SOLAR PAYBACK - TRAIN-THE-TRAINER
SOLAR HEAT FOR INDUSTRIAL PROCESSES

Design Principles

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www.ise.fraunhofer.de

Solar Payback

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Content

- Pre-feasibility and feasibility procedures
- Energy efficiency measures
- Integration concepts
- System Dimensioning
- Solar Yield Assessment
- Key Performance Indicators (KPIs)

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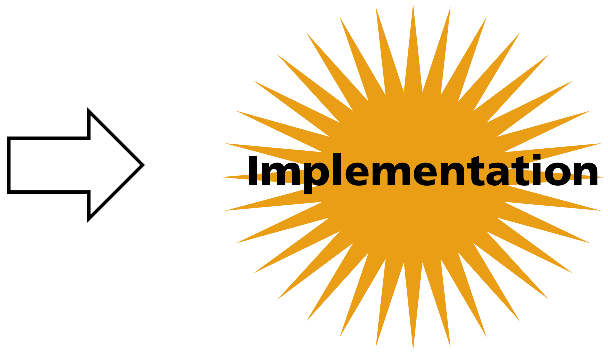
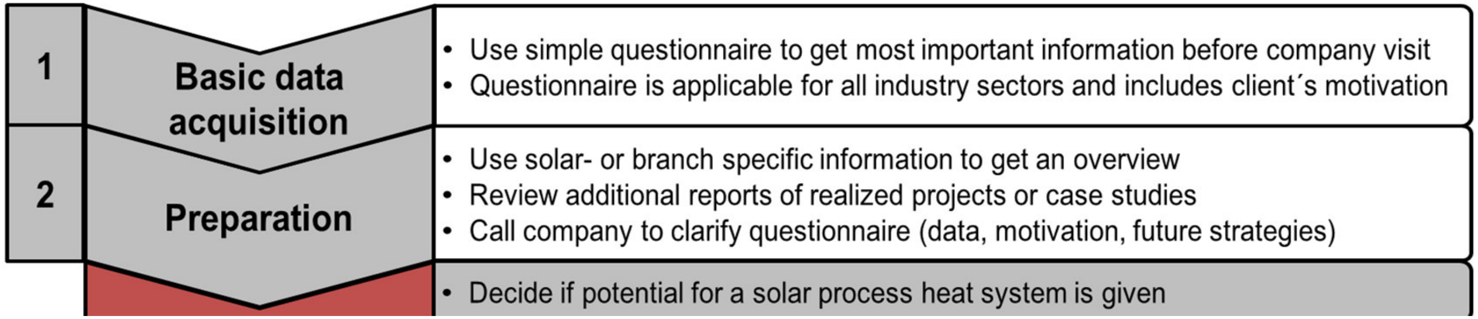
Prefeasibility and Feasibility Procedures
General procedure

- Definition of solar process heat potential
  - Pre-evaluation
- Identification of possible integration points
  - Technical analysis
  - Economic analysis
- Recommendation for solar integration



Prefeasibility and Feasibility Procedures
Pre-feasibility assessment

- Steps 1-2
  - Potential for solar process heat



[1]

[1] www.solar-process-heat.eu/checklist

Prefeasibility and Feasibility Procedures

Feasibility Study

- Steps 3-7
  - Define possible integration points

		• Decide if potential for a solar process heat system is given
3	Company visit	• Get overview of production site, heat consumers, and heat supply system together with responsible technical staff of company • Find out about future plans and strategy of the company • Collect, draw and discuss sketches (production flow, possible integration points, roof area, location for storages, etc.) with technical staff
4	Analysis of status quo	• Crosscheck gathered data with available benchmarks • Draw energy balance and flow sheet of production, try to estimate energy consumption of single production sections or processes *Actual depth of this analysis is based on available data and resources of auditor*
5	Process optimization & energy efficiency	• Investigate energy saving potential for processes (installations, control, etc.) • Check heat recovery potential within utilities (supply of heat, cold, compr. air) *Effort and depth of this step is based on the knowledge and resources of auditor*
6	Identification of integration points	• Apply the following criteria to all production processes with heat demand: integration temperature level, load profile, amount of thermal energy consumed, effort for integration, sensitivity to changes, and possible solar fraction • Rank heat consumers based on these criteria
7	Analysis of integration points	• Identify suitable collector type, necessary area and storage volume, proposed solar fraction and yield, overall costs (solar heating system, integration and installation) for the integration points of your ranking from prior step • Compare technical and economical facts of your ranking *Analysis can be done by simulations or estimative figures*
		• Create short report with overview of most suitable integration points

[1]

[1] www.solar-process-heat.eu/checklist

Prefeasibility and Feasibility Procedures
Conclusion

- Steps 8-9
  - Decision and detailed planning

		• Create short report with overview of most suitable integration points
8	Decision	• Discuss possibilities for solar process heat system with company • Based on the results of the prior step, the company should be able to decide if a solar heating system is desired and which concept shall be realized
9	Detailed planning	• Start detailed planning based on the company's decision • Repeat some of the prior steps again if necessary (e.g. to measure specific energy flows that are important to verify status quo)

[1]

[1] www.solar-process-heat.eu/checklist

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Energy efficiency measures
Holistic planning approach

- Process optimization and energy efficiency measures [1]
  - Heat exchanger optimization (pinch analysis)
  - Maximum heat recovery potential
  - Processes state-of-the-art?
  - Future plans?

➤ Identification of effective heat demand

EINSTEIN thermal energy industry audit

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

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

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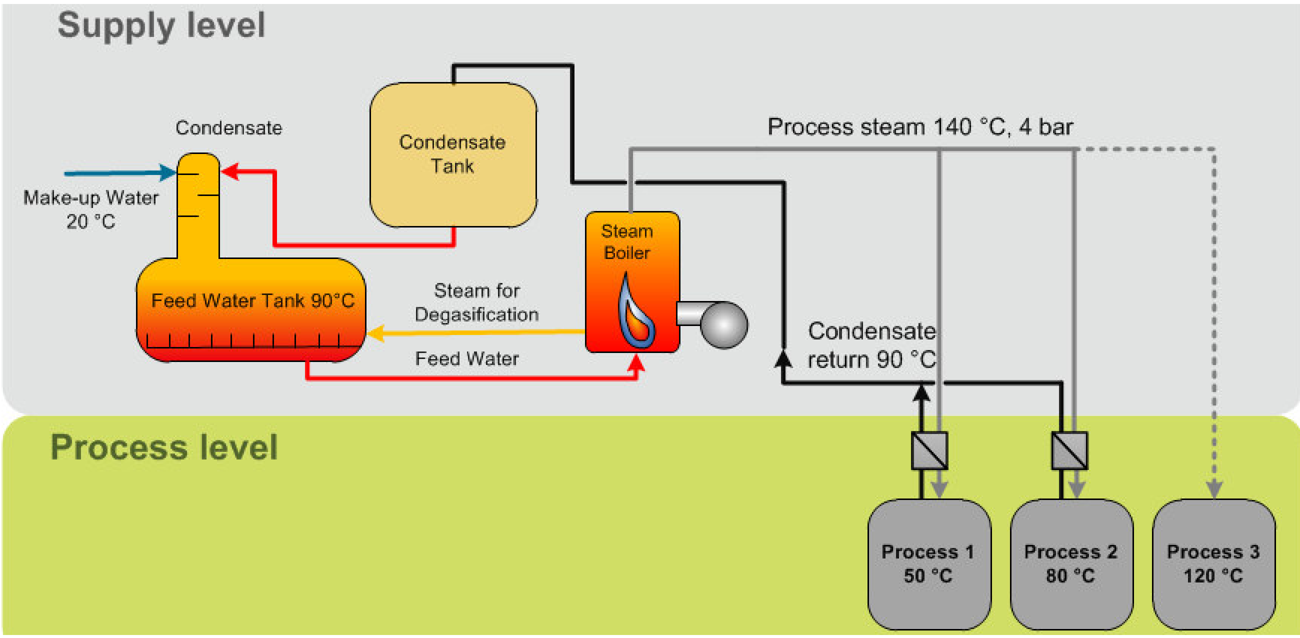
Integration Concepts
Definitions

- Heat demand
  - Thermal load: Energy demand per day or year
  - Load profile: daily, weekly and annual variation of the heat demand
  - Available temperature level: temperature at the heat integration point
- Open/closed processes
  - Open processes: Medium to be heated is not circulated
  - Closed process: Medium to be heated is circulated
- Directly/indirectly heated processes
  - Directly heated processes: Heat transfer fluid is process fluid
  - Indirectly heated processes: Heat supply to process via heat exchanger
- Integration point
  - Integration on process level: Solar heat supports a process
  - Integration on supply level: Solar heat supports hot water/steam network

Integration Concepts
Classification

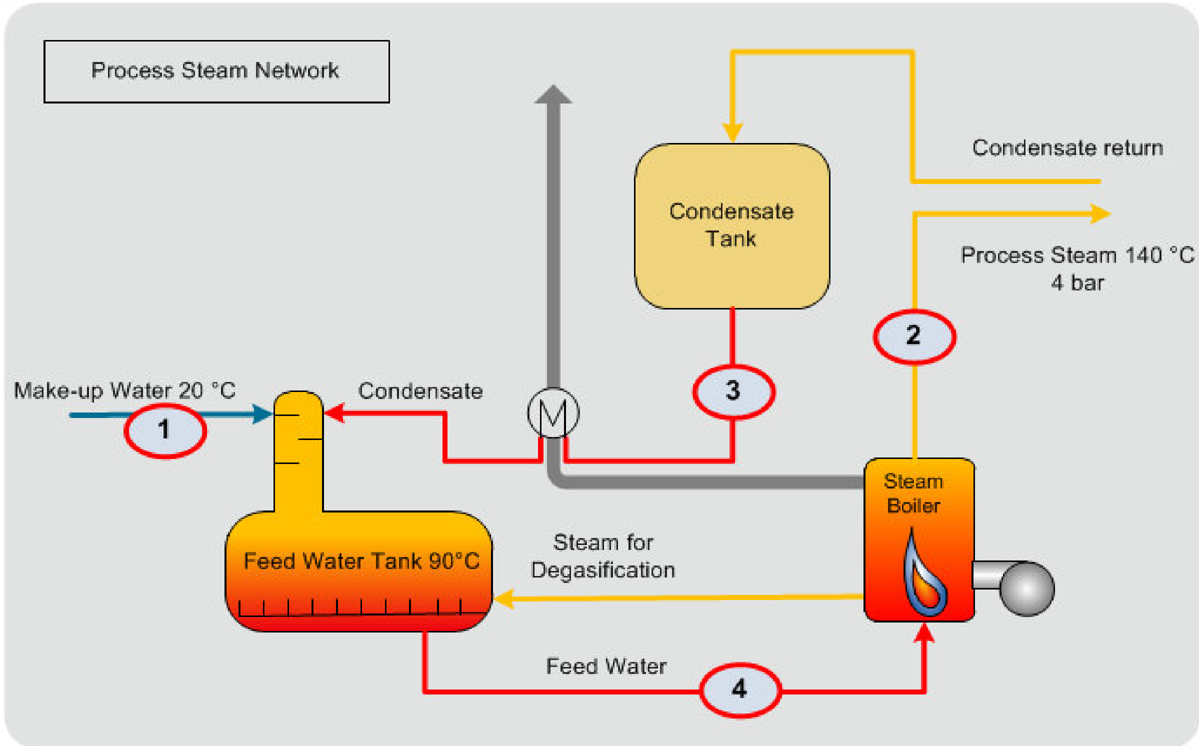
- Solar heat (steam or hot water) can be integrated into
  - heat distribution network
  - different processes



