IKI SOLARPAYBACK
TRAINING ON SOLAR PROCESS HEAT IN SOUTH AFRICA

Design Principles and System Simulation

Dr. Wolfgang Kramer

Fanny Hübner

Fraunhofer Institute for Solar Energy Systems ISE

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Content

- Integration Concepts
- System Dimensioning
- Key Performance Indicators (KPIs)
- System Simulation

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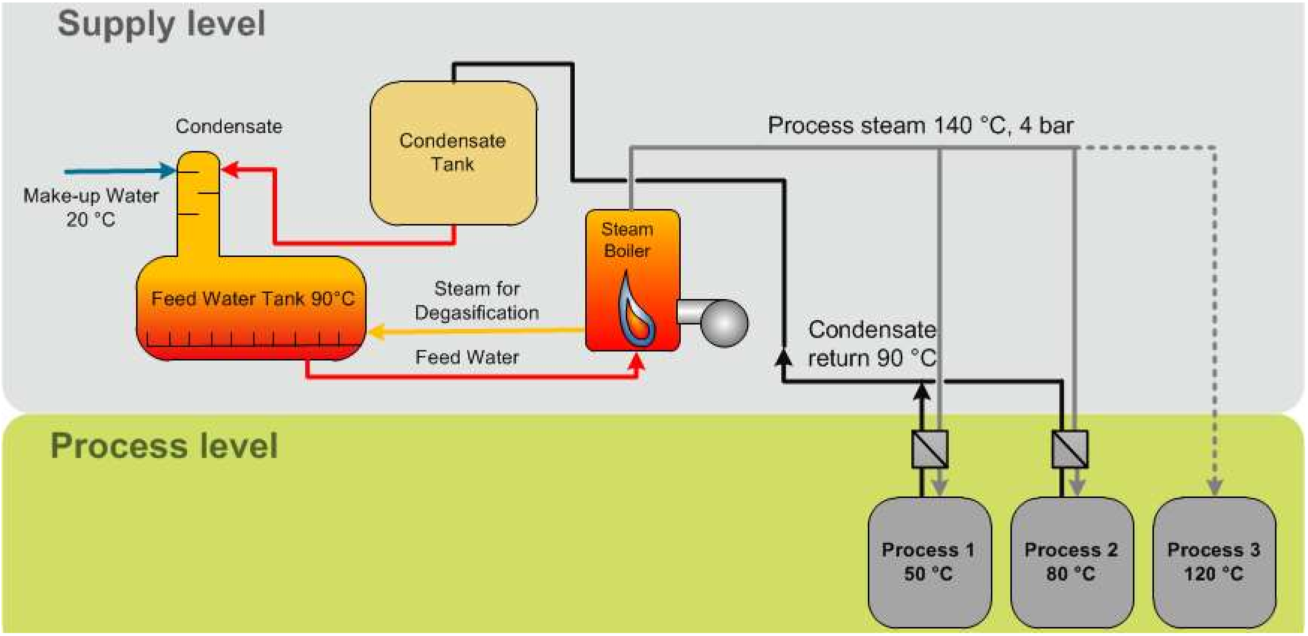
Integration Concepts
Definitions

- 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

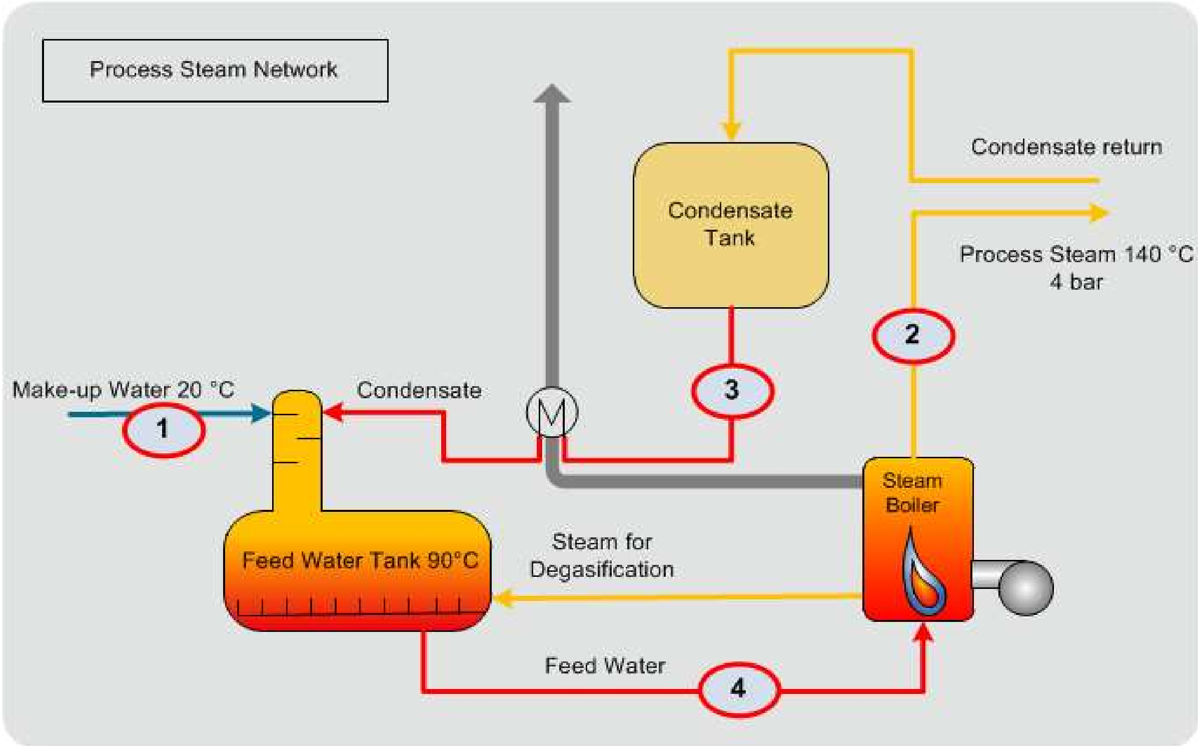
- Solar heat (steam or hot water) can be integrated into
  - heat distribution network
  - different processes



Integration Concepts
Supply Level

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

- Options:
- Make-up water pre-heating and/or condensate (1/3)
- Steam generation to directly feed steam network (2)
- Pre-heating of boiler feed water (4)



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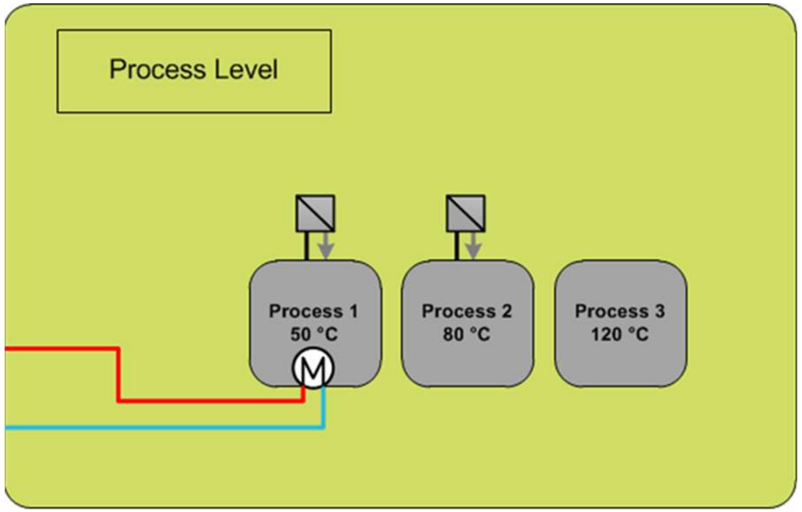
Integration Concepts
Process Level

