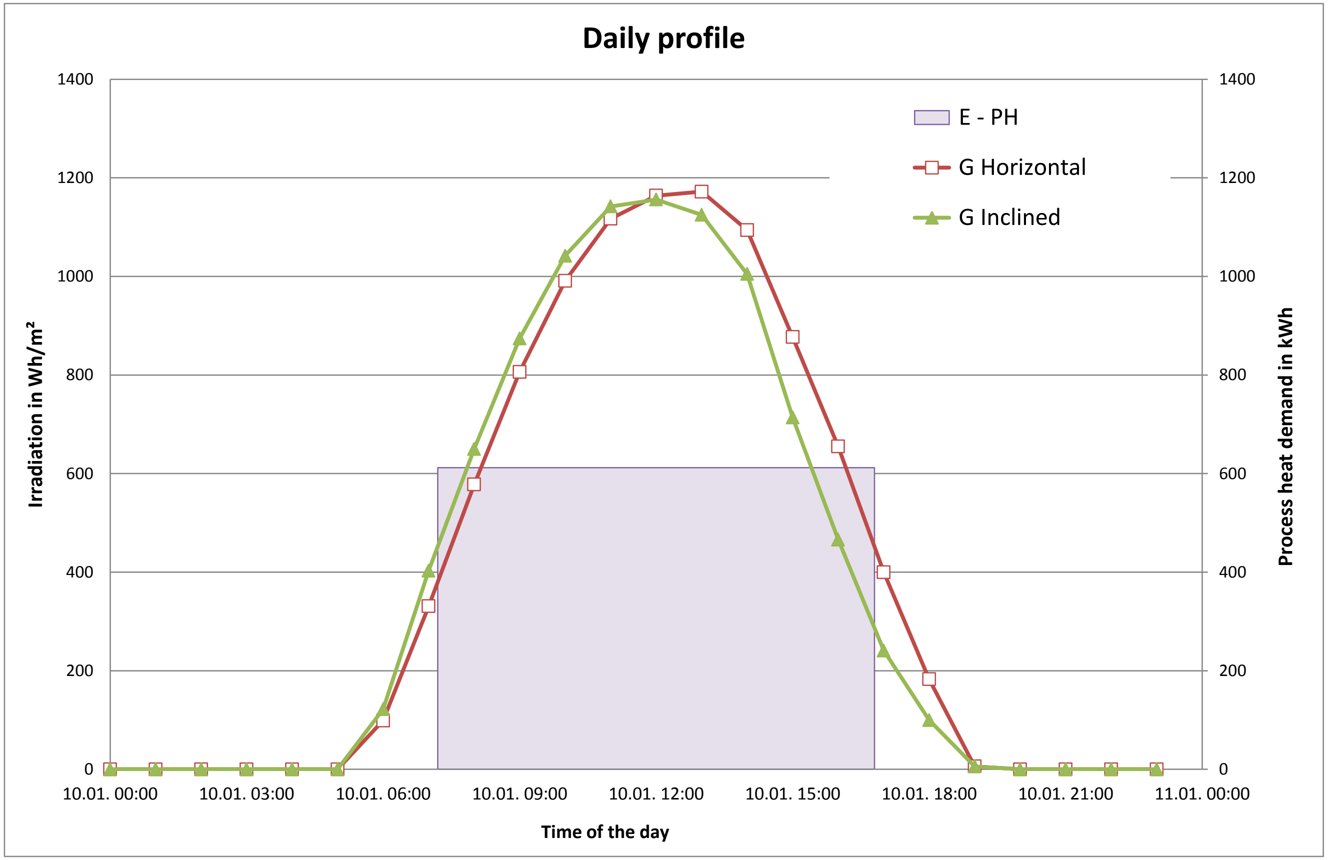
– Dimensioning of the collector field

- Collector field size is designed in a way to cover daily process heat demand to 100% **at the hottest day**
- This ensures that the solar thermal system is not over-dimensioned
- For this calculation hourly climate data for the site are needed for the hottest day in the year
  - e.g.: Meteonorm, T-SOL, Polysun, GIS data bases (commercial)
  - e.g.: PV-GIS: http://re.jrc.ec.europa.eu/pvgis/ (free, but only average daily radiation data)

Design study (Part II)

