SFERA-III

Solar Facilities for the European Research Area

1st Summer School “Thermal energy storage systems, solar fields and new cycles for future CSP plants”
WP1 Capacity building and training activities
Odeillo, France, September 9th-11th 2019

“Increasing dispatchability and the capacity factor of CSP: Lessons learned from a lab-scale thermocline storage”

NETWORKING

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INCREASING DISPATCHABILITY AND THE CAPACITY FACTOR OF CSP

Lessons learned from a lab-scale thermocline storage

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Shahab Rohani

Fraunhofer Institute for Solar Energy Systems ISE

SFERA III Summer School

Odeillo, 2019-09-09

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Fraunhofer ISE

At a Glance

Institute Directors:
Prof. Dr. Hans-Martin Henning
Dr. Andreas Bett

Staff: ca. 1200

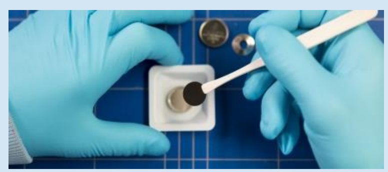
Budget 2018: €94.3 million

Established: 1981

Photovoltaics

Energy Efficient Buildings

Solar Thermal Power Plants and Industrial Processes



Hydrogen Technologies and Electrical Energy Storage

Power Electronics, Grids and Smart Systems

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Business Area
Solar Thermal Power Plants and Industrial Processes

photo ©Fraunhofer ISE/Dirk Mahler

Research Themes

- Solar Thermal Power Plants
- Concentrating Solar Collectors
- Water Treatment and Separation
- Thermal Energy Storage for Power Plants and Industry
- Industry Processes and Process Heat
- Efficient Heat Exchangers

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AGENDA

- Introduction to thermal storage in CSP
- Sensible heat storage
- 1-Tank thermal energy storage with stratification
- 1-Tank Storage: Prototype at Fraunhofer ISE

INTRODUCTION

- Introduction
  - Purpose of (thermal) energy storage in CSP plants
  - Capacity factor of CSP w/ and w/o storage
  - Storage capacity, solar multiple and full load hours
  - Thermal storage classification
- Latent heat storage
- 1-tank thermal energy storage with stratification
- 1-Tank Storage: Prototype at Fraunhofer ISE

Purposes of energy storage

- Solar radiation is a fluctuating source of energy

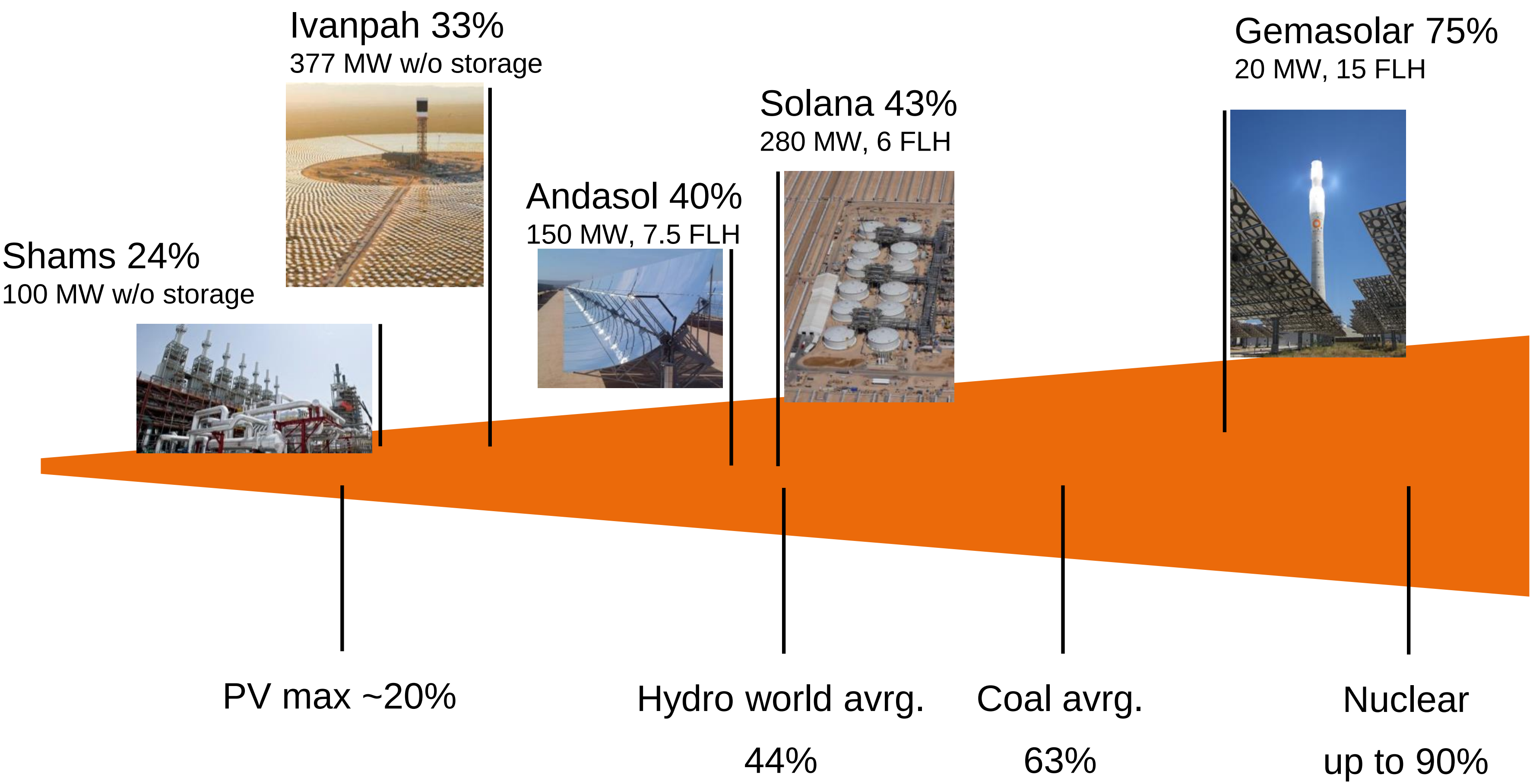
  → Solar energy is not always available when needed

  → Solar energy is not always needed when available

- Energy storage can synchronize energy supply and demand
  - Dispatchability → Energy on demand
  - Higher revenues by load management
  - Power production can be forecasted
- Stabilize operation of power block, especially of the turbine (e.g. clouds)
- Increase power block utilization (capacity factor, CF)
  - $CF = \frac{Actual\ annual\ energy\ production}{Nameplate\ capacity * 24\ h * 365\ d}$

Capacity factors of CSP

CSP provides wide range of plant types with different CF



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PE2: Linear Fresnel – Direct Steam Generation