- Solar heat directly supplied to process

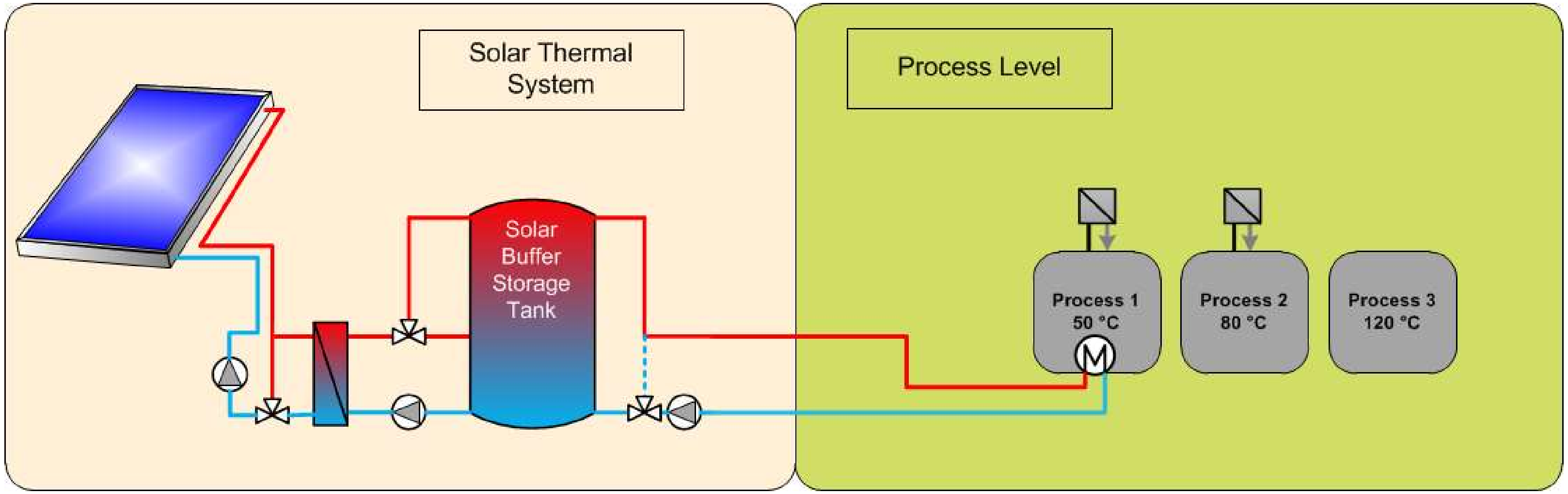
- For processes that require low temperature heat (until 100 °C)
  - Examples: washing, cleaning, heating of industrial baths, hot air drying
    - Often lower temperatures than supply level
    - Lower thermal losses lead to higher solar gains per square meter

- High dependency on changes in the process



Integration Concepts
Process Level - Example

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



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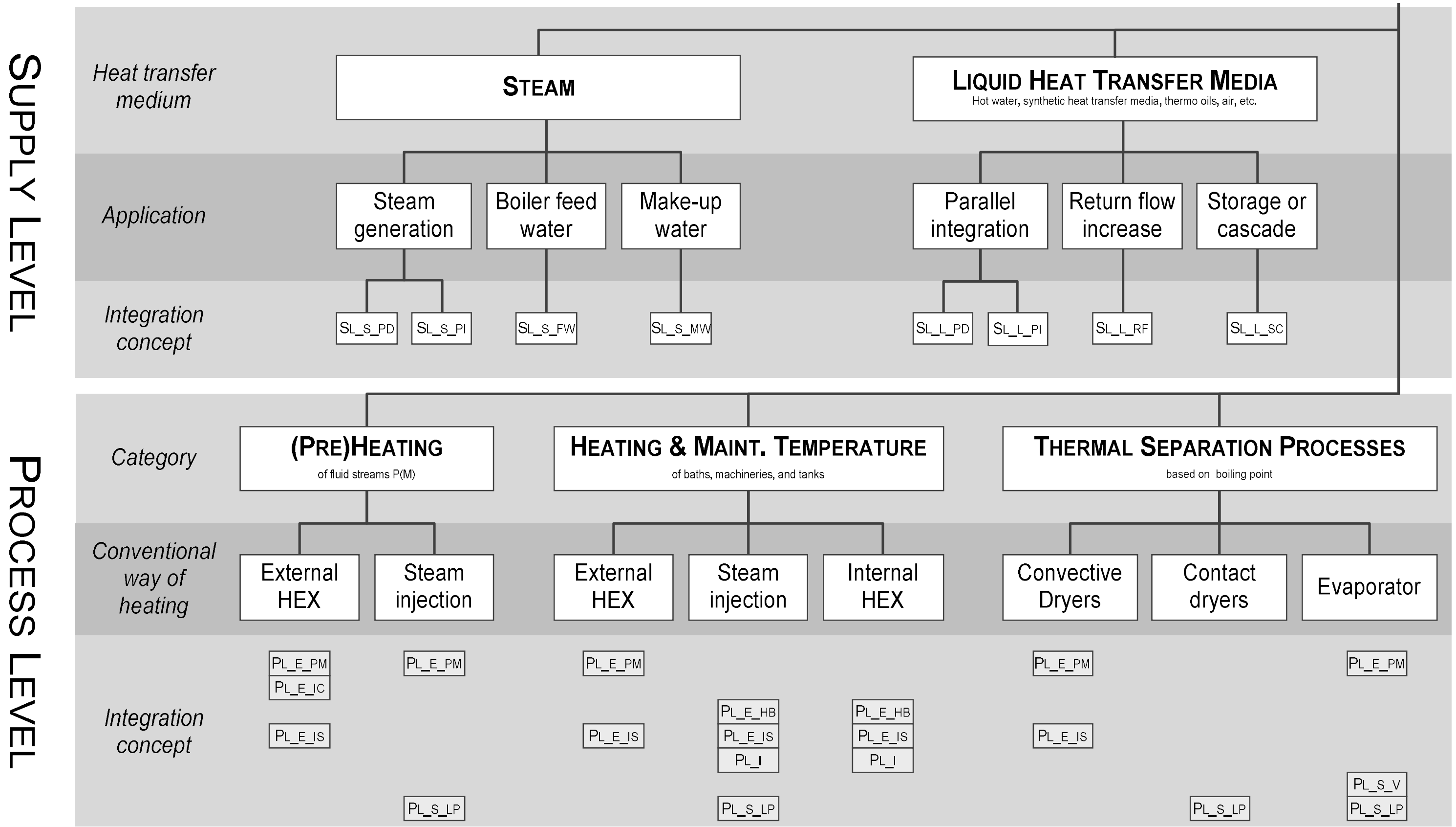
Integration Concepts
Criteria for Process or Supply Level Integration