2.4) Basic (detail) engineering of the solar thermal system

– Dimensioning of the collector field



specific max. daily **horizontal** irradiation

$$G_{hor.max} = 9.5\ kWh/(m^2 \cdot day)$$

specific max. daily **inclined** irradiation

$$G_{incl.max} = 9.0\ kWh/(m^2 \cdot day)$$

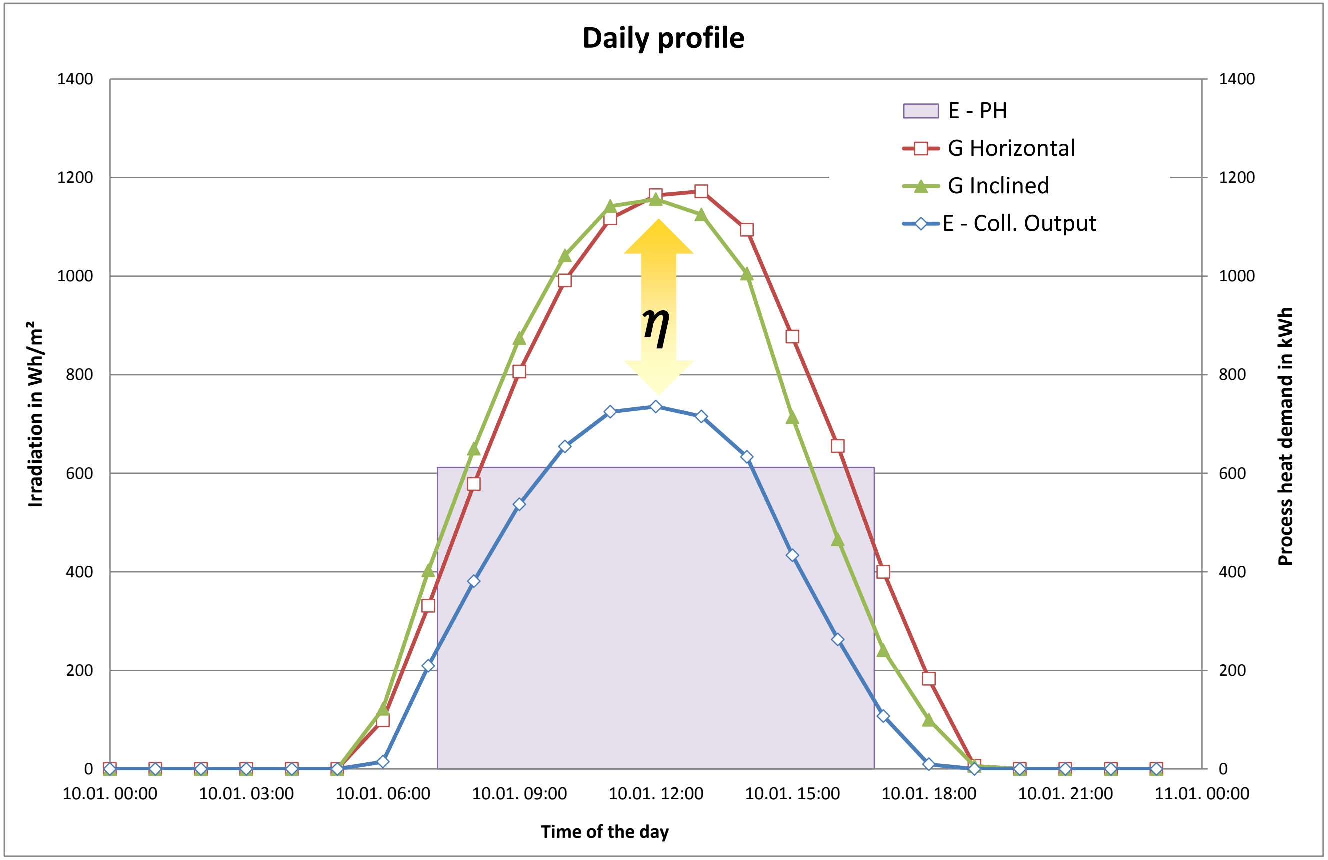
daily process heat demand

$$E_{PH} = 9{,}800\ kWh/day$$

Design study (Part II)

2.4) Basic (detail) engineering of the solar thermal system

– Dimensioning of the collector field



specific max. daily collector output

$$E_{coll,max} = 5.4\ \mathrm{kWh/(m^2 \cdot day)}$$

max. daily utilization ratio:

$$\eta_{coll,day} = \frac{E_{coll,max}}{G_{incl,max}} [-]$$

max. collector area:

$$A_{coll,max} = \frac{E_{PH}}{E_{coll,max}} [m^2]$$

Design study (Part II)

2.4) Basic (detail) engineering of the solar thermal system

- Dimensioning of storage tank size
  - Storage tank should be dimensioned in a way that energy produced by the collector field can be stored during weekend still-stands (this example: for one day)
  - **NOTE**: If weekend still-stand is longer than one day, storage volume can be dimensioned smaller if night cooling is taken into consideration!

$$Q_{storage}\,[kWh] = E_{coll,max} \cdot A_{coll,max}$$

$$V_{storage}\,[m^3] = \frac{Q_{storage} \cdot 3600}{\rho \cdot cp \cdot \left(T_{Storage,max} - T_{Storage,avg}\right)}$$