Integration Concepts
Supply Level

- Solar heat supply to all processes through heat distribution network
- Steam networks and high temperature networks

- Options:
  - Pre-heating of boiler feed water
  - Steam generation to directly feed steam network



Integration Concepts
Process Level

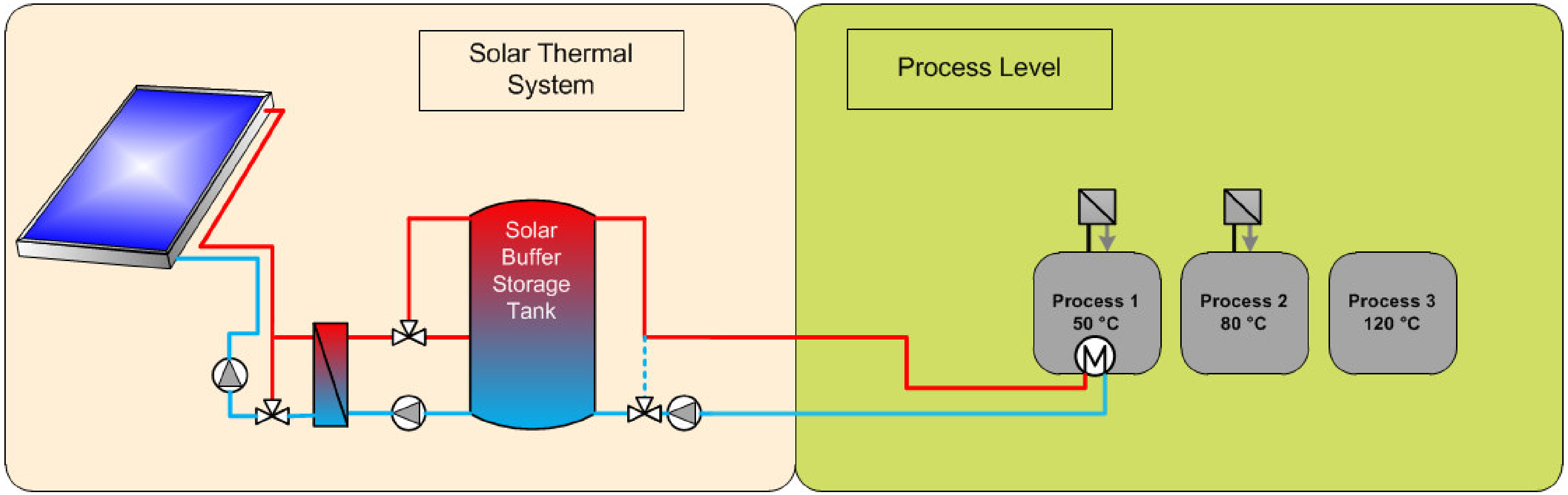
- Solar heat directly supplied to process

- For processes that require low temperature heat (until 100 °C)
  - Examples: washing, cleaning, heating of industrial baths, hot air drying
    - Often lower temperatures than supply level
    - Lower thermal losses lead to higher solar gains per square meter

- High dependency on changes in the process

Integration Concepts
Process Level - Examples

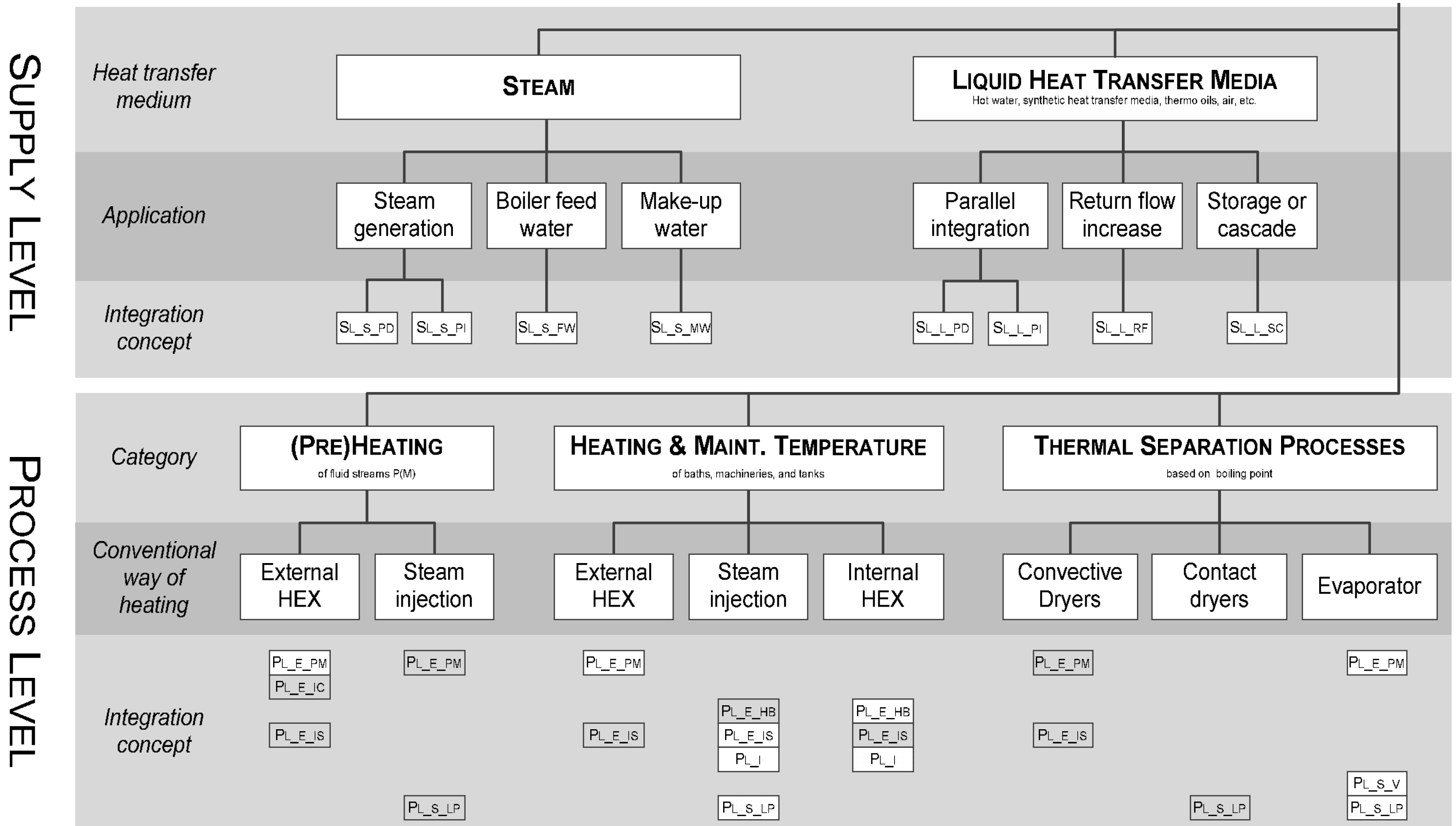
- Heating of cleaning or process water
- Heating of galvanic baths
- Heating of drying air



Integration Concepts
Criteria for Process or Supply Level Integration

Criteria	Process level	Supply level
Detailed process data	Required	Not needed
Preliminary process integration analysis	Essential	Generally recommended
Flexibility to adapt to later changes in processes	Low	High
Collector efficiency	Potentially higher	Usually lower
Solar heat contribution potential	Restricted	Usually higher
Heat storage necessity	Depends on the profile of the selected process stream(s)	Not necessary if not exceeding the base load of the utility

Integration Concepts
Integration of Solar Heat in Industrial Applications



[1]

[1] Muster B. et al.: Integration Guideline, IEA TASK 49, Technical Report B2, 2015

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Integration Concepts
Solar Heat Integration Concept Classification

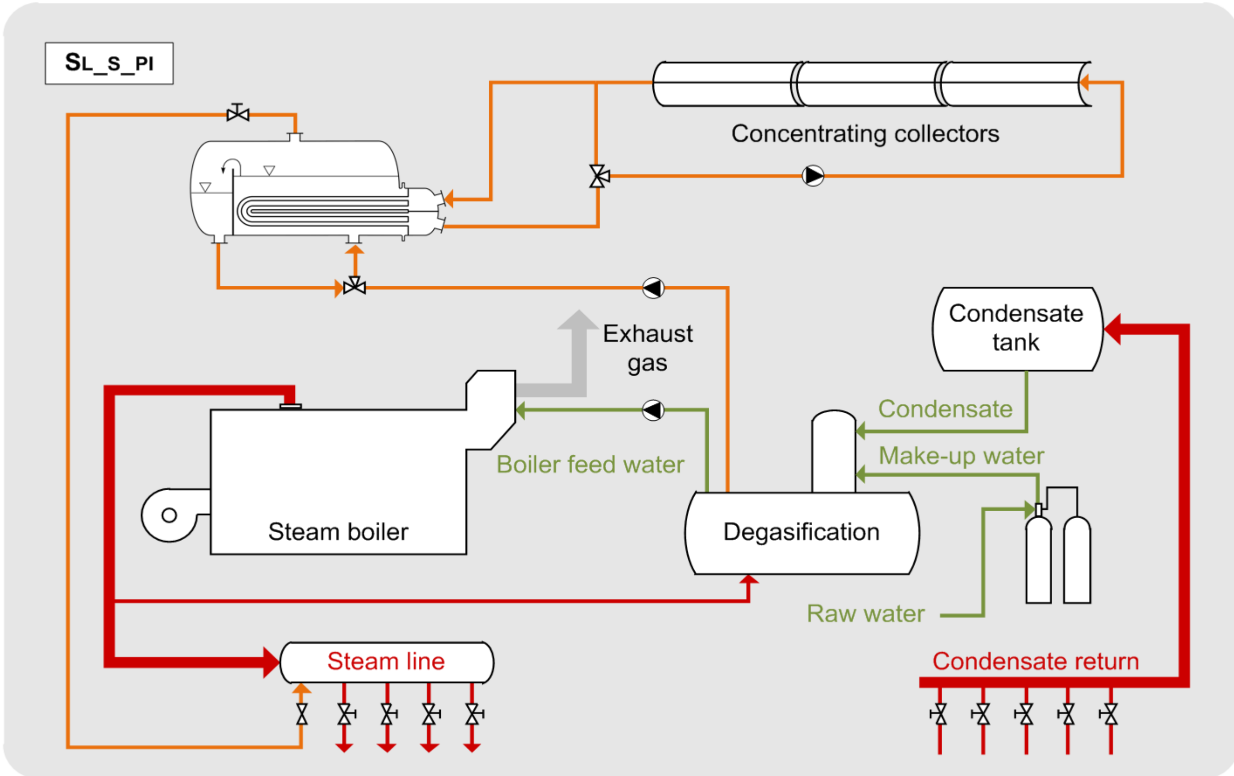
Level of integration	Heat transfer medium		Conventional way of heating		Solar heat integration concept	
Supply Level	S	Steam			PD/PI	parallel integration (direct or indirect)
					FW	heating of feedwater
					MW	heating of make-up water
	L	Liquid			PD/PI	parallel integration (direct or indirect)
					RF	return flow boost
					SC	heating of storages or cascades
Process level			E	external heat exchanger	PM	heating of process medium
					IC	heating of intermediate hot water circuit
					HB	heating of bath, machinery, or tank
					IS	heating of input streams
			I	internal HEX		
			S	steam supply	V	vacuum steam
					LP	low pressur steam