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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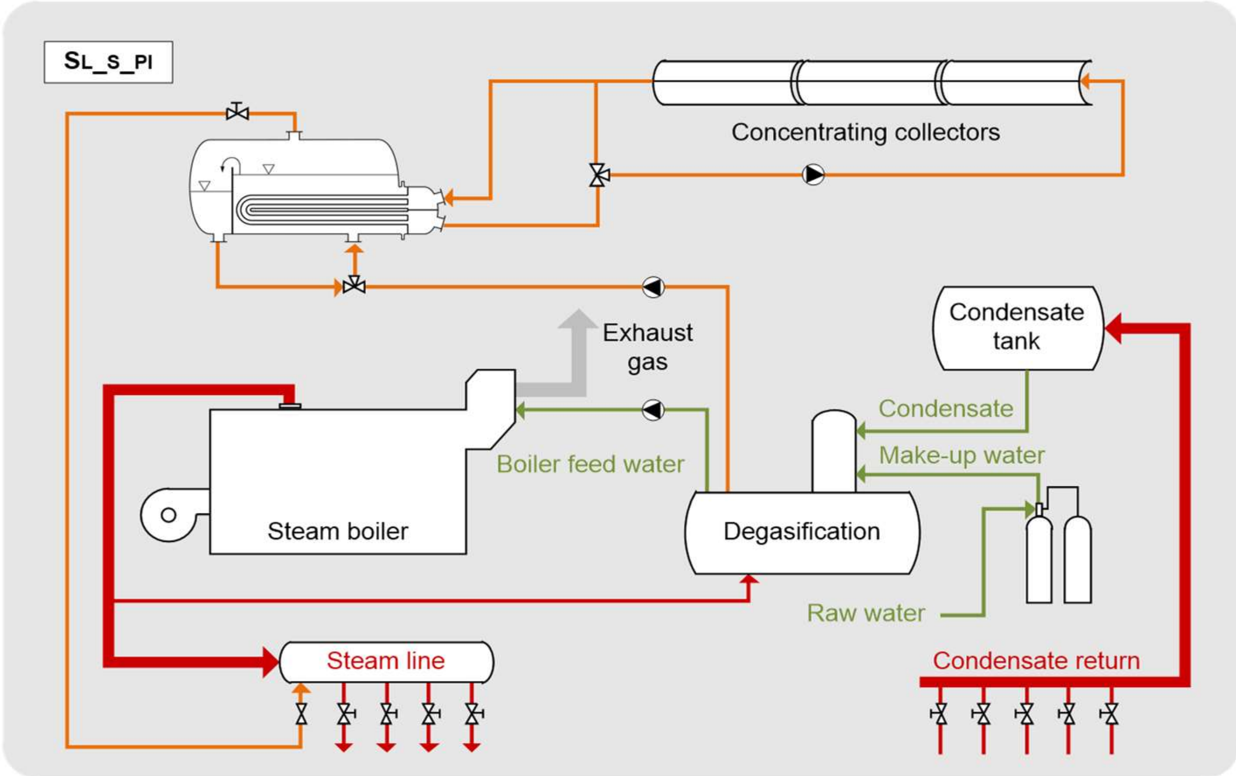
Integration Concepts
Examples

- **SL_S_PI**
  - Indirect solar steam generation

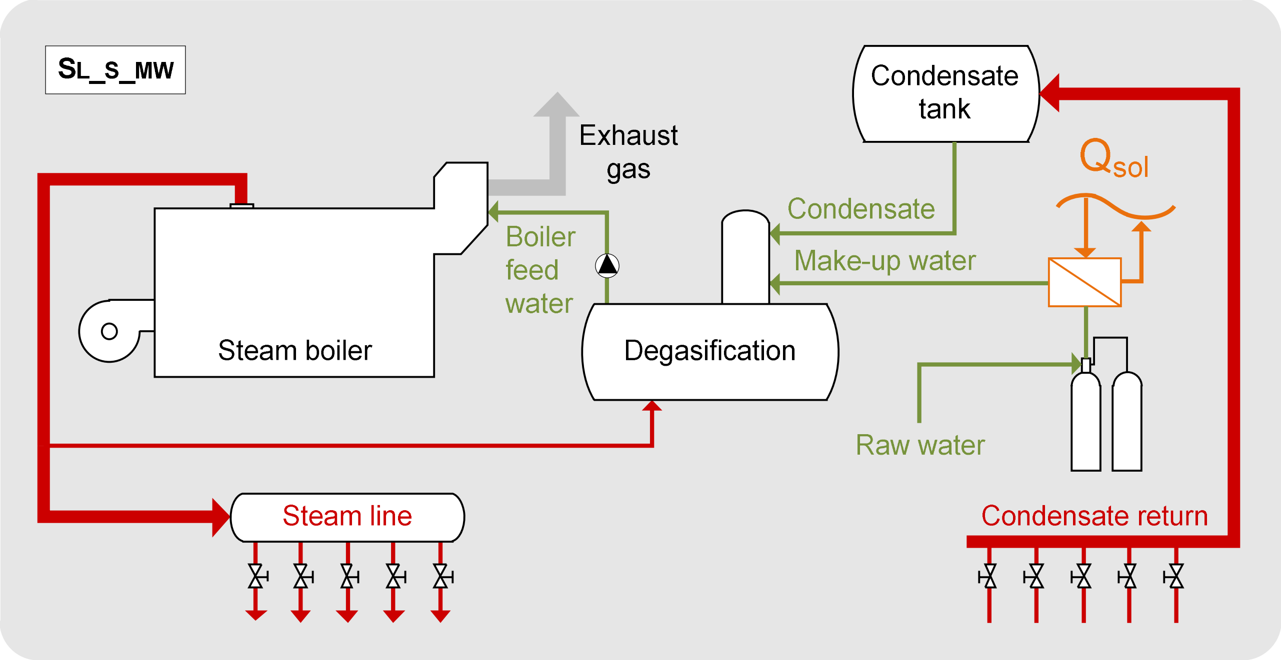


[1]

[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

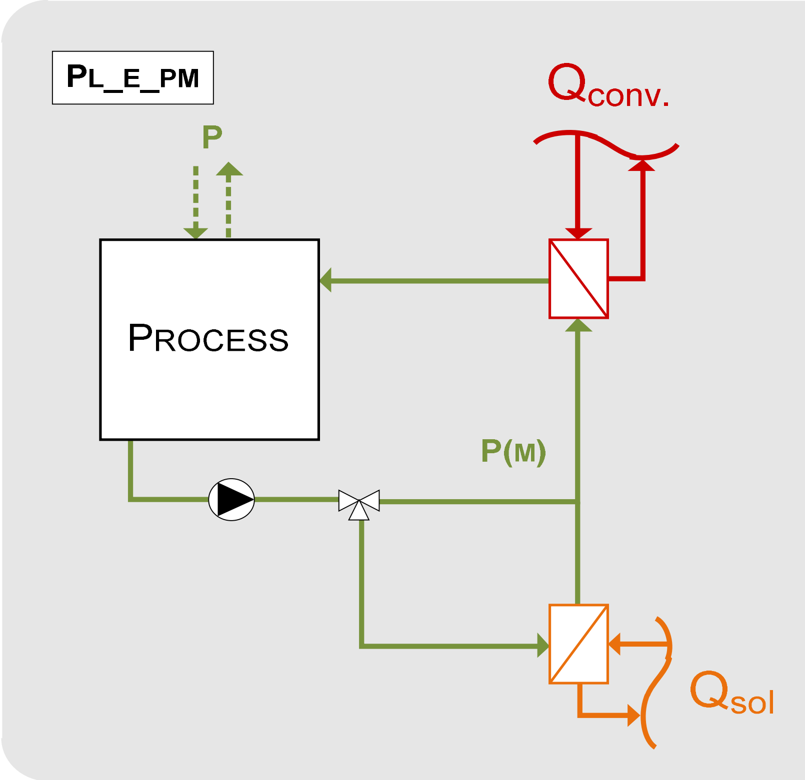


[1]