Design study (Part II)

2.4) Basic (detail) engineering of the solar thermal system

– Calculation of solar loop heat exchanger

- The capacity of the solar loop heat exchanger $P_{HX\text{-}Solar}$ [kW] equals the max. hourly collector field power $P_{coll,max}$ @ **design** mean collector temperature (**this case: 110/80 → Tm=95°C**).

$$P_{HX-Solar} = P_{coll,max}\,[kW] = \dot{G}_{incl,max} \cdot \eta_{coll,max}\,(95°C)$$

- $G_{incl,max}$ [W/m²] is in the range of 1,100 – 1,200 W/m² all over the world
- $\eta_{coll,max}$ need to be calculated according to the efficiency curve with max. **hourly** irradiation on inclined surface and **mean** design collector temperatures

Design study (Part II)

2.4) Basic (detail) engineering of the solar thermal system

– Calculation of solar loop cooler (water / water HEX)

- For large scale solar process heat applications it might be necessary to install an active cooling device to avoid overheating resp. stagnation.
- → **pros:** less temperature and pressure stress of the solar lop components
- → **pros:** small expansion devices (only to absorb liquid expansion)
- → **cons:** uninterruptable power supply to run the control and the pumps in case of power outages needed
- The capacity of the primary loop cooler $P_{HX\text{-}Cooler}$ [kW] equals the max. hourly collector field power $P_{coll,max}$ @ **max**. mean collector temperature (**this case: 150/120 → Tm=135°C**).

$$P_{HX-Cooler}\,[kW] = \dot{G}_{incl,max} \cdot \eta_{coll,max}\,(135°C)$$

Design study (Part II)

2.4) Basic (detail) engineering of the solar thermal system

– Dimensioning of expansion vessels in solar primary and secondary loop

- If an active cooling device for stagnation prevention is used expansion vessels only need to be designed to absorb liquid expansion

Design study (Part II)

2.4) Basic (detail) engineering of the solar thermal system

– Dimensioning of pumps in the solar primary loop

- Max. pump mass flow is calculated from the max. hourly collector field power P coll,max [kW] and the design collector loop supply and return temperatures

$$\dot{m}_{solar} = \frac{P_{coll,max}}{cp \cdot (T_{supply} - T_{return})}$$

- Pressure loss in the system need to be calculated from losses in the collector field. piping. fittings. heat exchanger. etc.

$$\Delta p_{system} = \lambda \cdot \frac{l}{d} \cdot \frac{\rho}{2} \cdot v^2 + \sum \zeta \cdot \frac{\rho}{2} \cdot v^2$$

- E.g.: Grundfos WebCABS – Pump design software

Design study (Part II)

2.4) Basic (detail) engineering of the solar thermal system

- Task 2.4:
  - Define suitable collector field size considering load, collector and radiation
  - Calculate heat exchanger capacity in solar loop
  - Design appropriate solar energy storage volume
  - Dimensioning of pipes and pumps
  - Dimensioning of expansion and safety devices
  - Draw hydraulic diagram of the collector field (considering hydraulic balancing of the system)

Group work

Design study (Part II)

2.5) Simulation of annual energy gains

– Simulation studies are necessary to
  - determine annual energy gains, final energy savings, etc. of the solar thermal system (MWh/a)
  - determine annual CO_2 reductions (tons of CO_2 equiv./a)
  - compare different system concepts and / or collector types
  - optimize system parameters (e.g. insulation thickness, control strategy, storage size, etc.)

  - **→ basis for techno-economic comparison of different variants (resp. cases)**

Design study (Part II)

2.5) Simulation of annual energy gains

- Task 2.5:
  - What is the annual heat output (MWh/a) of the solar thermal system designed?
  - How much final energy can be saved?
  - How much parasitic energy is needed for pumps, etc.?
  - Comparison of several cases

Demonstration with the software T-Sol Expert 4.5

Design study (Part II)

2.6) Techno-economic comparison of results

- Based on the outcomes of the simulation case studies several cases (variants) can be compared in terms of
  - Levelized cost of heat (LCOH) of solar thermal heat produced [€/kWh]
  - Return on investment - ROI
  - Net present value over system life-time
  - Etc.

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{th}}{(1+i)^t}}$$

LCOH	Levelised cost of heat in €/kWh
I_0	initial capital cost in €
A_t	annual operating cost in €/a
M_{th}	(useful) annual solar yield in kWh/a
i	discount rate in %
n	project life time in years
t	year (1,2, …n)

Design study (Part II)

2.6) Techno-economic comparison of results

- Task 2.6:
  - Based on techno-economic consideration – which collector technology should be used?

Group work

Summary of results (project report)

Summarize the results in a project report

Thank you for your attention!

Franz Mauthner

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