Quelle: NOVATEC, SolarPACES 2014

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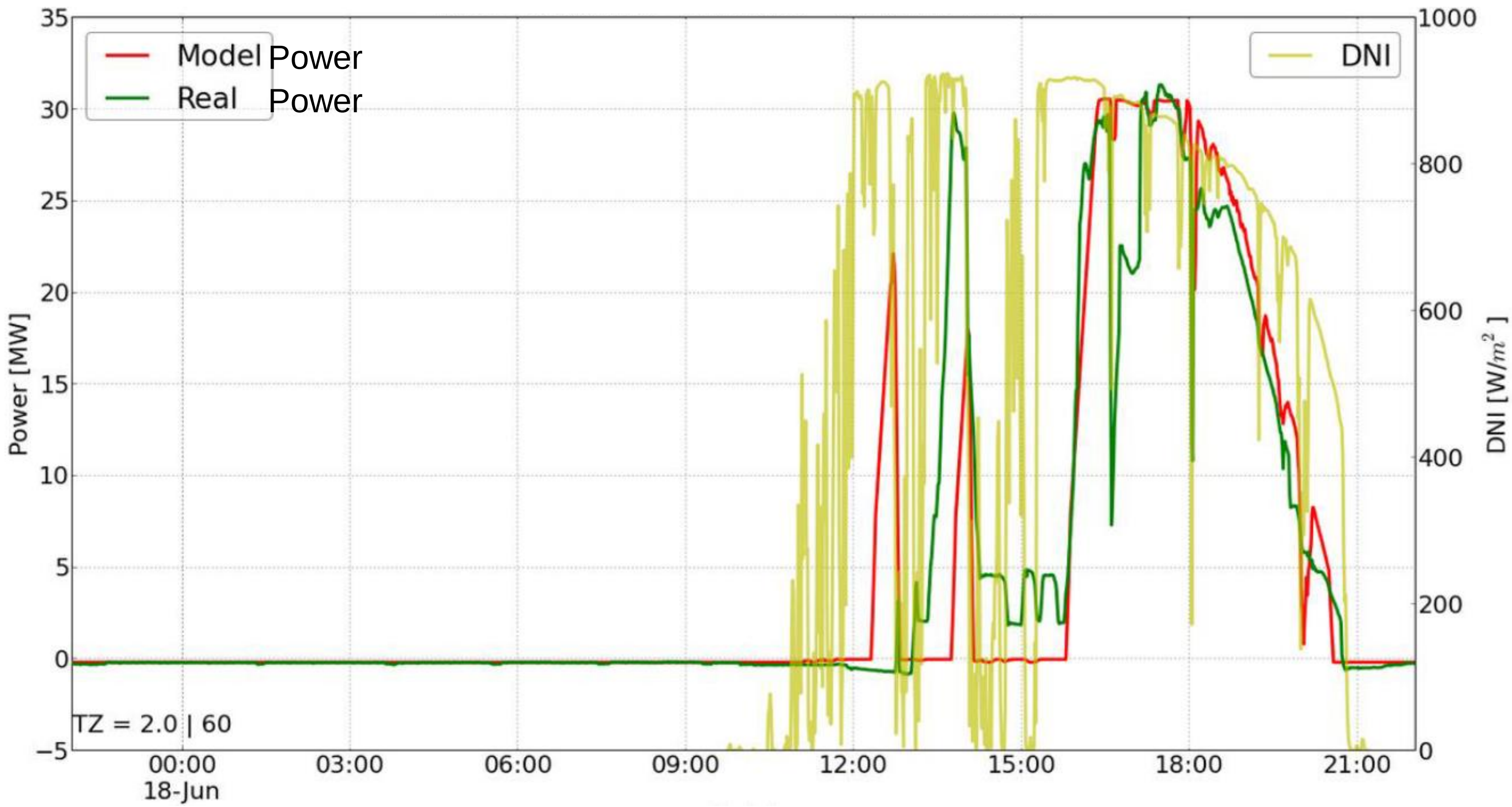
PE2 without Storage, 30 MW_{el}:
Power production on a day with volatile irradiance



Quelle: Selig, SolarPACES 2014

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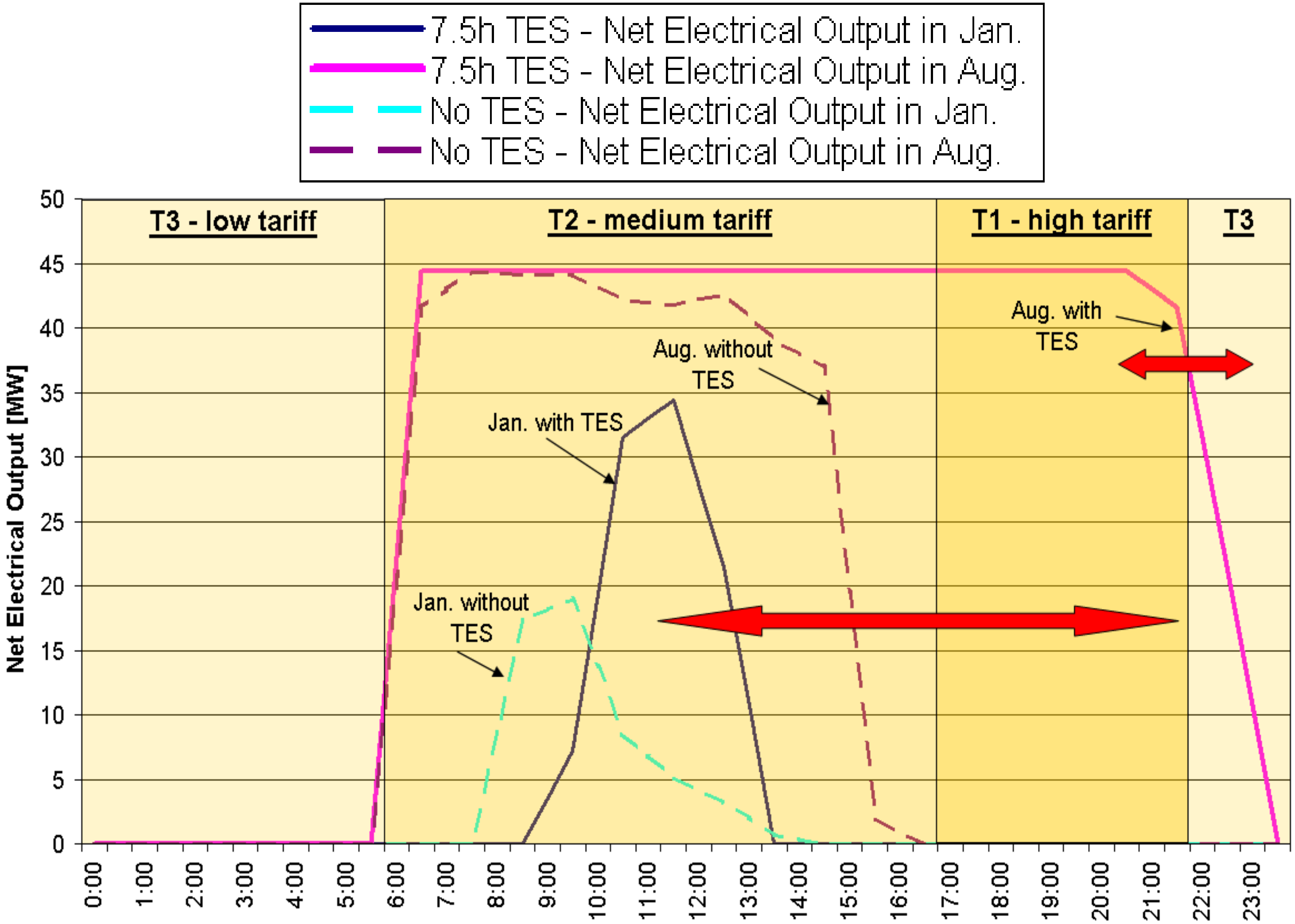
Higher revenues by load management