[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



[1]

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

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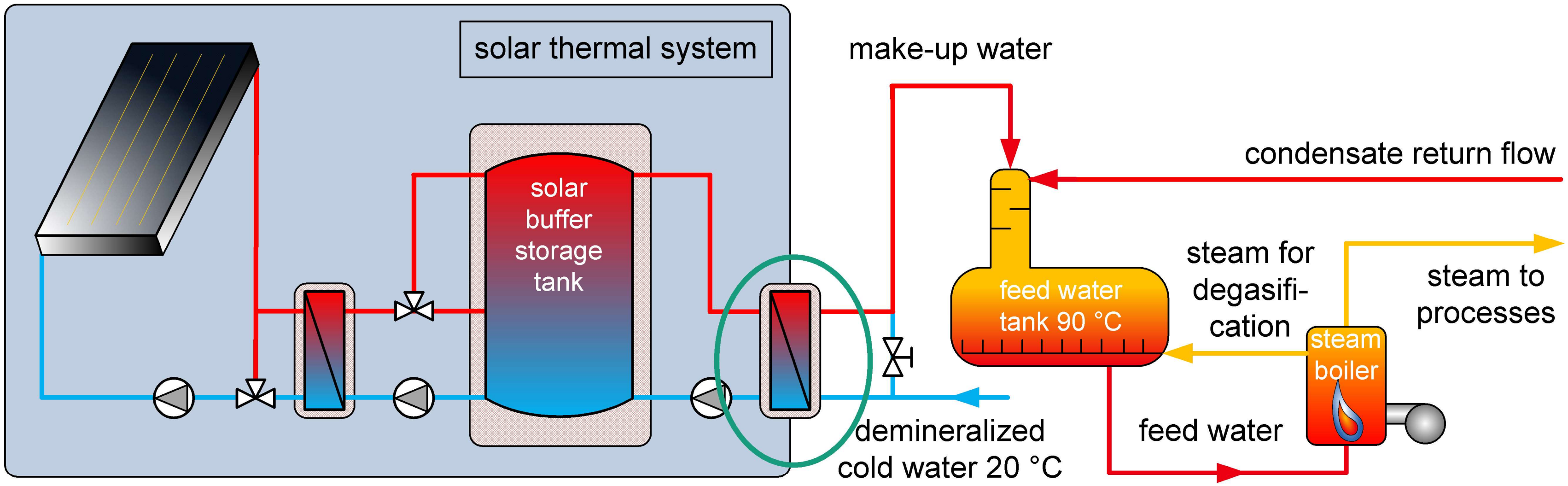
Integration Concepts
Most favorable integration points

- Selection of company
  - Location with high irradiation (> 1500 kWh/year)
  - Sufficient available space for collector installation
  - High fossil fuel cost
- Selection of integration point
  - Low temperature level -> higher efficiency
  - High temperature difference (inlet & return) -> better storage utilization & efficiency
  - Continuous load profile (preferably 7 days a week, little fluctuations) -> higher efficiency
  - Easy connection to existing system -> lower cost
  - Existing storage can be used -> lower

Integration Concepts

Layout - Pre-heating of make-up water



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

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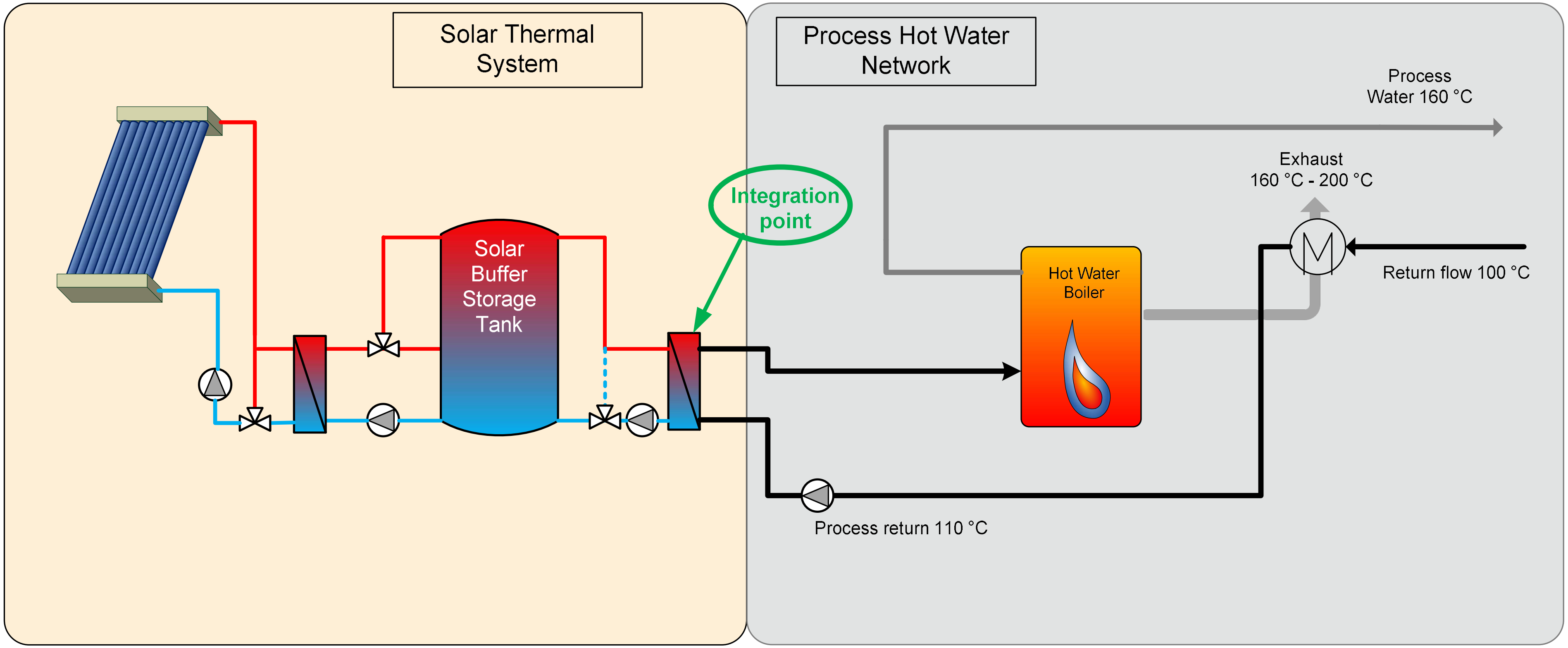
Integration Concepts
Return flow temperature lift