[1]

[1] Muster B. et al.: Integration Guideline, IEA TASK 49, Technical Report B2, 2015

Integration Concepts
Examples

- **SL_S_PI**
  - Indirect solar steam generation

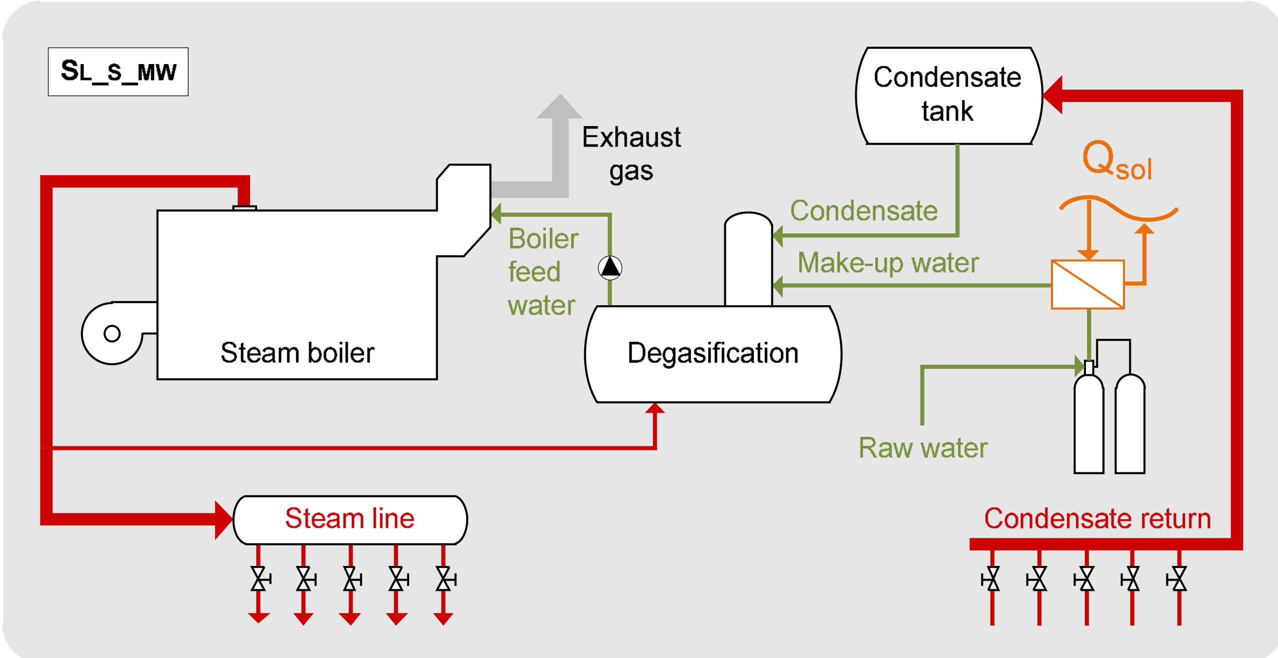


[1]

[1] Muster B. et al.: Integration Guideline, IEA TASK 49, Technical Report B2, 2015

Integration Concepts
Examples

- **SL_S_MW**
  - Solar heating of make-up water

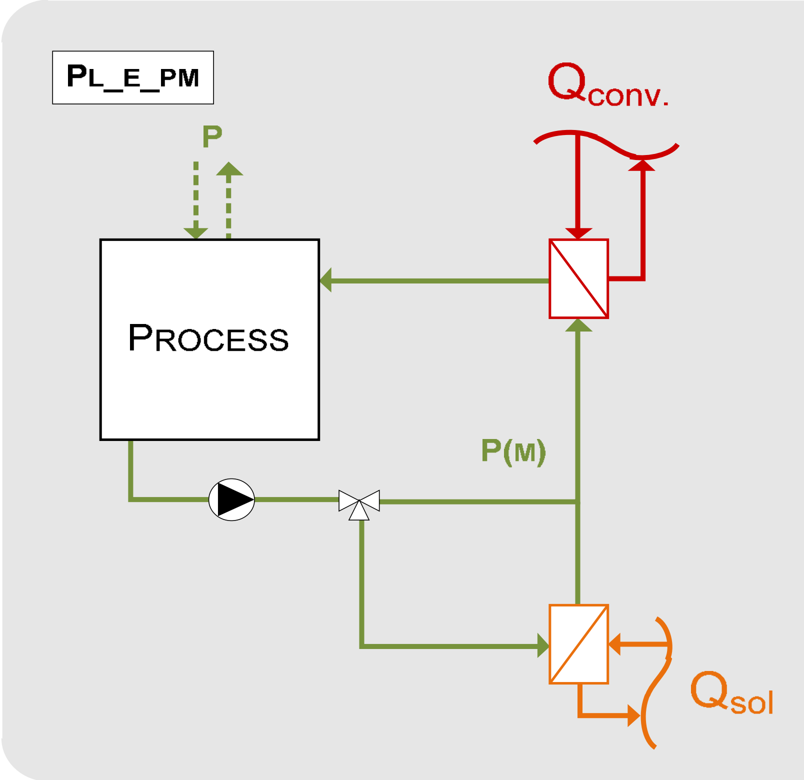


[1]

[1] Muster B. et al.: Integration Guideline, IEA TASK 49, Technical Report B2, 2015

Integration Concepts
Examples

- **PL_E_PM**
  - External HEX for heating of product or process medium



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Design Principles
Solar Field Size Criteria

SMALL ← **Solar Field Size** → **LARGE**

- Low demand
- Small storage (no/low shift from solar gain to night time)
- High solar potential
- Low temperature level
  → Lower thermal losses

- High demand
- Large storage (shift from solar gain to night time)
- Low solar potential
- High temperature level
  → Higher thermal losses

Design Principles
Storage Size Criteria

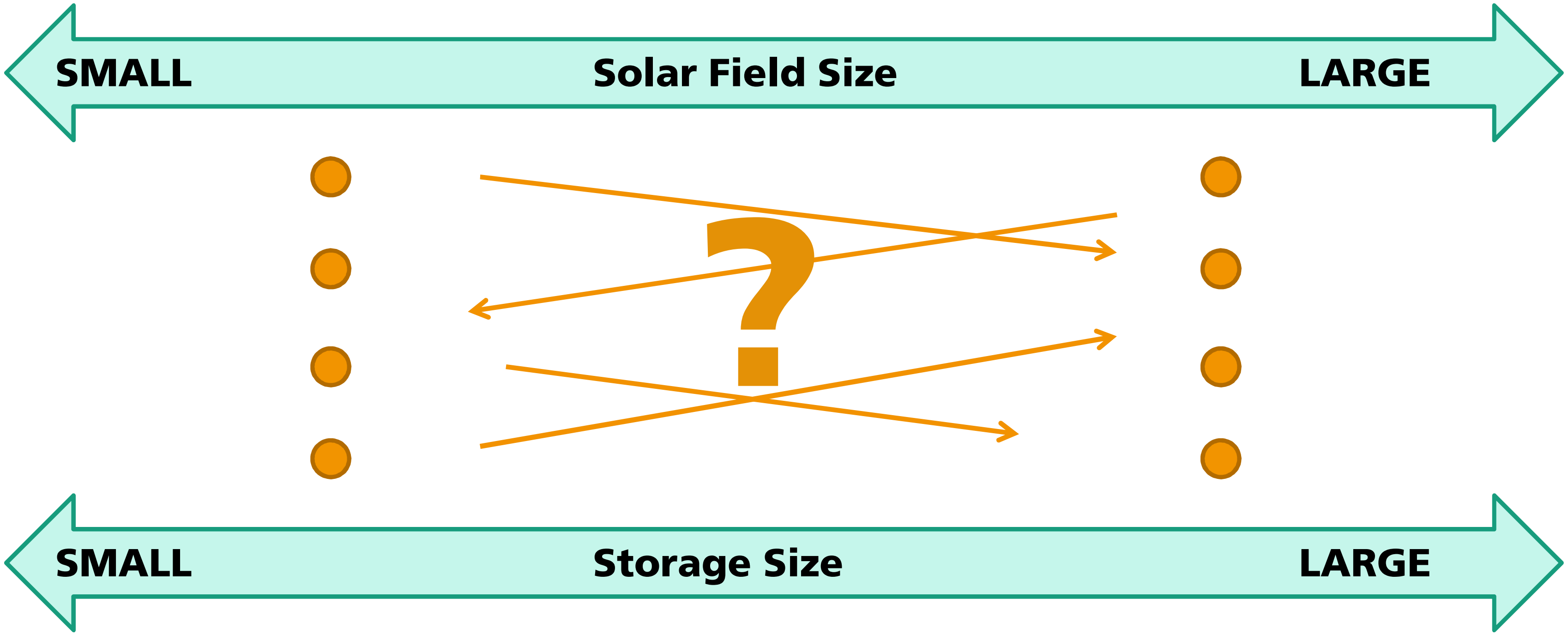
SMALL ⟵ **Storage Size** ⟶ **LARGE**

- High temperature difference
  → High storage capacity per volume
- Demand occurs during daytime
- Demand curve is stable