Production is shifted to high demand & high tariff times

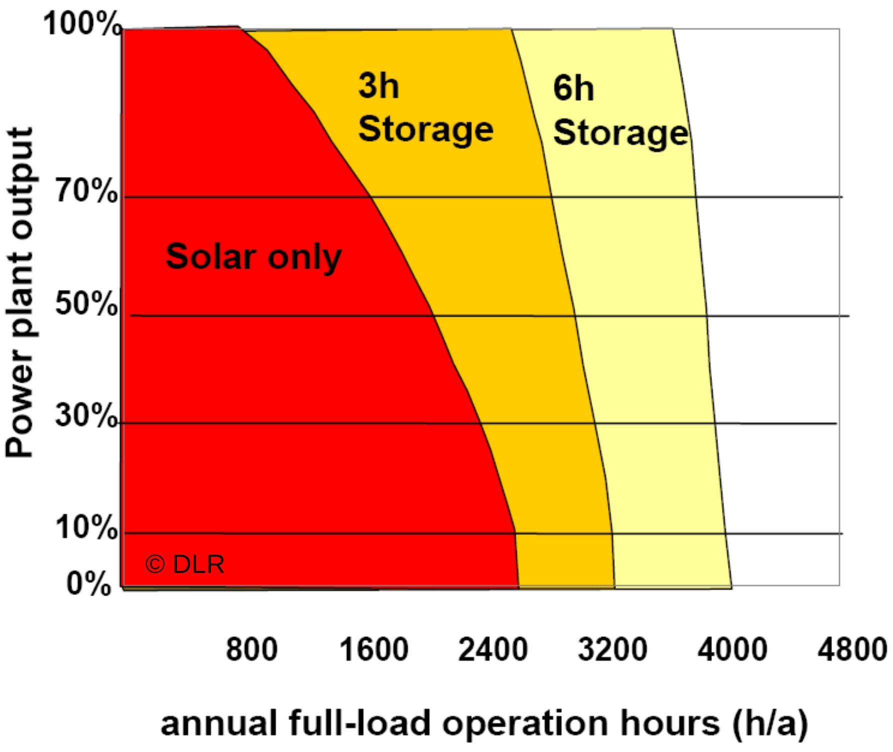


Some defintions:
Storage Capacity and Full Load Hours (FLH)

- Storage capacity: Amount of thermal energy stored
  - Q = mass * specific heat capacity * temperature difference (in case of a sensible storage)
- Equivalent storage capacity: Amount of usable energy (electricity) stored
- Capacity in terms of CSP usually stated in MWh or GWh
- Full load hours (FLH) = Duration in which the plant can deliver a “full” power output through storage (nameplate capacity of turbine)

Increase of full load hours by storage

- Increase of power block utilization with storage
- Overall efficiency of the plant increases due to power conversion at **nominal load** of turbine
- Load management according to demand is possible
  → higher revenues



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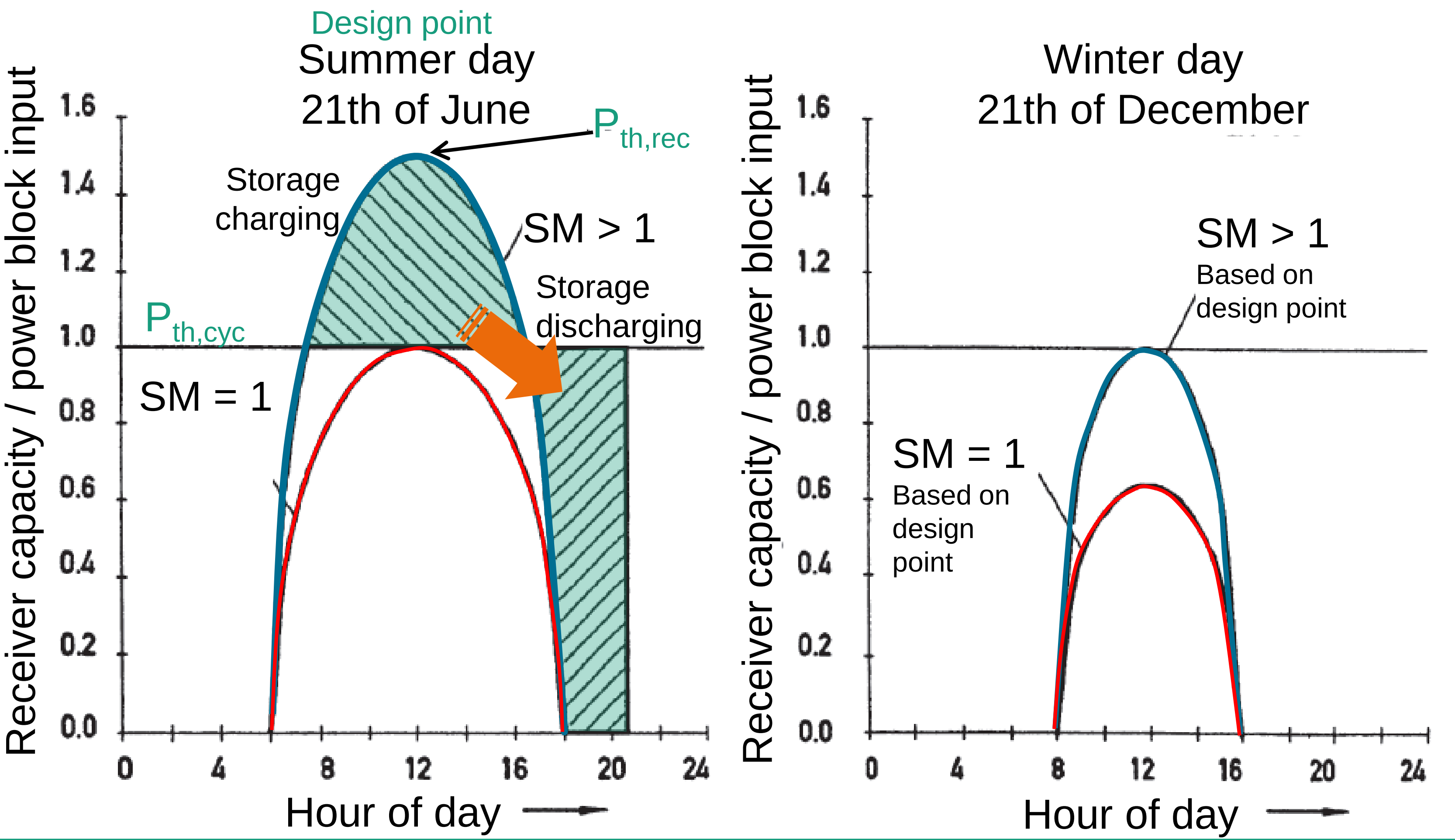
Solar multiple (SM)

$$SM = \frac{P_{th,rec}}{P_{th,cycle}}$$

Ratio of thermal receiver power ($P_{th,rec}$) at design point to the nominal inlet power of the power block ($P_{th,cyc}$)