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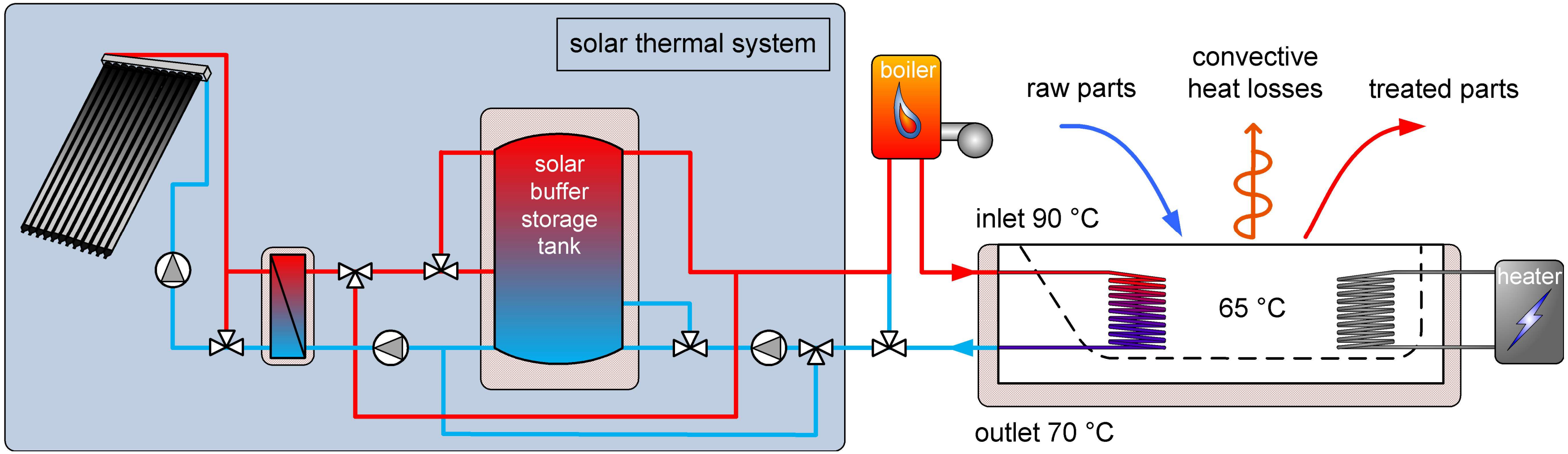
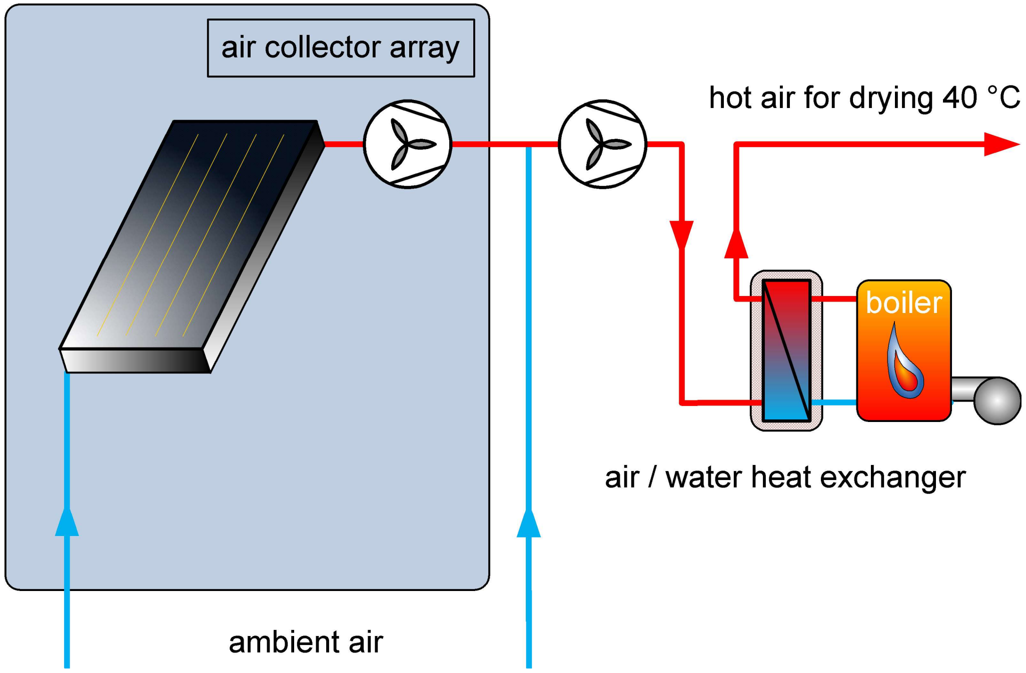
Integration Concepts
Layout - Solar Heating of Industrial Bath



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

Integration Concepts
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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Content

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- System Dimensioning
- Key Performance Indicators (KPIs)
- System Simulation

System Dimensioning
Solar Field Size Criteria

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

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

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

System Dimensioning
Storage Size Criteria

- High temperature difference
  → High storage capacity per volume
- Demand occurs during daytime
- Continuous load

- Low temperature difference
  → Low storage capacity per volume
- Demand occurs during nighttime
- Fluctuating load

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

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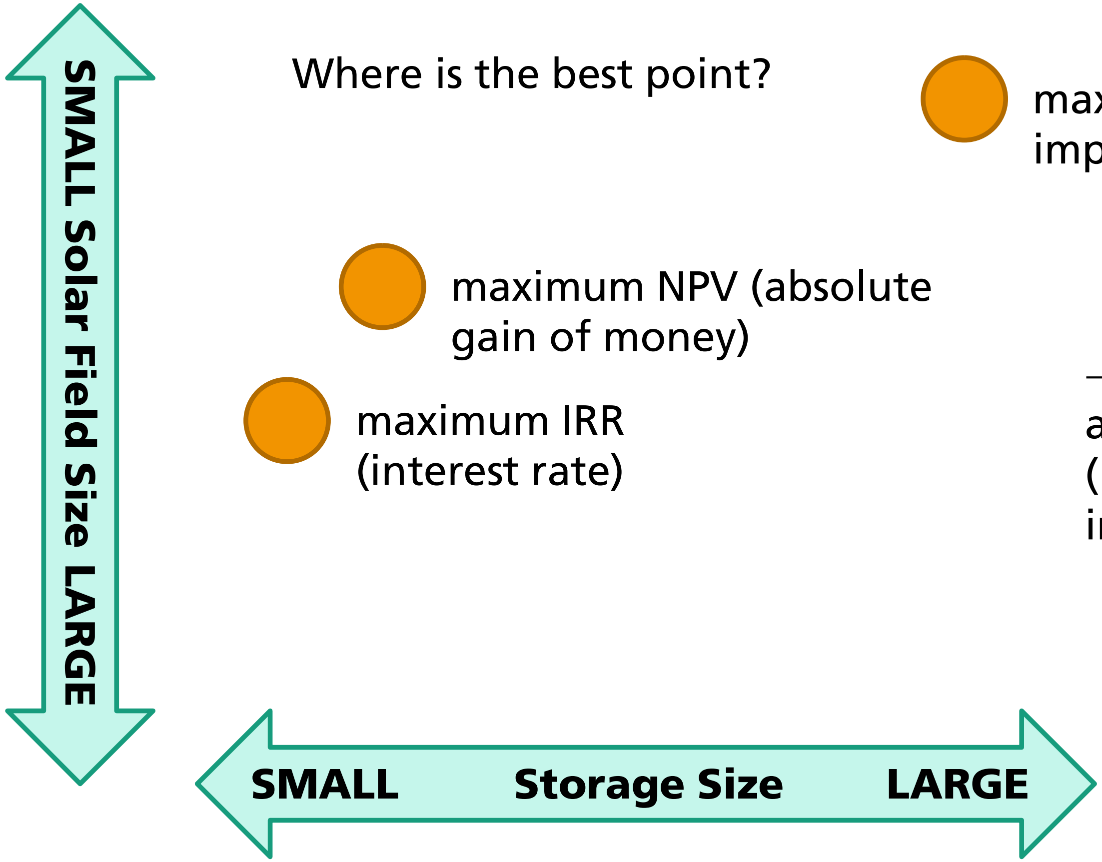
System Dimensioning
Optimization Problem

Where is the best point?