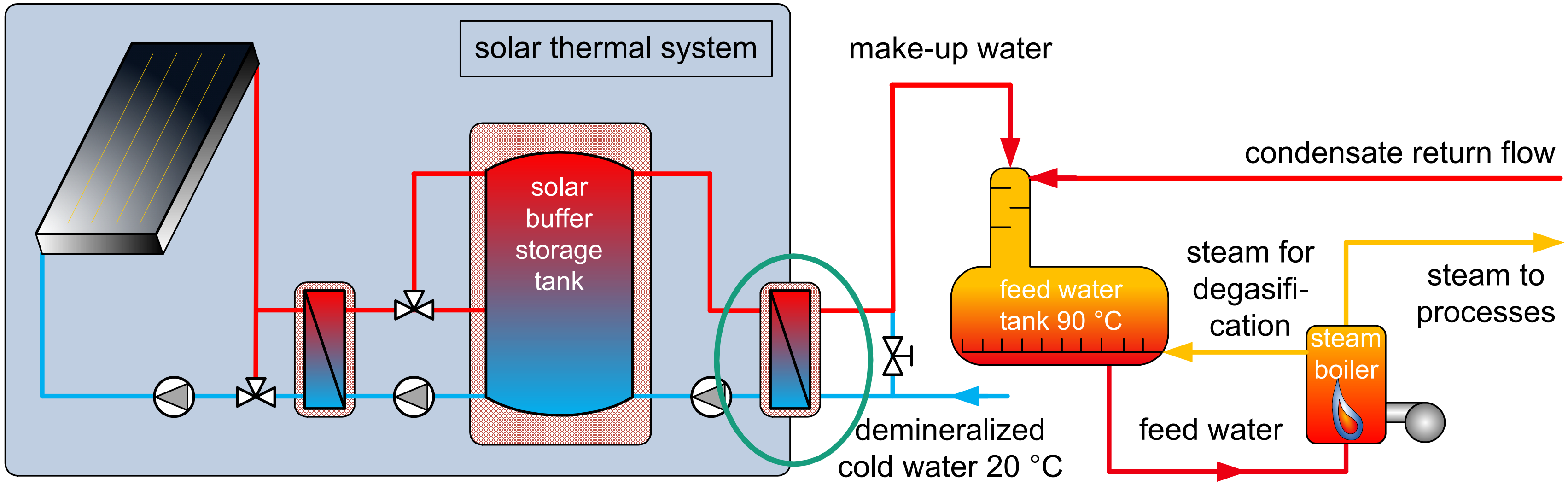
- Low temperature difference
  → Low storage capacity per volume
- Demand occurs during nighttime
- Demand curve is fluctuating

Storage capacity: $Q_{sto,cap} = V_{sto} \cdot \rho_{sto} \cdot c_p \cdot (T_{upper} - T_{lower})$

Design Principles
Optimization Problem

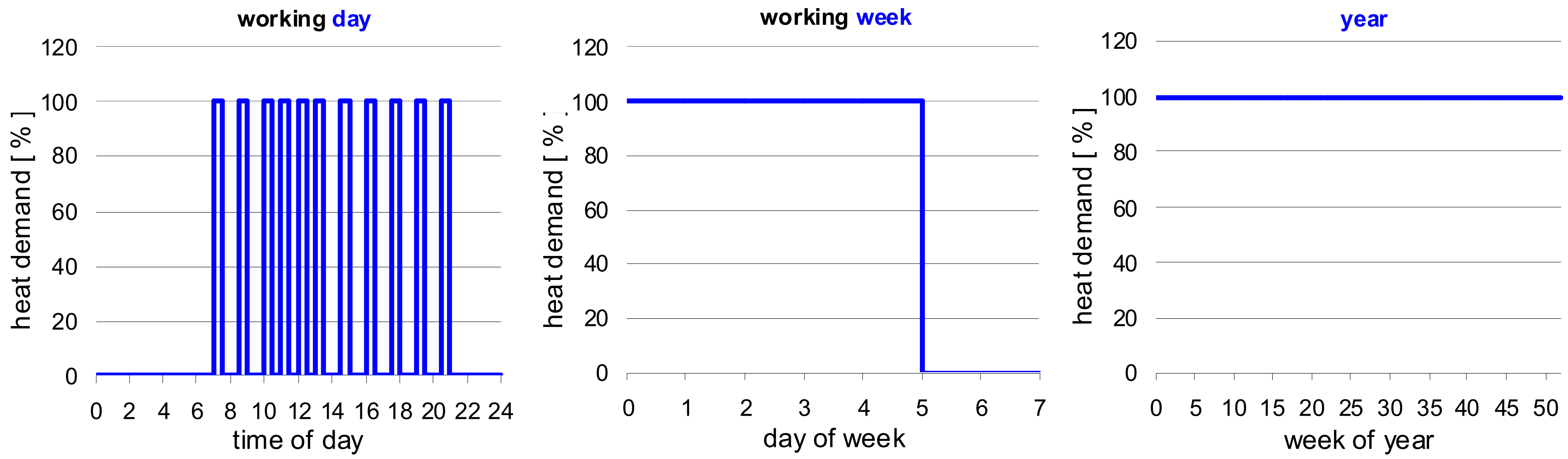


Design Principles
Layout - Pre-heating of make-up water



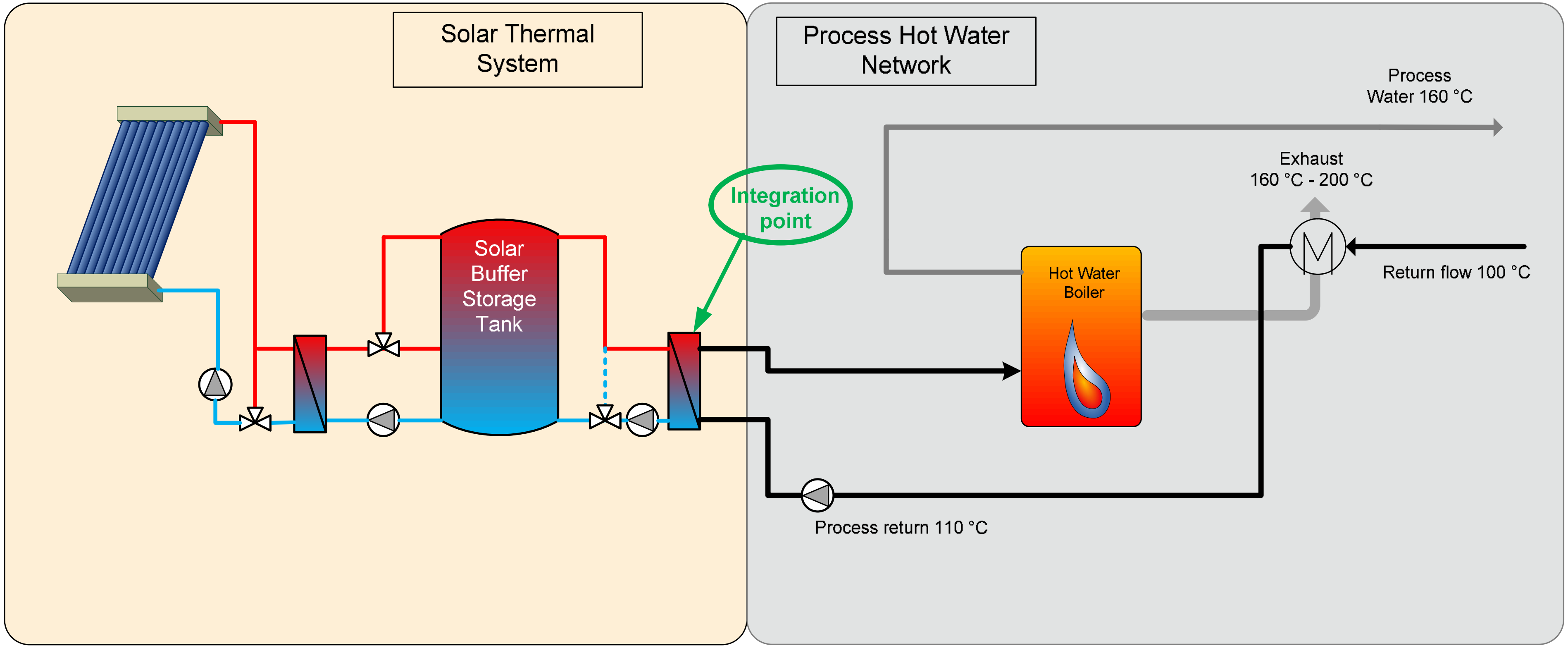
- Example: Small laundry
- High solar gains because of low temperature level

Design Principles
Thermal Load Profile - Pre-heating of make-up water



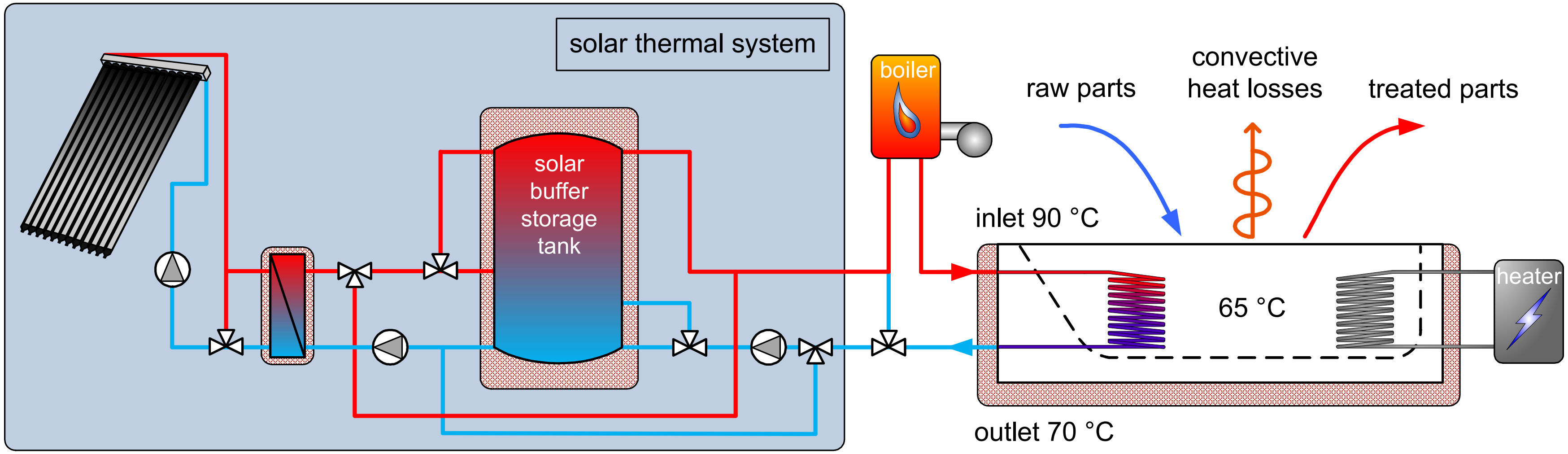
- Two shifts (5:30 am to 10 pm), weekend, no company holidays
- The fill-level control of the feed-water tank opens for intervals of 30 min
- Storage necessary due to fluctuations and demand after sun-set