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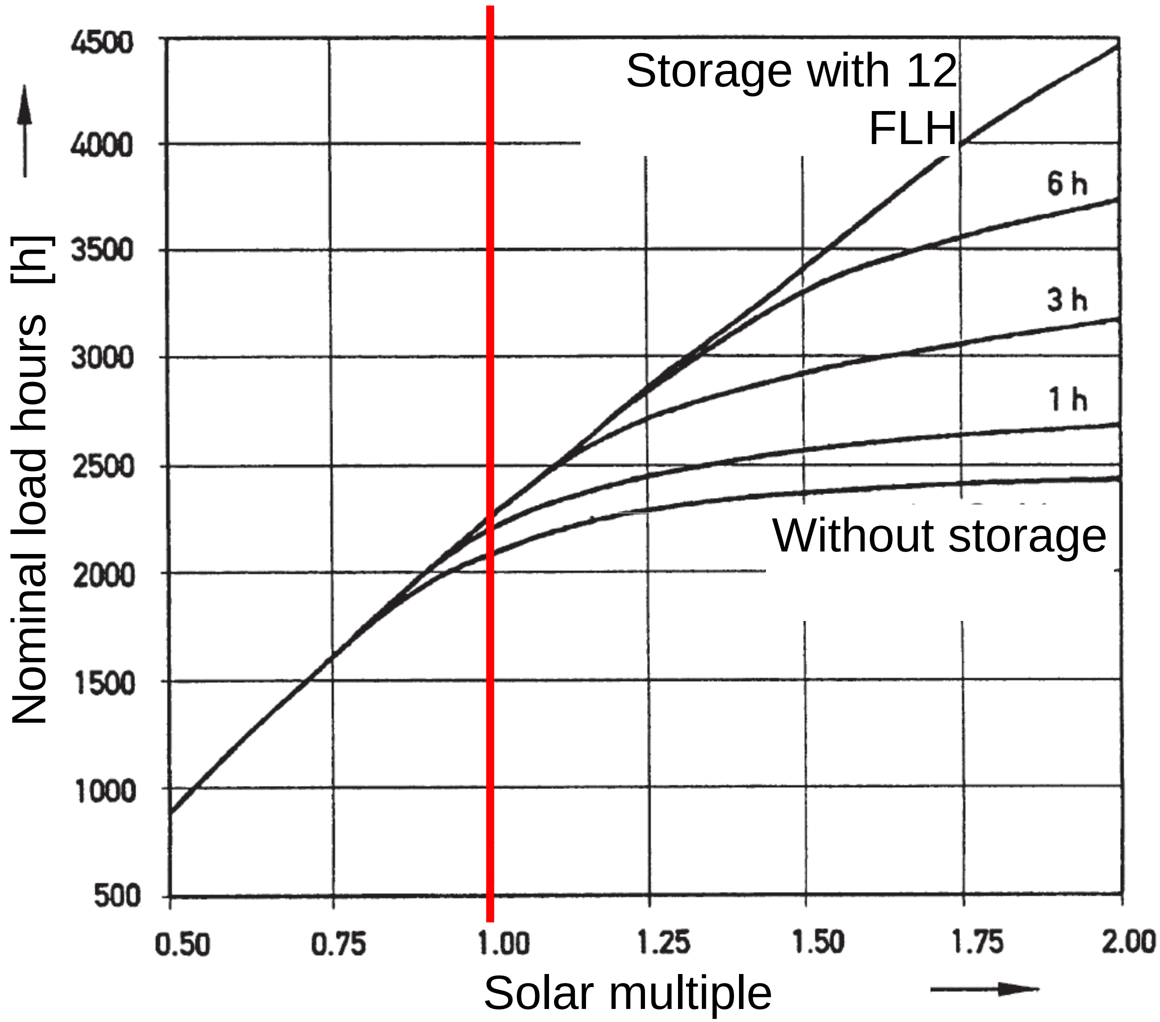
Solar multiple



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Classification of storage options

Increasing energy density

- **Sensible** heat storage
  - Steam, Oil
  - Concrete
  - Molten salt
  - Iron, Rocks, Sand in combination with oil
  - Liquid sodium
- **Latent** heat storage
  - Phase Change Materials (PCM – e.g. salt nitrates)
- **Chemical storage**

SENSIBLE HEAT STORAGE

- Introduction
- Sensible heat storage
  - Types of sensible heat storage
  - Steam accumulator
  - 2-Tank indirect
  - 2-Tank direct
  - Cost comparison
  - Realized solar thermal plants with storage (examples)
- 1-Tank thermal energy storage with stratification
- 1-Tank Storage: Prototype at Fraunhofer ISE

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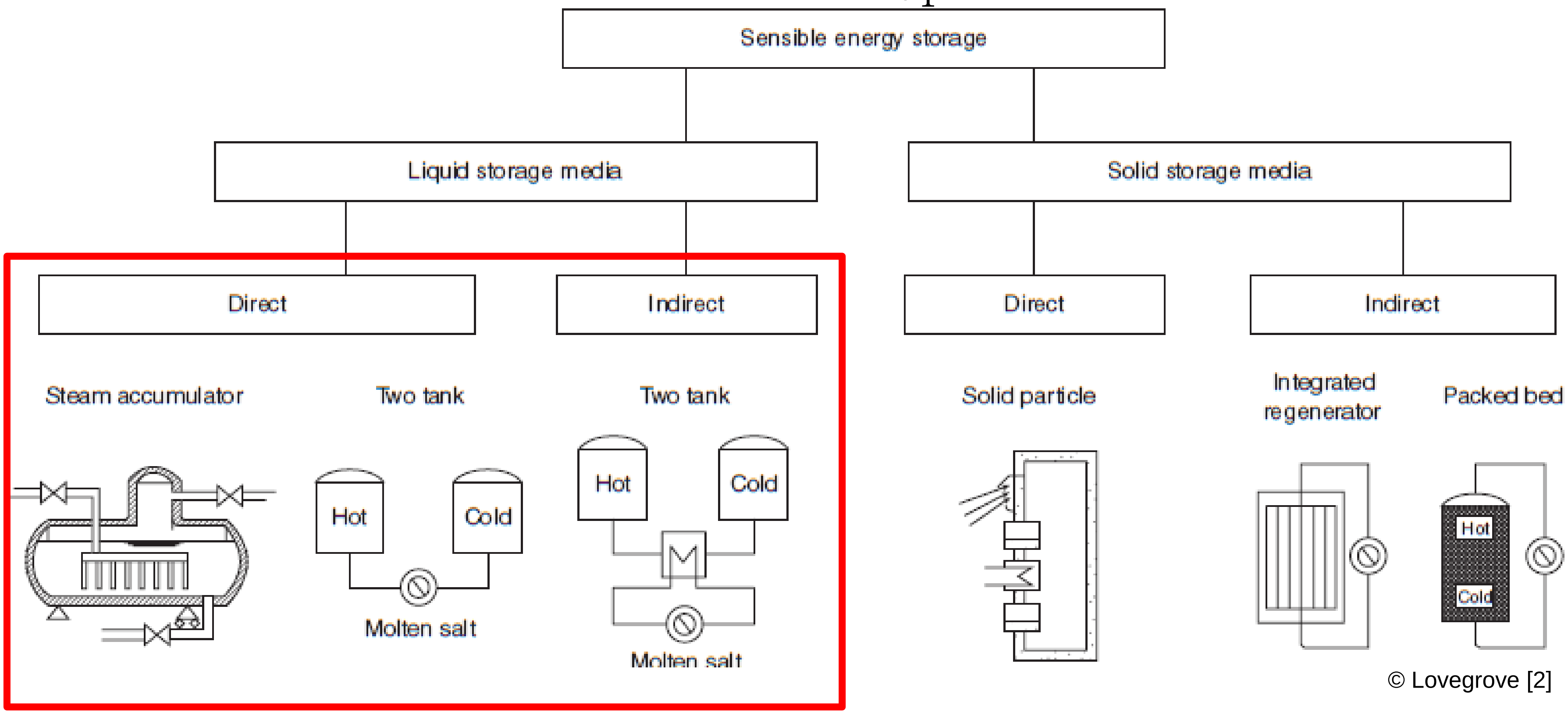
Overview of sensible energy storage