→ Solar Yield Assessment and Optimization Criteria (KPI Key Performance indicator) are needed

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Question

1. What is a typical Solar Fraction of a well designed solar thermal installation (Solar Energy Input devided by the process heat demand)?
2. What is a typical system efficiency of a well designed solar thermal installation. Useful solar thermal energy divided by the accumulated yearly solar irradiation on the collector field?

Please answer on

https://forms.gle/rY2xL4e7pbf7yPin8

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System Dimensioning
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)

System Dimensioning
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?

System Dimensioning
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

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System Dimensioning
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)

System Dimensioning

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:

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

System Dimensioning
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

Content

Question

1. Which one of the following KPI's do you know?

Pay-Back Time

Internal Rate of Return

Net Present Value

Levelized Cost of Heat

Please answer on

https://forms.gle/9BmvaR2S1yF9eZt59

Key Performance Indicators (KPIs)
Economic performance criteria

- Payback time (risk criteria)
- Internal rate of return (IRR)
- Net present value (NPV)
- Levelized cost of heat (LCoH)

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

Key Performance Indicators (KPIs)
Environmental performance

- Figures of merit can be very individual and many options are possible
  - Savings of CO2-, SOx, NOx-emissions
  - Life cycle analysis

- Environmental Impact comes into economic relevance when this is accounted for in economic terms (e.g. carbon tax accounting for external cost)

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

[1]

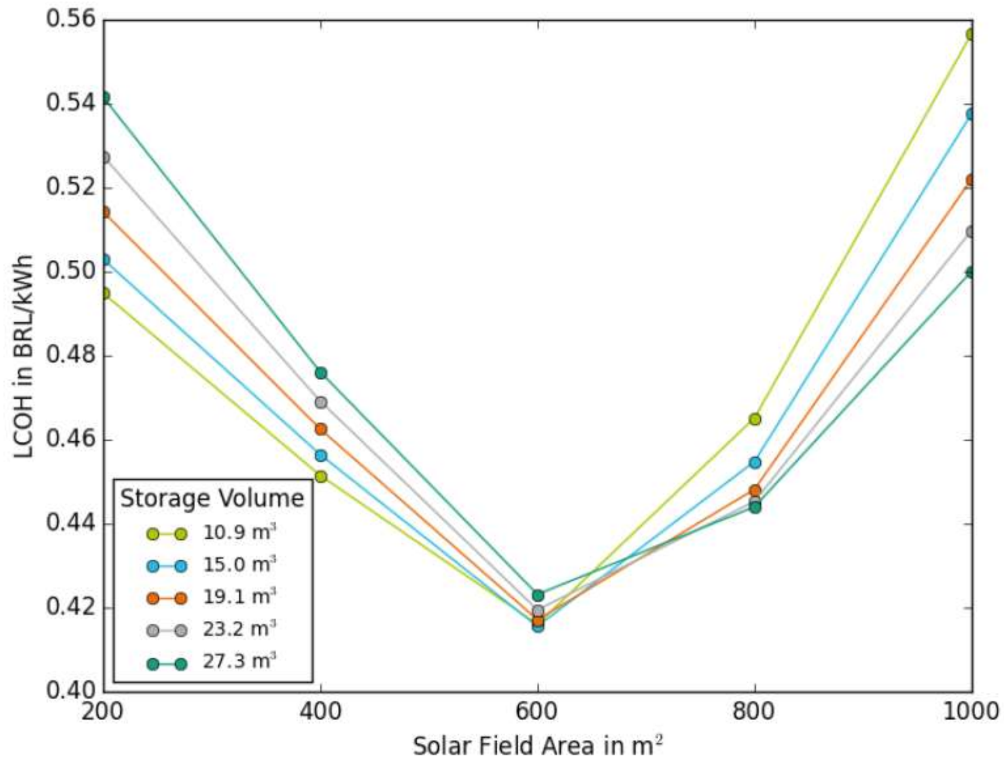
[1] World Resources Institute. (2015). GHG Protocol tool for stationary combustion. Version 4.7

Key Performance Indicators (KPIs)
Benefits

- Feasibility assessment of a plant and decision making should be based on the individually weighted combinations of KPIs
- Other Decision criteria (hard to quantify)
  - Safety of energy supply throughout lifetime of plant
  - Independence of volatility of fossil fuel prices
  - Reliable heat production costs
- Marketing advantage due to „green“ perception of company

Key Performance Indicators (KPIs)
Techno-Economic Optimization

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



Example for Brazilian pharmaceutical company

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System Simulation
Relevance for Solar Technologies

- Thermal yield is very site specific
  - Irradiation throughout the year
  - Solar angles (seasons)
  - Site assessment
  - Heat load may vary over time

- Increased control complexity
  - Back-up heater, storage …
  - Increased optimization potential
  - More complex design

System Simulation
Goals of system simulation

- System design
  - Calculate system behavior before it is built
  - Build an optimized system from the beginning
- Test operating strategy
  - The effects of a change of operation strategy can sometimes hardly be foreseen
- Obtain more information about system
  - Example: Direct steam generation (steam quality)
  - Optimize system control

System Simulation
Reasons for simulation

- Evaluation of system is possible before it is built

- Investigations of the real system or a small scale physical model are
  - not possible
  - too time consuming
  - too dangerous
  - too expensive

- Increase knowledge about system

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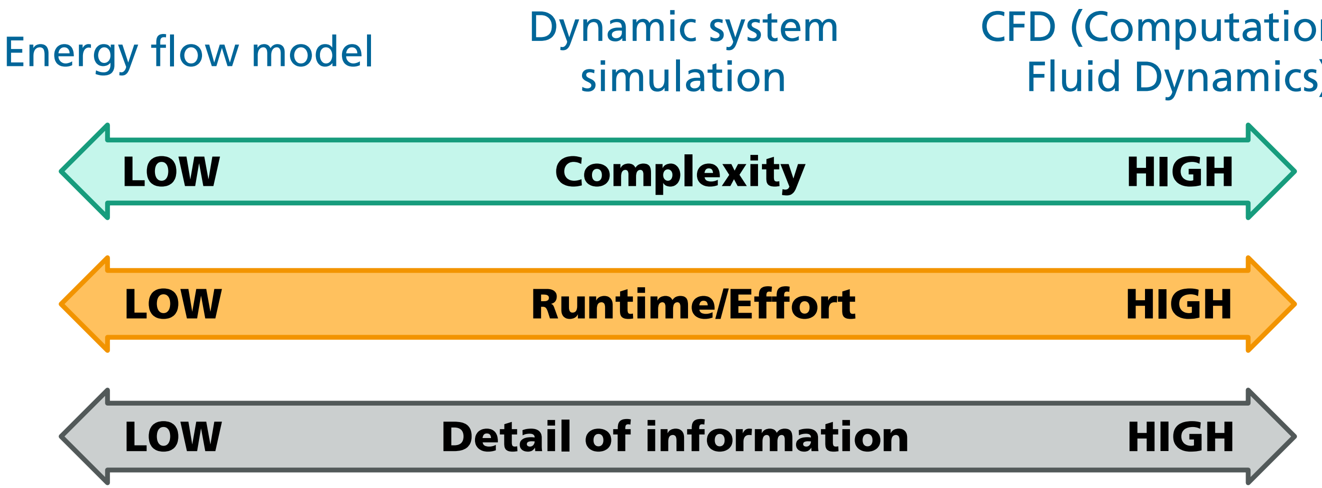
System Simulation
Level of Detail