Design Principles
Return flow temperature lift



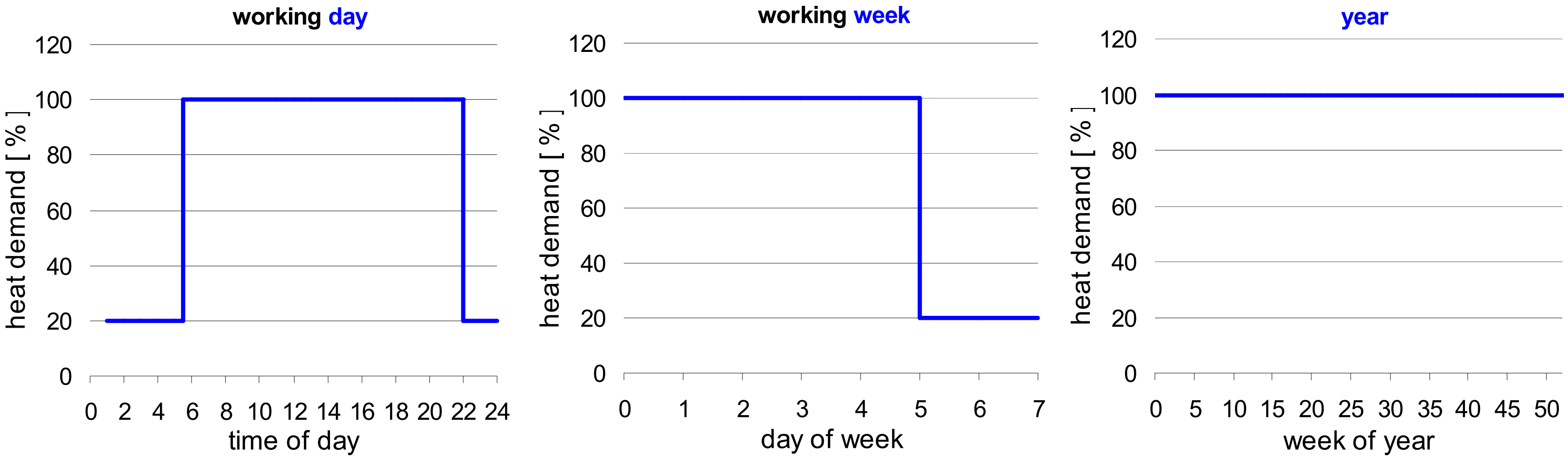
Design Principles

Layout - Solar Heating of Industrial Bath



- Closed process: Economics highly depend on the bath temperature
- The electrical heater is used for temperature control

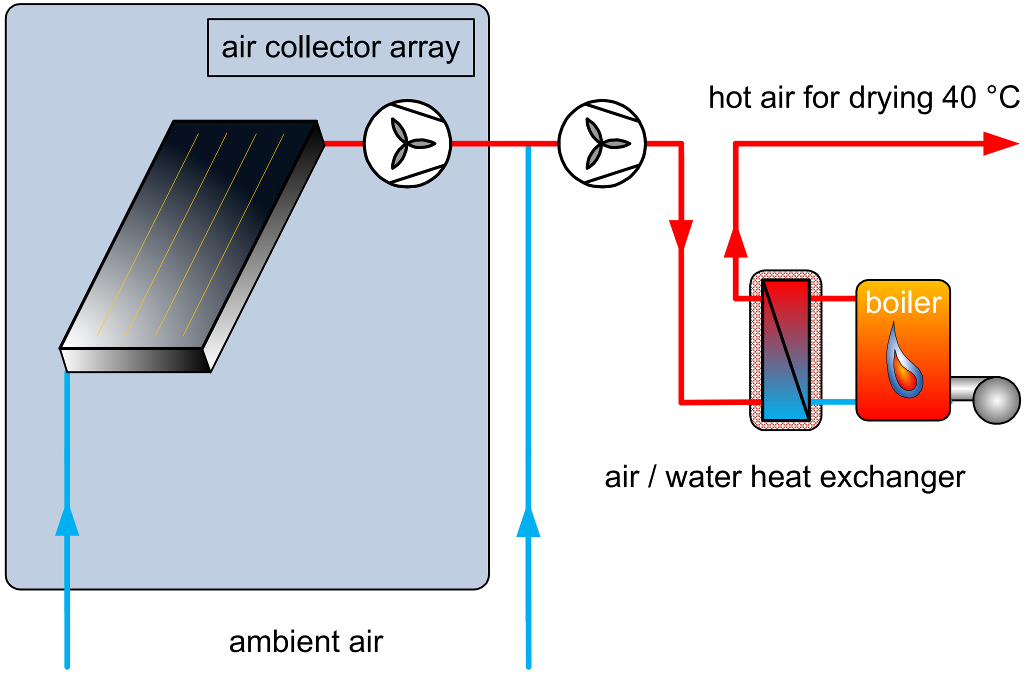
Design Principles
Thermal load profile - Solar Heating of Industrial Bath



- Electrolyte has to be kept at a certain temperature all the time
- Heat demand at night and at weekends to compensate heat losses
- Storage necessary due to demand during nighttime

Design Principles
Layout - 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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Design Principles
Thermal Load and Daily Heat Demand

$$\dot{Q} = \dot{m} \cdot c_p \cdot \Delta T$$

- $\dot{Q}$ - current heat demand (W)
- $\dot{m}$ - mass flow rate of working fluid (kg/s)
- c_p - specific heat capacity of working fluid (J/kgK)
- ΔT difference between inlet and outlet water temperature (K)

$$Q_{day} = m \cdot c_p \cdot \Delta T$$

- Q - useful energy (J)
- m - daily demand of working fluid (kg)
- c_p - specific heat capacity of working fluid (J/kgK)
- ΔT mean difference between inlet and outlet water temperature (K)

Design Principles
Example: Daily Energy Demand

- Load profile of hot water
  - 0.4 m³/h between 05:30 and 20:00
  - 2.1 m³/h between 20:00 and 22:00
- 10 m3 hot water (~80°C) per working day
- Temperature difference: 45 K

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

- 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.
- Location: Freiburg, Germany

➢ Which part of this annual demand can be covered by solar thermal in a reasonable way?

Design Principles
Solar Field Design by Rules of Thumb

- Annual solar potential multiplied by mean annual efficiency 0.45:

$$Q_{Solar} = GHI_{annual} \cdot 0.45 = 1150\ \frac{kWh}{m^2 a} \cdot 0.45 \approx 500\ \frac{kWh}{m^2 a}$$

➡ DNI for concentrating and GHI for stationary technologies [https://globalsolaratlas.info/]

- Aperture area A_{Ap}:
- Annual thermal energy demand of the processes multiplied by a solar fraction of 40 %, divided by 500 kWh / (year * m^2_{Ap})

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

➡ Note: Aperture area << Solar field space requirements

Design Principles
Storage Design by Rules of Thumb I

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

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

➡ But depends highly on demand and temperature profile!
(mainly applicable for domestic hot water systems)

Design Principles
Storage Design by Rules of Thumb II

- Storage capacity C_{Sto}
  - Multiplication of operation hours during nighttime $h_{nighttime}$ and mean thermal load Q_{mean} :

$$C_{sto} = h_{nighttime} \cdot \dot{Q}_{mean} = 4\text{ h} \cdot \frac{522.5\ kWh}{16.5\ h} = 126\ kWh$$

$h_{nighttime}$ should always be above 2h and below 8h

- Storage volume V_{Sto}
  - with density ρ, heat capacity c_p and temperature difference dT of storage fluid:

$$V_{sto} = \frac{C_{sto}}{c_p \cdot dT \cdot \rho} = \frac{126\ kWh \cdot 3600}{4.18\frac{kJ}{kgK} \cdot 45K \cdot 980\frac{kg}{m^3}} \approx 2.5\ m^3$$

Design Principles
Accuracy for Rules of Thumb

- Accuracy is limited
- Sufficient for pre-feasibility assessments
- Giving indication about order of magnitude
- Load variations, daily and seasonal weather variations, detailed collector characteristics as well as effect of temperature level neglected

➡ System simulation for more detailed assessment

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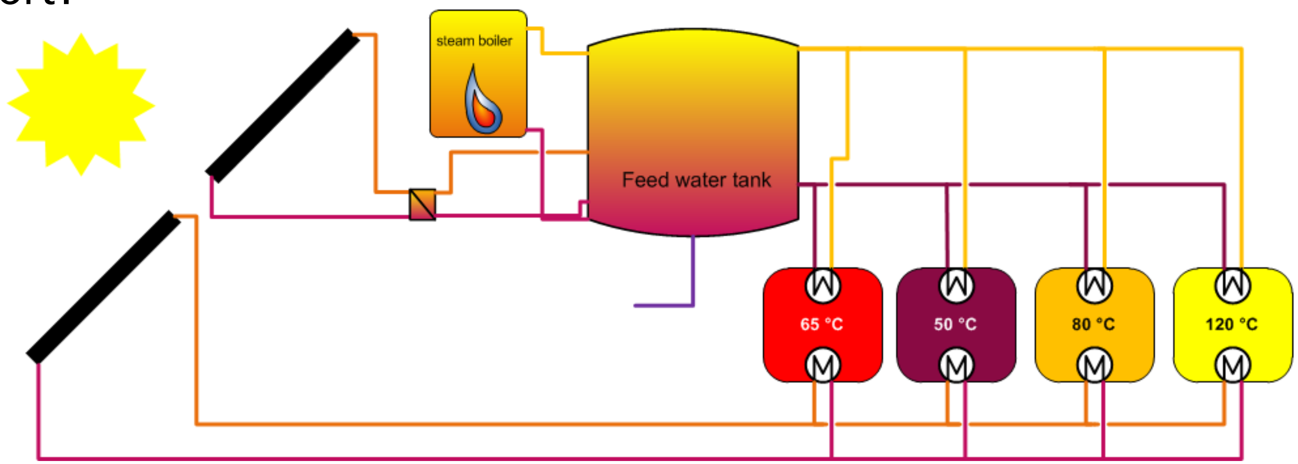
Key Performance Indicators (KPIs)
Key questions

- Solar Thermal System Performance Assessment
  - Highest solar yield?
  - Lowest energy costs?
  - Highest environmental impact?
  - Low operation&maintenance effort?



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Key Performance Indicators (KPIs)
Different Performance Aspects

- Technical performance
  - Reliability
  - Energy output
  - Financial savings
  - Emission savings

Key Performance Indicators (KPIs)
Reliability

- Pressure resistance
- Thermal shock (internal/external)
- Rain penetration
- High temperature resistance/Stagnation Temp.
- Mechanical loads: Wind / Snow
- Freeze protection
- Final inspection
- Hail/impacts
- Maintenance, documentation

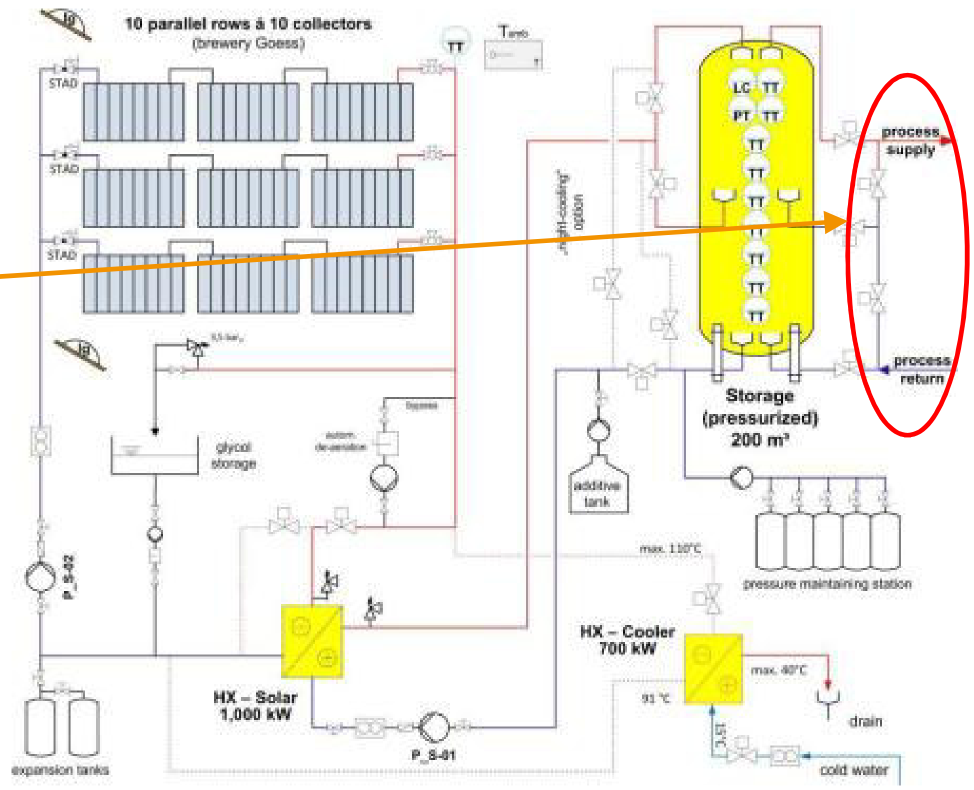
Key Performance Indicators (KPIs)
Energy performance

- Solar system with defined system boundary
- Measure heat flow to process side

$$\dot{Q} = \dot{m} \cdot c_p \cdot (T_{supply} - T_{return})$$

- Integrate over time (e.g. hour, day, …. Year)

$$Q = \int_{t1}^{t2} \dot{Q}\, dt$$



Key Performance Indicators (KPIs)
Energy performance

- Energy performance
  - Fractional thermal energy savings (incl./excl. Electricity)
  - Penalty functions for incomplete process coverage
- Measuring / monitoring
  - non-standardized boundary conditions
  - Real data with all problems included
- Dynamical simulation of system
  - Standard weather and loads possible as well as real data
  - How can measured data extrapolated to standardized conditions using simulation tools?
  - When is short-term testing in situ as basis acceptable?