$$Q_{1,2} = m * \int_1^2 c(T)dT$$



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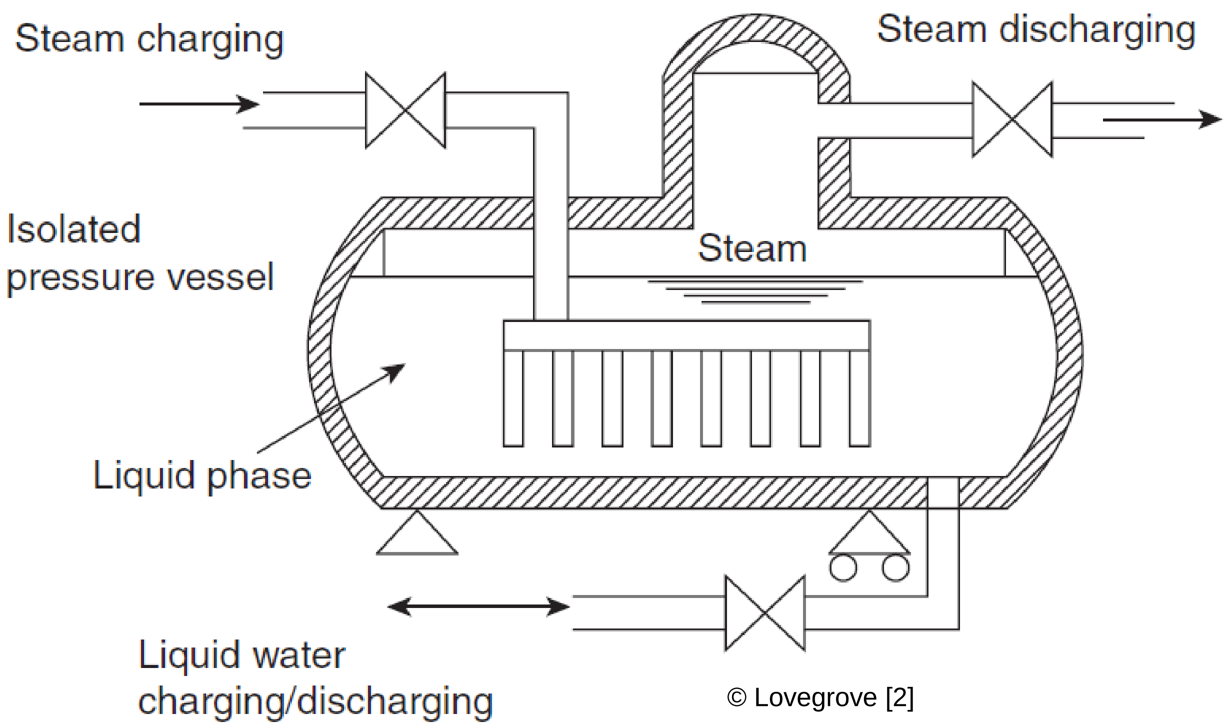
Sensible Heat Storage

Steam Accumulator „Ruths storage“

- Only small capacity
- Short term storage
- Pressurized water as storage medium
- “Low pressure”
- Cost intensive



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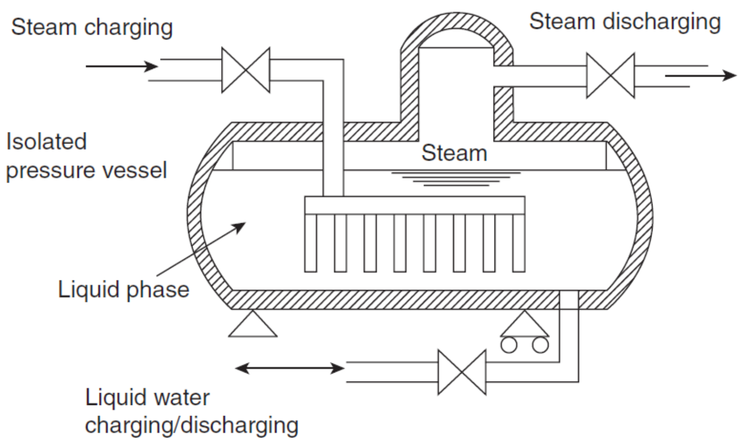
Sensible Heat
Steam Accumulator

- **Example:** PS10 (Spain)
- 11 MW_{el}
- 50 bar / 285 °C
- Storage can run the power block for 30 Minutes