- Simulations means simplication , but how simple?
  - ➢ **As simple as possible, as detailled as necessary!**

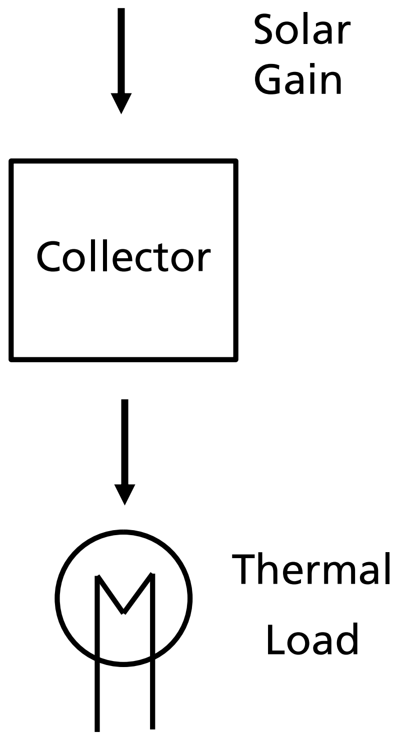
- Three main types of simulation



System Simulation
Static Energy Flow Simulation

- Solar gain is added to energy at input to calculate output
  - Temperatures/mass flows unknown
- Transient behavior of system is neglected

➢ Fast and simple simulations with low level of detail



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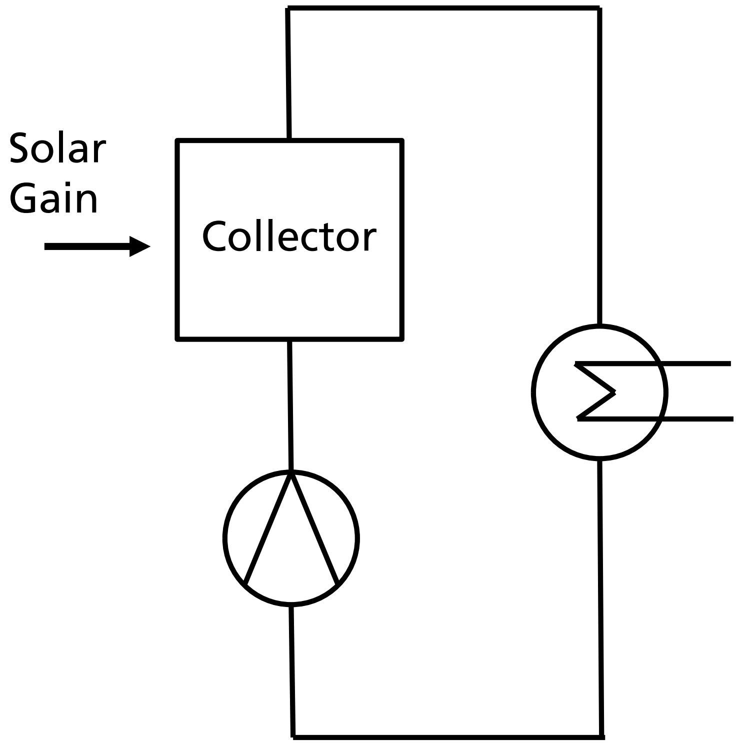
System Simulation
Dynamic System Simulation

- Solar gain is added to energy at input to calculate output
  - Temperatures/mass flows known

- Transience of the system is considered
  - Thermal capacity of fluid within pipes and pipe walls
  - Control limitations

➢ Still quite simple simulations with medium level of detail



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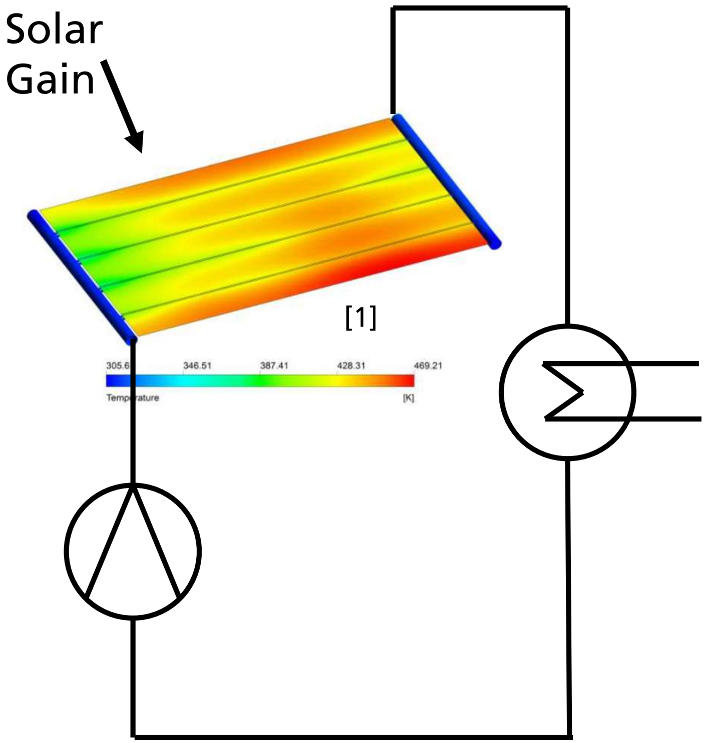
System Simulation
Computational Fluid Dynamics

- First CAD model of all components is created
- Model is split up in a big number of elements
- For each element mass, energy and momentum equation is solved
- Fluid flow at each part of system is known
- ➢ Slow and complex simulations with very high level of detail



[1] Ranjitha P., Somashekar V., Jamuna A.B., Numerical Analysis of Solar Flat Plate Collector for Circular Pipe Configuration by using CFD, International Journal of Engineering Research & Technology (IJERT), Vol. 2 Issue 12, 2013

System Simulation
Typical Software

Most suitable for solar system design

Energy flow model	Dynamic system simulation	CFD (Computational Fluid Dynamics)
LOW	**Complexity**	**HIGH**
Excel EES Engineering Equation Solver	TRNSYS 18 T*SOL ColSim Fraunhofer ISE POLYSUN	ANSYS STAR-CCM+ OpenFOAM