Relevant KPIs
Energy performance

- Different parameters to consider:

- Solar collector gain Q_{coll}
- Output measured for collector field (no storage losses, HX losses etc.)
- Not relevant for perfromance assessment

- Solar system gain Q_{sys}
- Output of complete solar system
  (transfer to process or distribution system)

- Solar fraction SF $SF = \frac{Q_{sys}}{Load}$

Relevant KPIs
Energy performance

- Saved energy:

- Auxiliary Energy Q_{aux}
  - Fuel/electricity needed from conventional system without solar system installed $Q_{aux}(0)$
  - Fuel/electricity needed from conventional system after solar system installed $Q_{aux}(1)$
  - Savings: $Q_{save} = Q_{aux}(1) - Q_{aux}(0)$

- Saved fraction

$$f_{save} = \frac{Q_{save}}{Q_{aux}(0)}$$

Relevant KPIs
Economic performance criteria

- Payback time (statical, dynamical)
- Net present value (NPV)
- Internal rate of return (IRR)
- Levelized cost of heat (LCoH)
- …

- Main cost factors:
  - Investment costs (planning, material, components, installation)
  - Operation and maintenance costs (incl. energy/fuel costs)

Relevant KPIs
Payback time

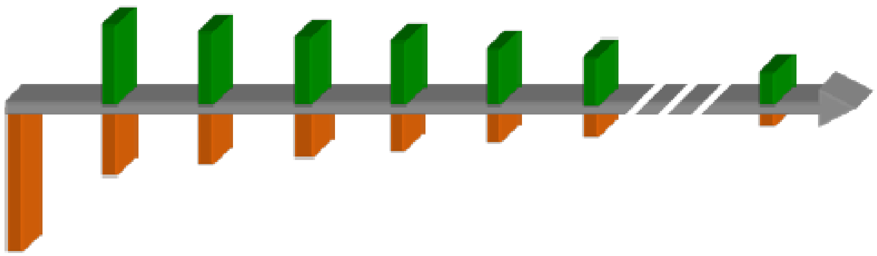
- Time required to recover the cost of investment
- The lower the payback time the better the investment
- Relates investment cost to annual cash flows
- Does not consider time value of money

➢ Easy to understand

Relevant KPIs
Net present value NPV

- Future capital flows will be discounted to the year of investment

$$\mathrm{NPV} = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n}$$



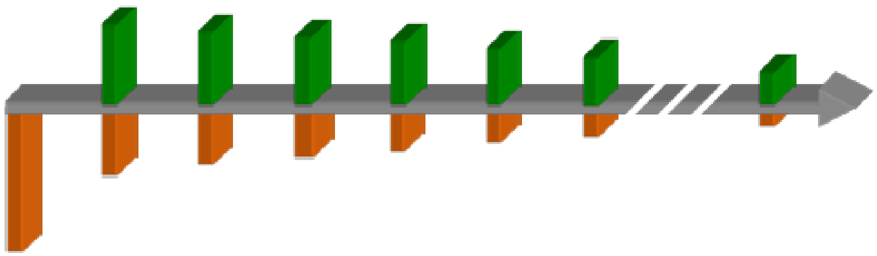
➢ Adequate for investor

Relevant KPIs
Internal Rate of Return (IRR)

- IRR is interest rate for which NPV is zero!

$$\mathrm{NPV} = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n}$$

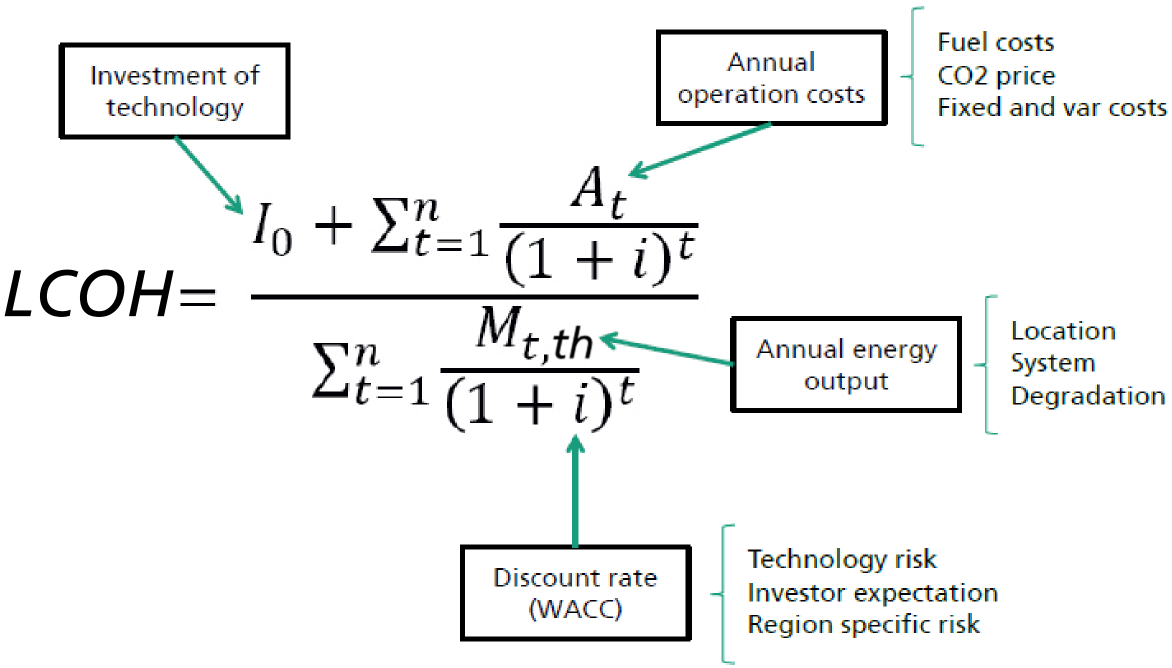
$r \rightarrow IRR$



➢ Adequate for investor

Relevant KPIs

Levelized Cost of Heat (LCoH)



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

➢ Good for comparison of different energy sources

Relevant KPIs
Simplified LCoH Calculation

- If operational cost and annual solar yield is the same in all operational years, this equation will give the same results

$$\mathrm{LCoH} = \frac{I_0 \cdot ANF + A}{M}$$

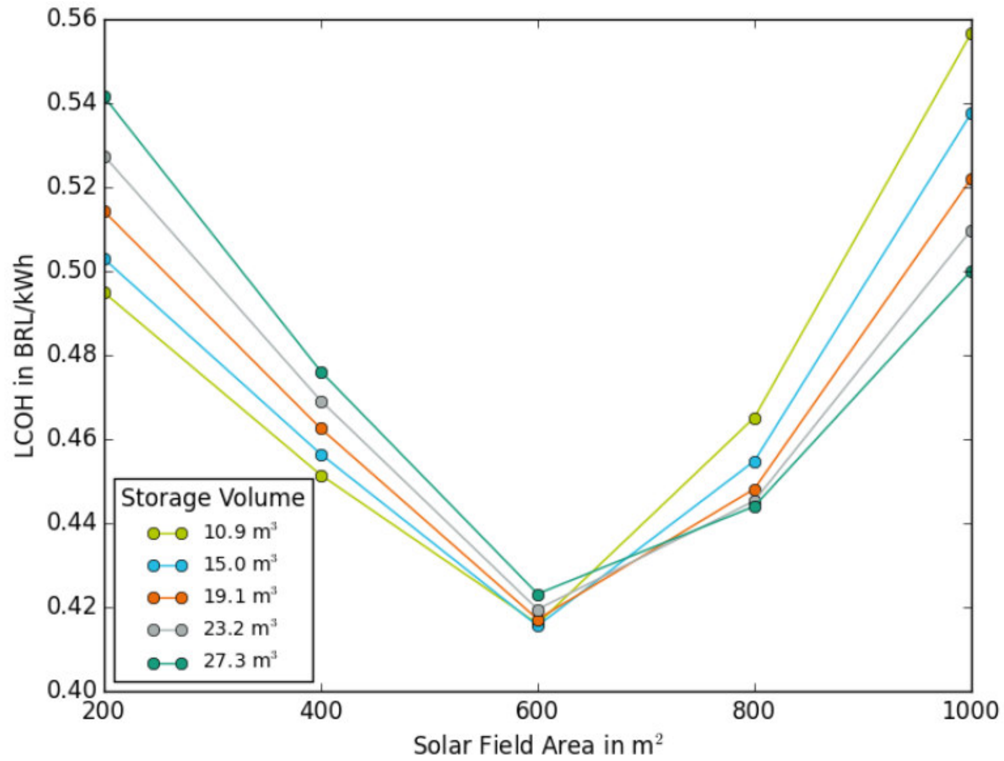
$$\mathrm{ANF} = \frac{(i+1)^n \cdot i}{(i+1)^n - 1}$$

I_0	Investment costs
ANF	Annuity factor
A	Operational cost
M	Solar Yield
i	Discount rate
n	Life time

Relevant KPIs
Techno-Economic Optimization

- Economic assessment for different plant layouts
- Which plant layout is the most cost effective?

Example for Brazilian pharmaceutical company



Relevant KPIs
Environmental performance

- Figures of merit can be very individual and many options are possible
  - Savings of CO2-, SOx, NOx-emissions
  - Resource consumption of non-replenishable materials
  - Availablility of fossil fuels limited
  - Life cycle analysis

Fuel type	*GHG emissions in* g_{CO2}/kWh
Natural gas	202
Diesel	254
Anthracite (coal)	356
Wood/wood waste	410

[1]

[1] World Resources Institute. (2015). GHG Protocol tool for stationary combustion. Version 4.7

Relevant KPIs
Combined criteria

- Single factor not useful for performance assessment of a plant
- Generation of one form of energy (heat, electricity)
  - ➢ levelized cost of electricity LCOE, heat LCOH etc.
- Combinations of energy efficiency measures plus renewable energies
  - ➢ cost of primary energy savings
- Saved primary energy is equivalent to reduced environmental damages!
  - ➢ So combination of monetary+energy+environmental performance not useful!