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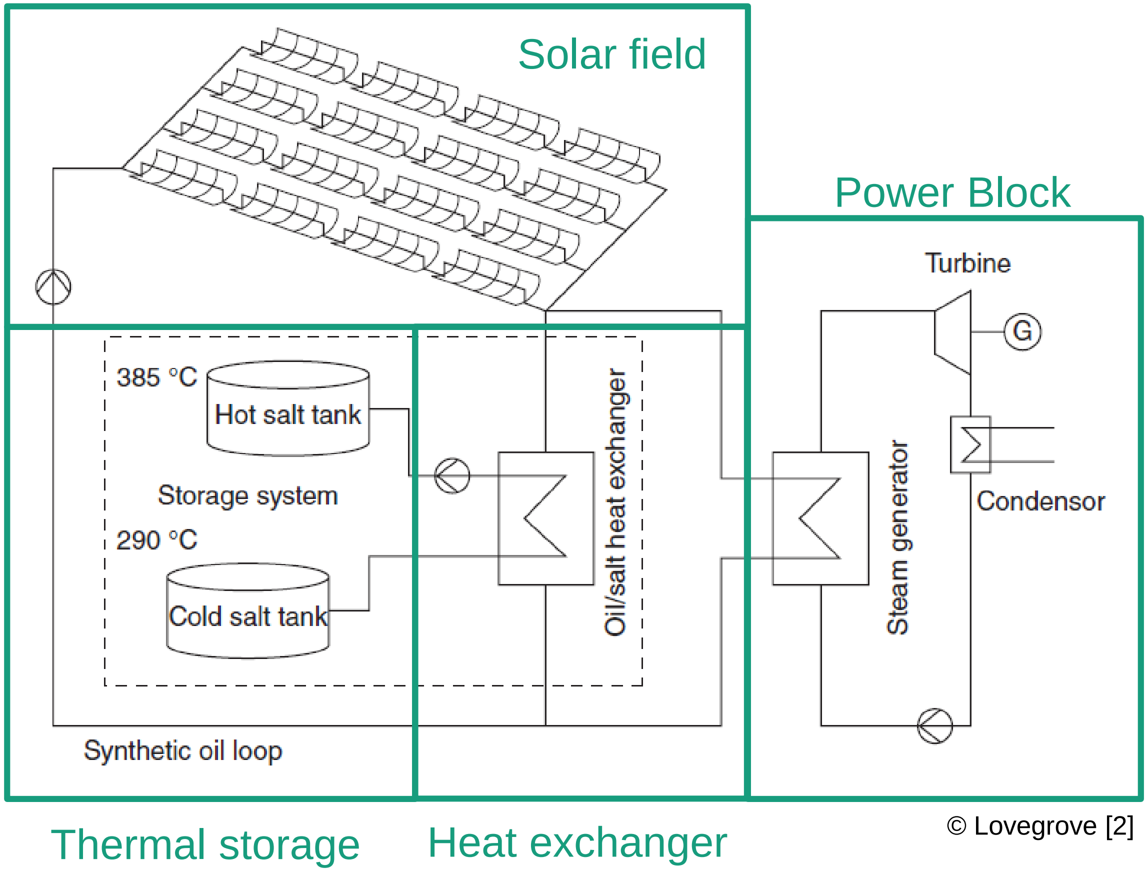
http://www.trec-uk.org.uk/images/heat_storage_tanks.jpg

https://en.wikipedia.org/wiki/PS10_solar_power_plant

Sensible Heat

Two-tank indirect molten salt storage

- Most commonly built system
- HTF in solar field and storage medium differ
- Over-dimensioning of solar field, surplus energy is stored during the day
  → solar multiple > 1



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Sensible Heat
Two-tank <u>indirect</u> molten salt storage

- **Example**: Andasol 3 (Spain)
- Electrical power: 50 MW
- Tank diameter: 38.5 m
- Height: 14 m
- Contents: about 28,000 m^3 molten salt
- Temperatures:
  cold 292°C, hot 386°C
  - Δt = 94 K
- 7.5 full load hours

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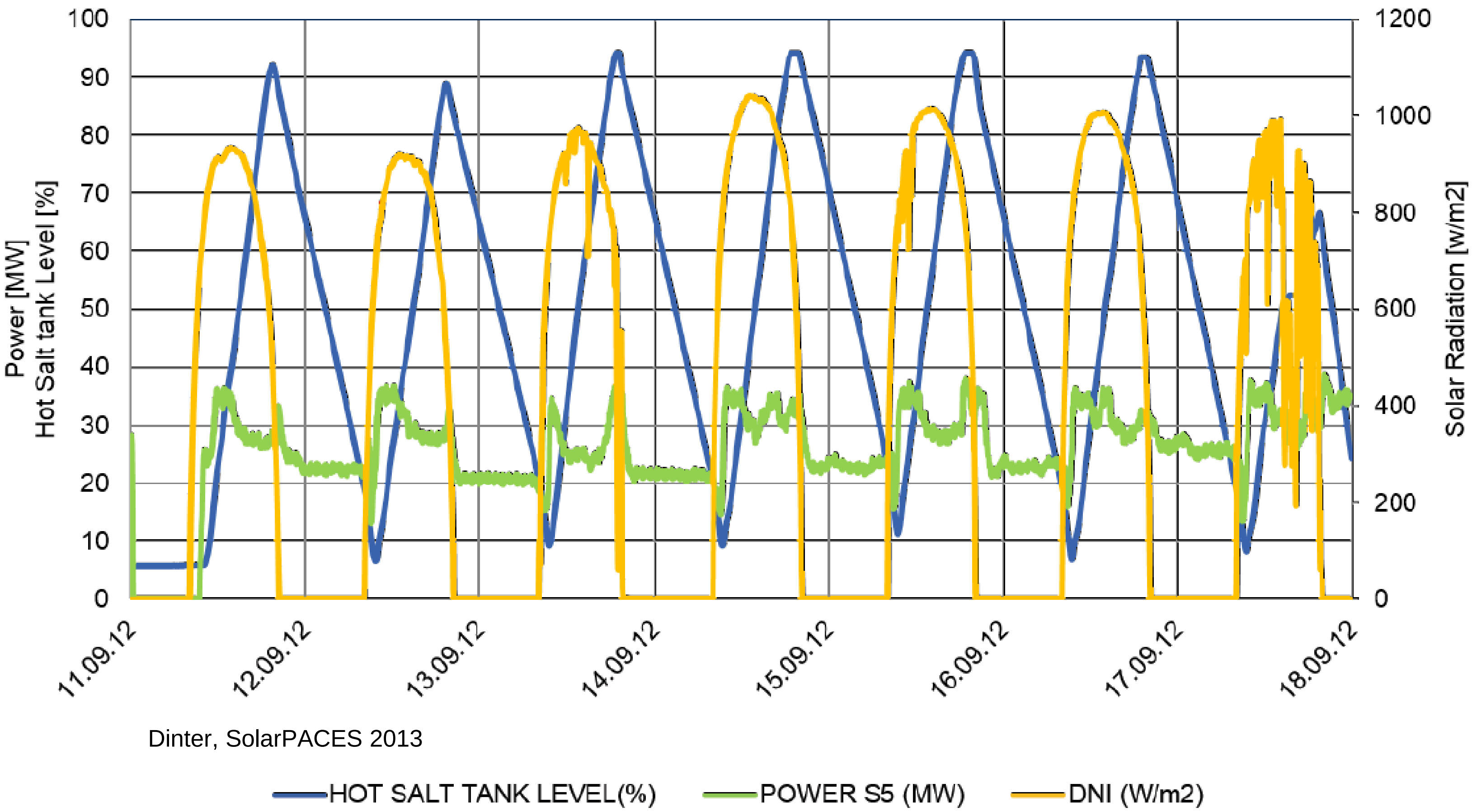
Sensible Heat
Two-tank indirect molten salt storage

- **Example**: Andasol 3



Dinter, SolarPACES 2013

Sensible Heat

Two-tank indirect molten salt storage

- **Example 2:** Solana (USA)
- Electrical power: 280 MW (net)
- Capacity factor: 43 %
- 6 Full load hours
- Storage capacity: 1680 MWh_{el}
- **≈ 47 times** the capacity of the biggest electrical storage (December 2016)