…or many other simulation and programming tools

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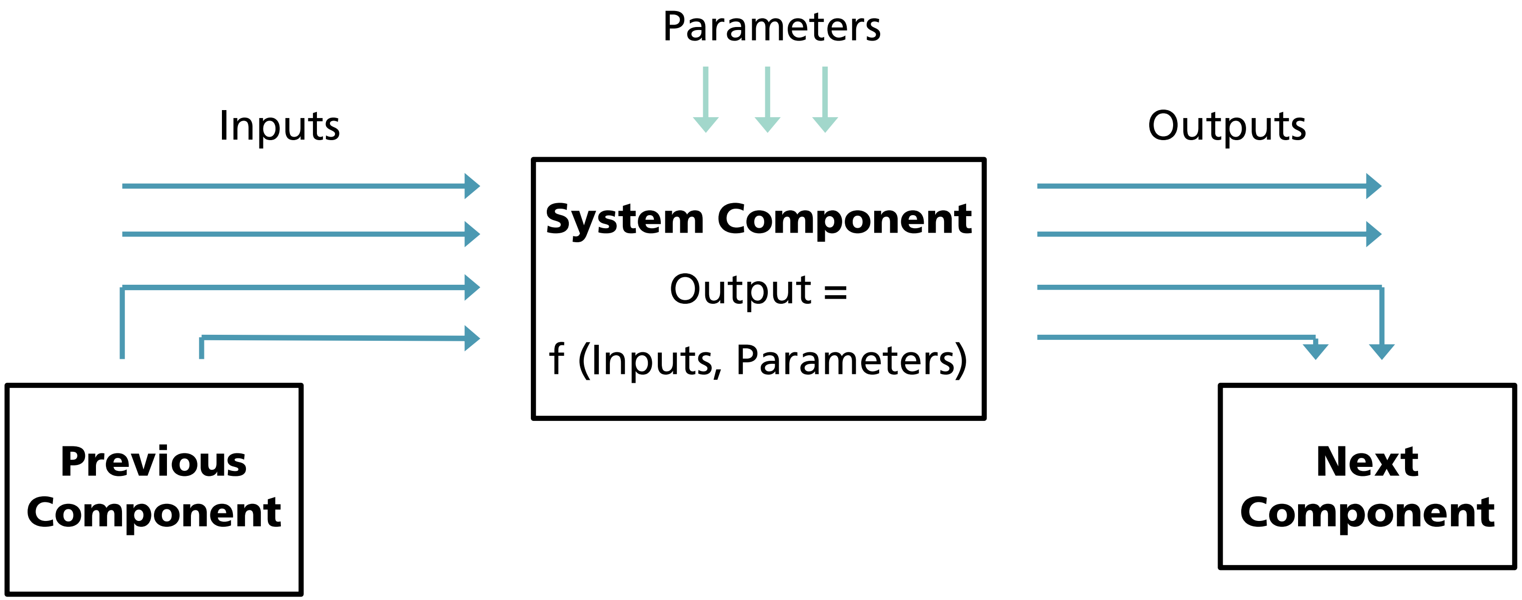
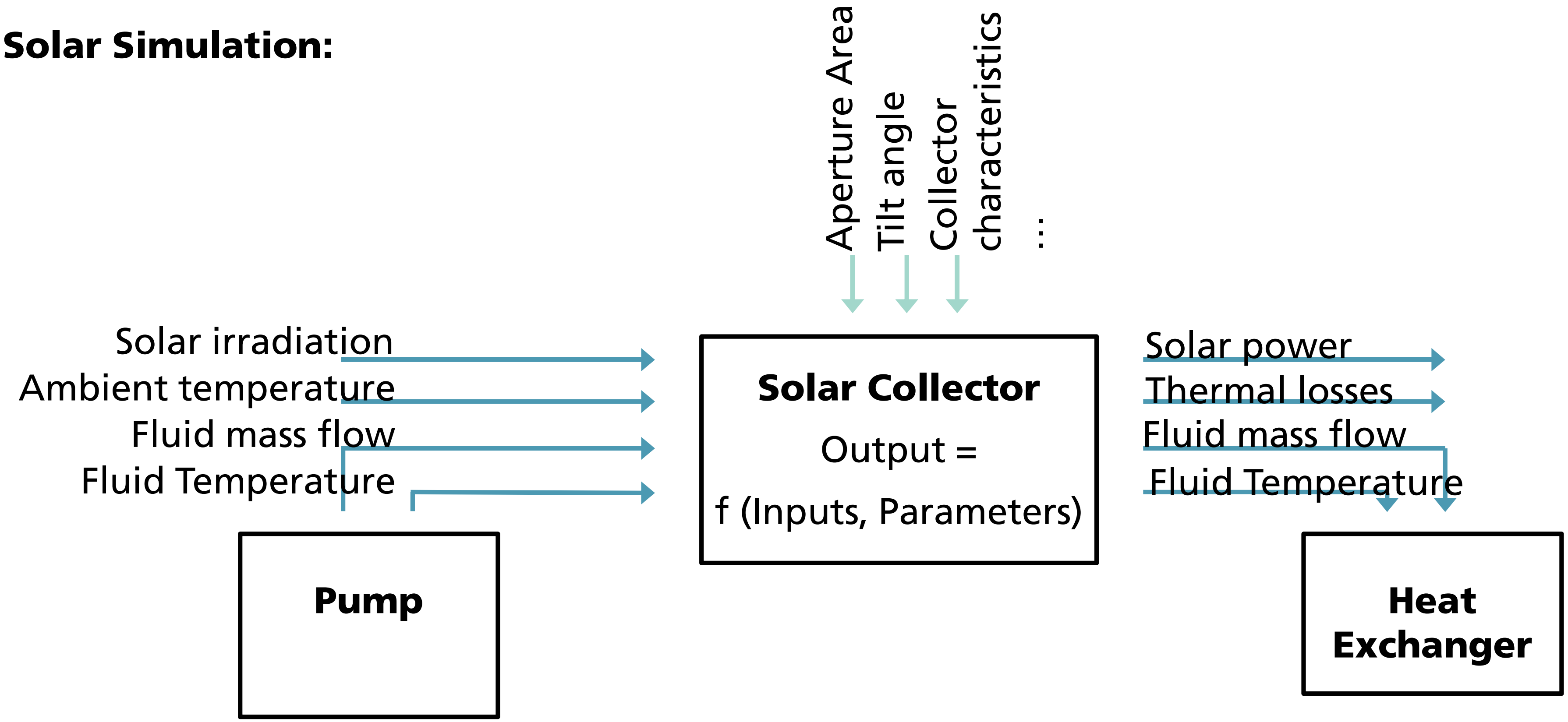
System Simulation
Inputs, Outputs and Parameters

Principle:



System Simulation
Inputs, Outputs and Parameters

Solar Simulation:



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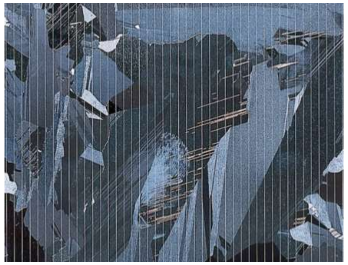
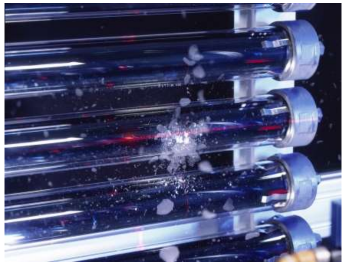
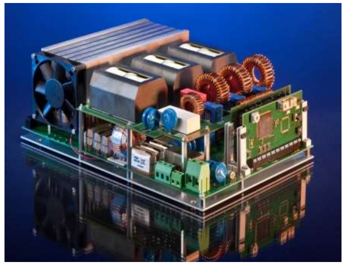
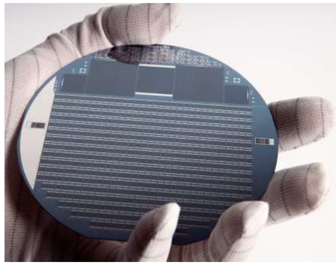
System Simulation
Uncertainty of simulation results

- Uncertainty highly depends on
  - Simulation method
  - Complexity of system
  - Knowledge of system parameters
  - Accuracy of weather data

- Validation improves credibility
  - Comparison with measured data

- Possibilities to guarantee accuracy are limited!

Thank you for your Attention!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Dr. Wolfgang Kramer

Fanny Hübner

www.ise.fraunhofer.de

wolfgang.kramer@ise.fraunhofer.de
fanny.huebner@ise.fraunhofer.de