Relevant KPIs
Combined criteria

Whole Life Costs (WLC/LCC)

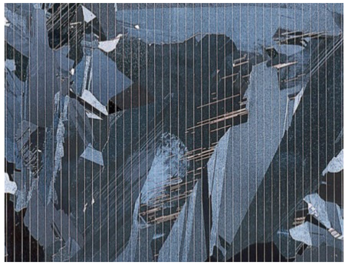
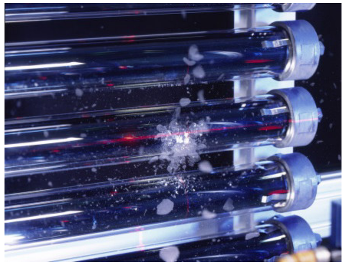
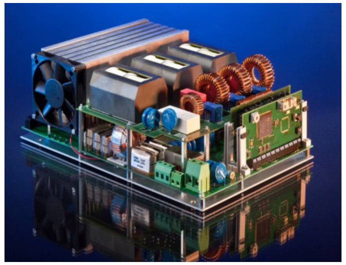
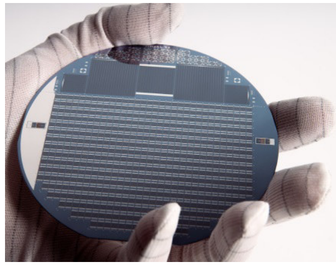
- Appraise all environmental, social and financial impacts from cradle to grave in one economical cost figure
- What is the cost of environmental damages?
- LCA is based on the standard ISO 14040

Relevant KPIs
Combined criteria

Suggested performance criteria in IEA Task 49

- Financial performance:
  - Levelized cost per demand unit LCD [€/kWh]
- Environmental performance:
  - PE consumption per demand unit PECD [kWh/kWh]
- Combined performance:
  - CP = LCD + fPE * PECD
- Using a monetary factor f [€/kWhPE] appraising environmental costs.

Thank you for your Attention!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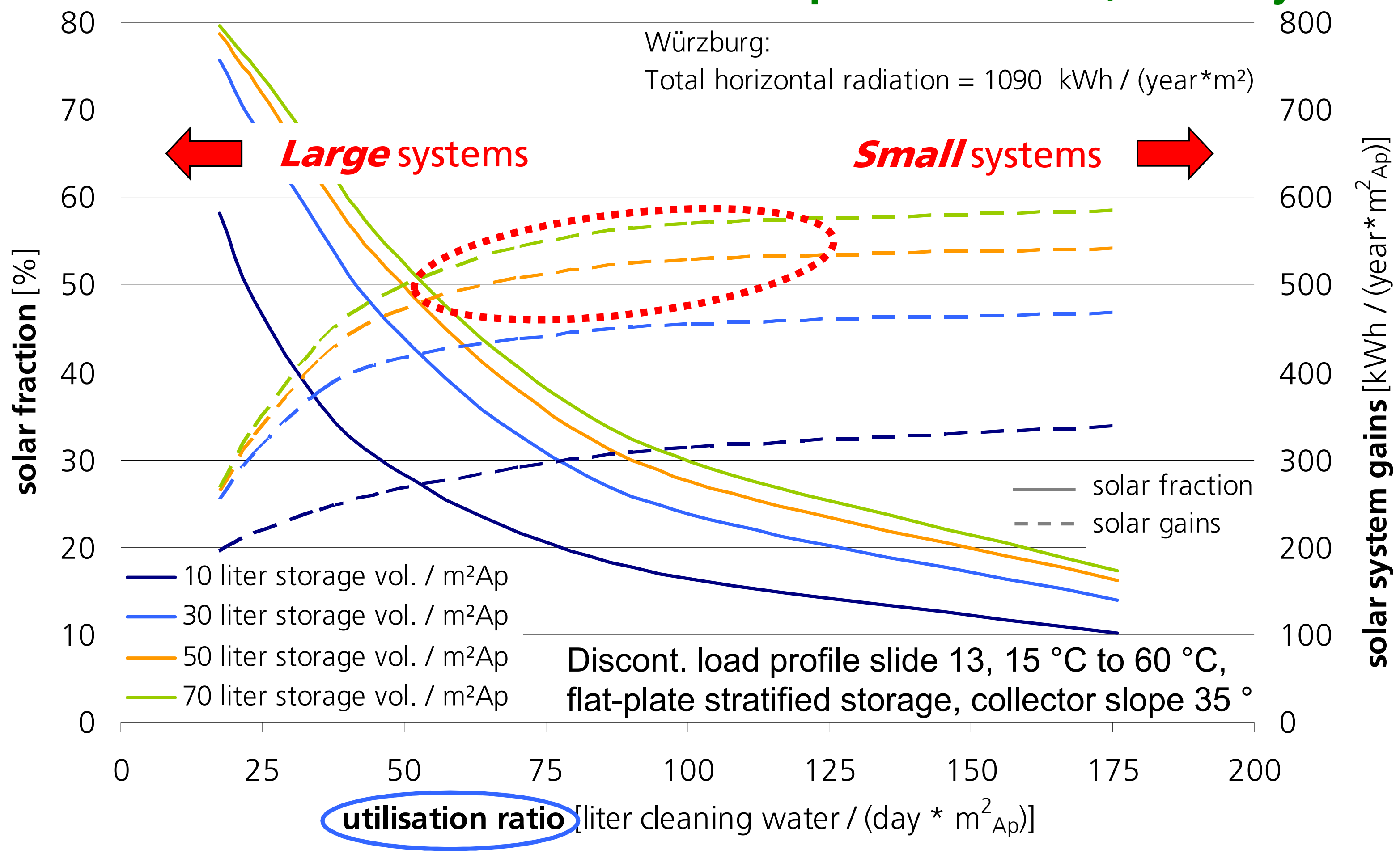
Design Nomogram

Example: demand = 10,000 l / day
Example: demand = 20,000 l / day



400 m²	200 m²	133 m²	100 m²	80 m²	66 m²
800 m²	400 m²	266 m²	200 m²	160 m²	132 m²

Solar Payback
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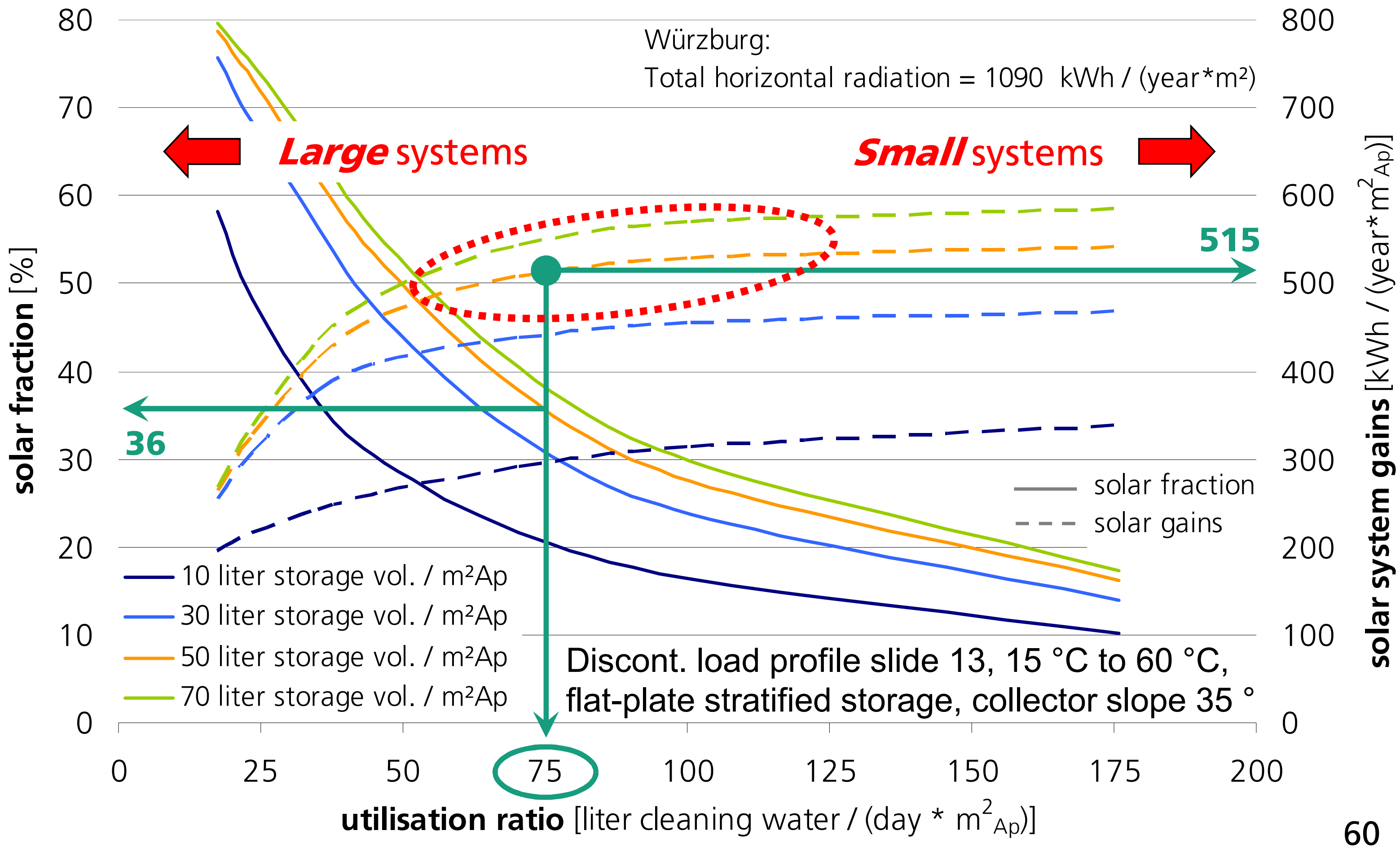
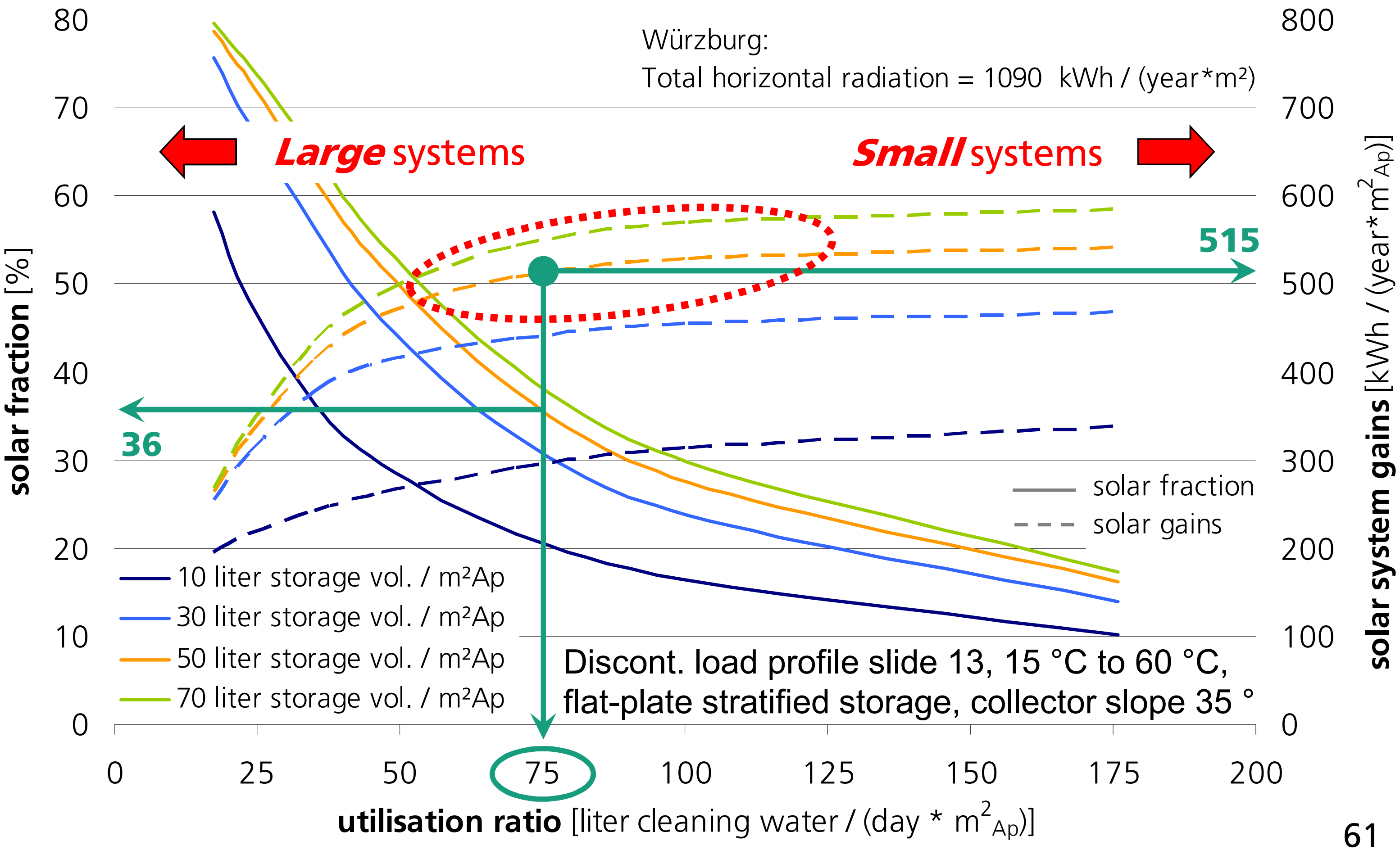
Design Nomogram