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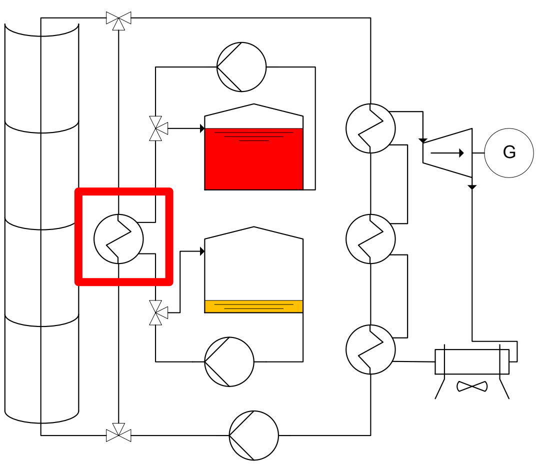
Evolution of molten salt storages

The path to lower cost

Two-tank **indirect**

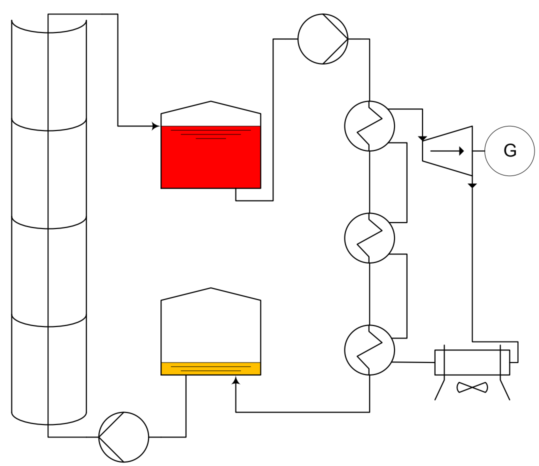
- Temperature loss due two double HX
- Temp. limited by oil
- One tank always empty



- Andasol

Two-tank **direct**

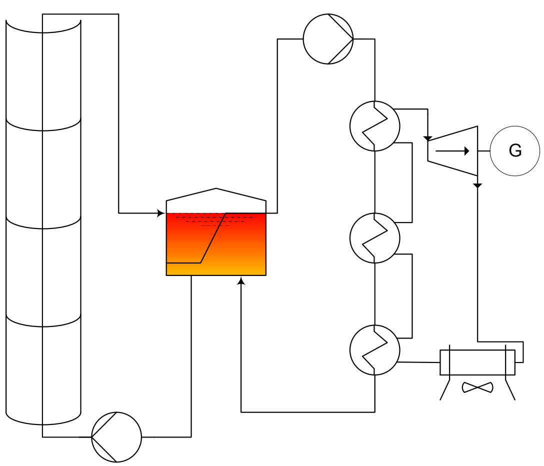
- Molten salt also in collector
- Higher temp. possible
- Less T loss & equipment



- Gemasolar

Single thermocline tank

- One tank less
- Possible integration of HX
- Additional use of filler material reduces amount of salt

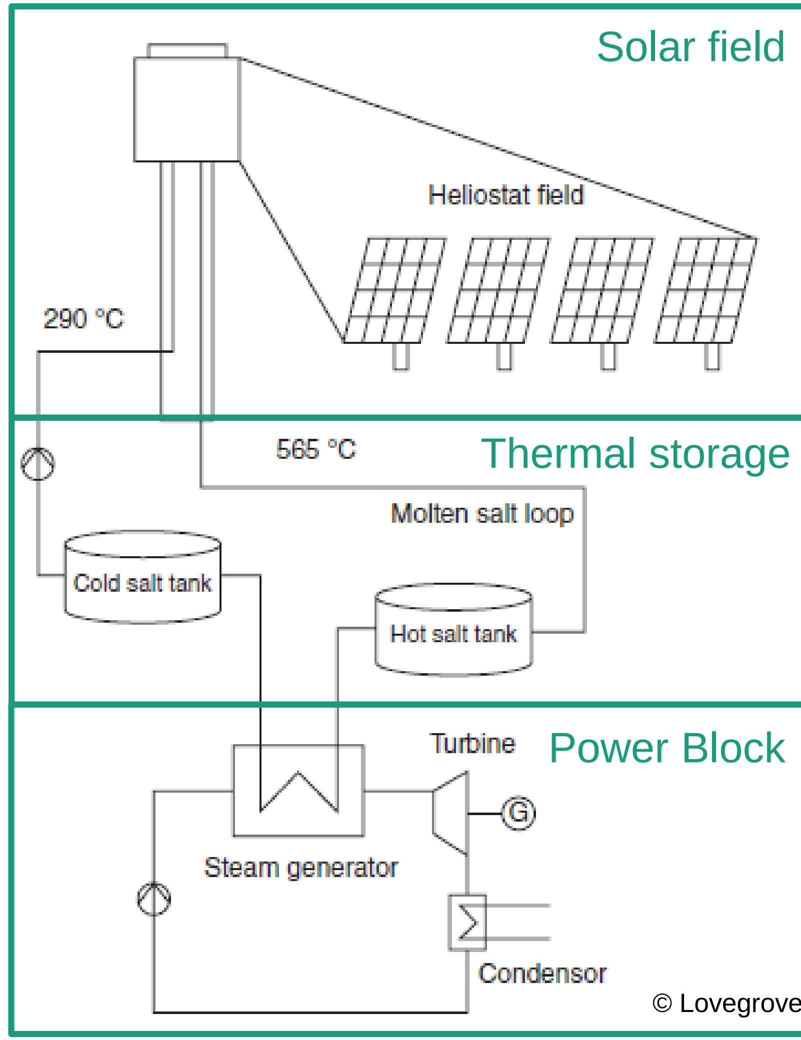


- Testing / Pilots

Sensible Heat

Two-tank direct molten salt storage

- Trend towards direct storage
- Heat transfer fluid = Storage medium
- → No additional heat exchanger needed
  - Cost reduction, less equipment
  - Reduction of heat losses



Sensible Heat

Two-tank direct molten salt storage

- **Example:** Gemasolar (Spain)
- Storage capacity: 15 FLH
- 2650 heliostats
- Rated electrical power: 19.9 MW
- Capacity factor: 75 %
- Can produce **electricity over 24 hours a day** (during several month a year)