60

Design Nomogram

Example: demand = 6,440 l / day



61

258 m² **129 m²** **86 m²** **64 m²** **52 m²** **43 m²**

Solar Payback

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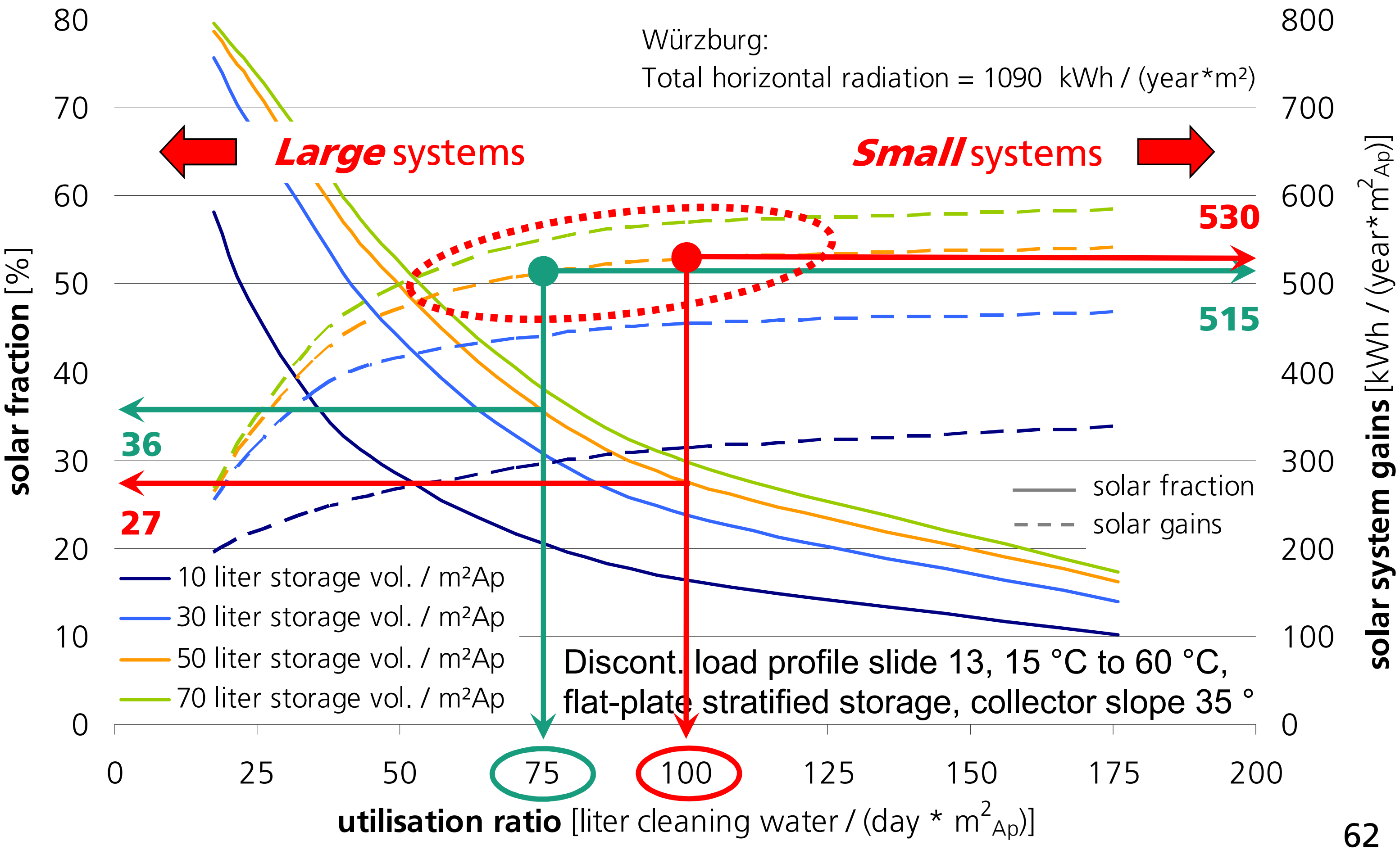
Variation: A “smaller” system?

Example: demand = 6,440 l / day



62

258 m² 129 m² **86 m²** **64 m²** 52 m² 43 m²

Solar Payback

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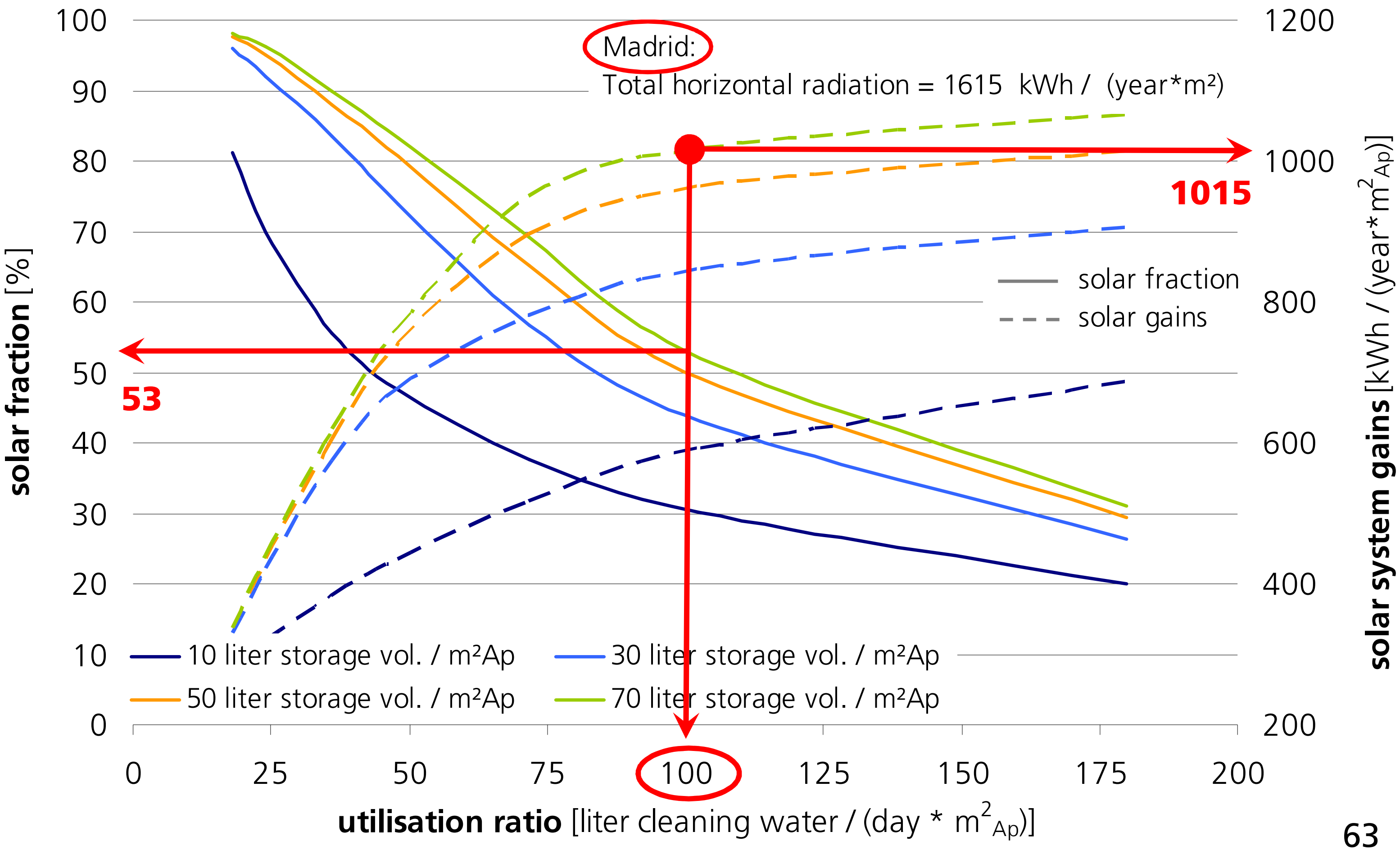
Location Madrid

Example: demand = 6,440 l / day



63

258 m² 129 m² **86 m²** **64 m²** 52 m² 43 m²

Solar Payback

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