http://www.torresolenergy.com

Source: Wikipedia

Location of Gemasolar in Spain

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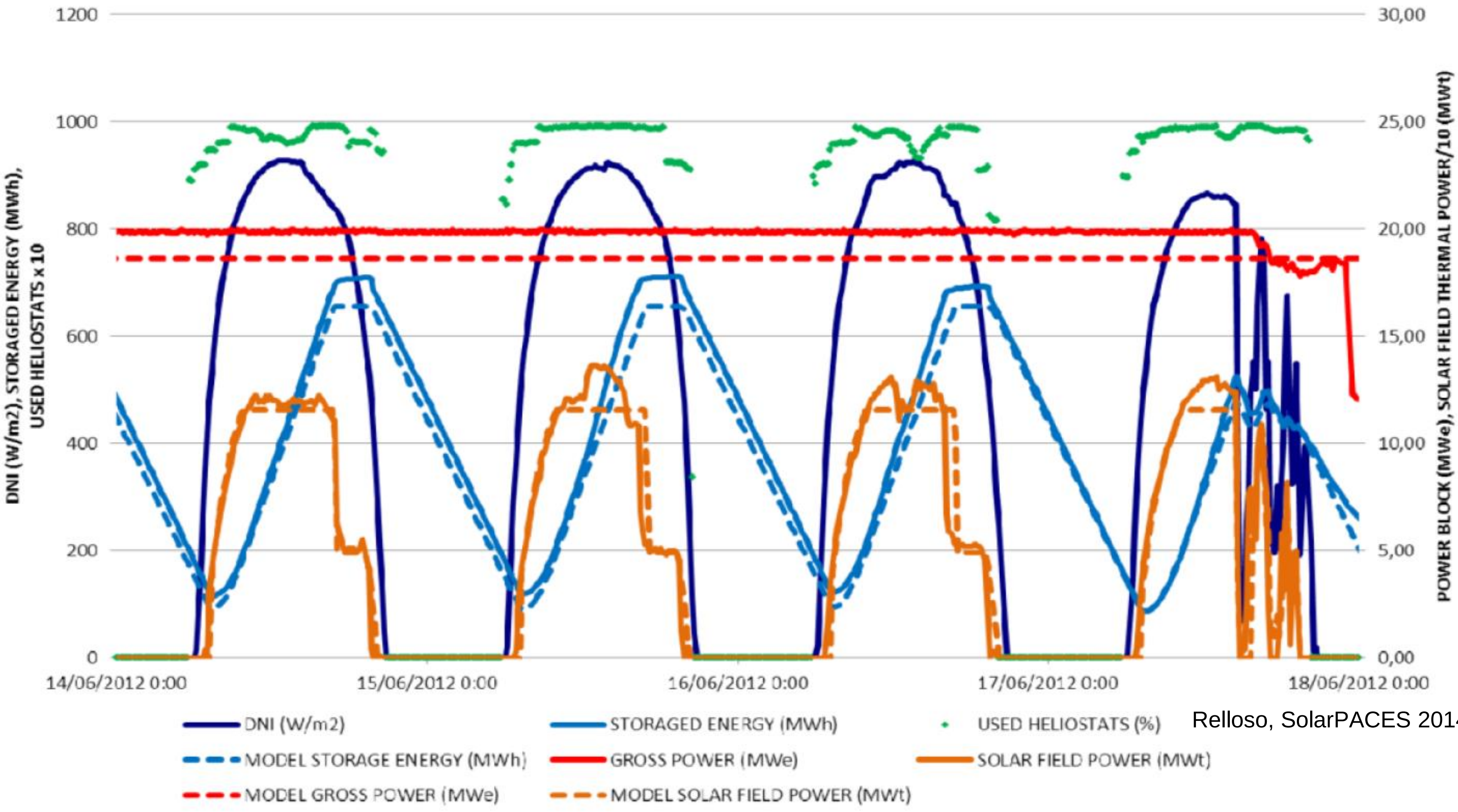
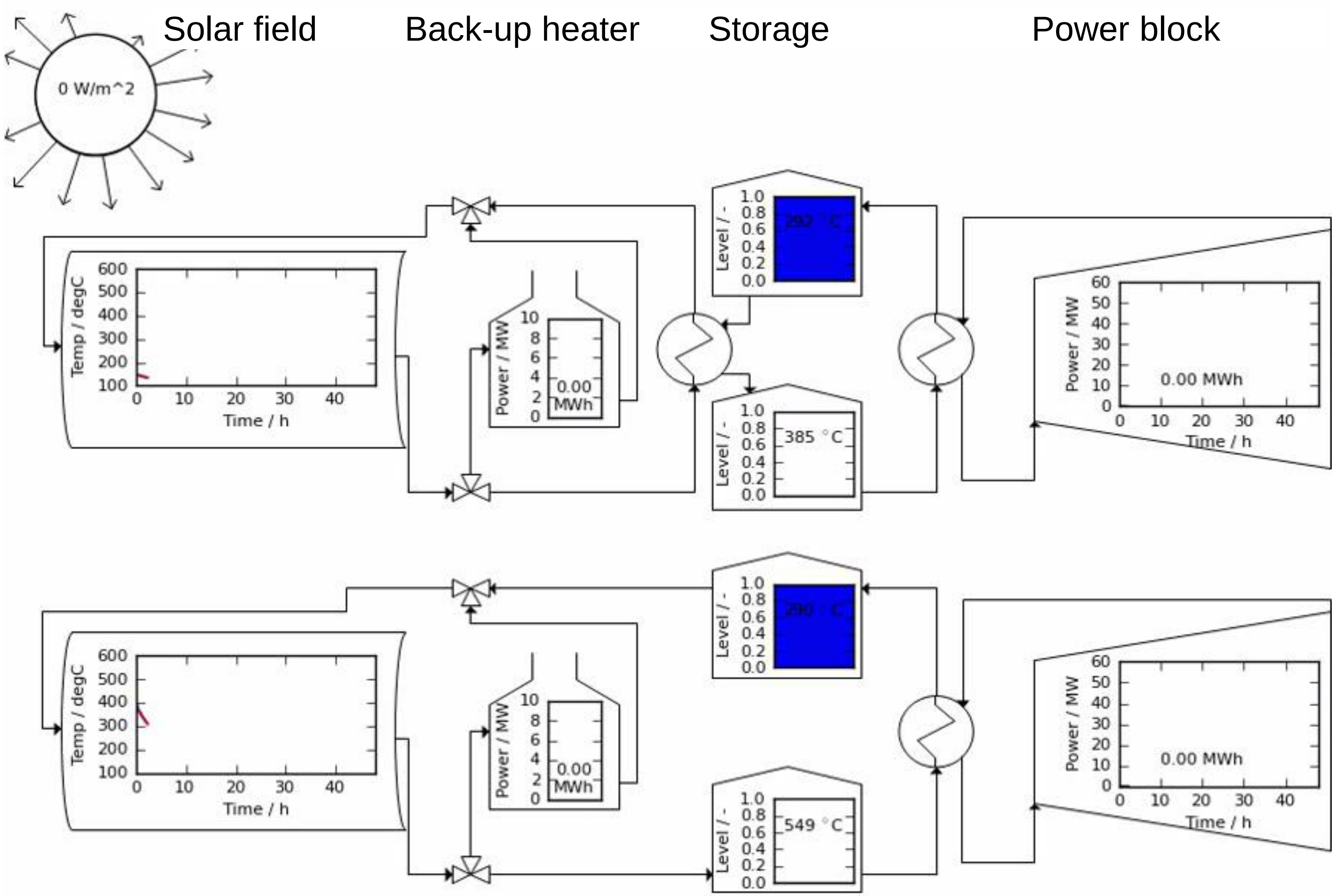
Sensible Heat
Two-tank direct molten salt storage

- **Example:** Gemasolar (Spain)



Relloso, SolarPACES 2014

Direct vs. indirect storage



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Different storages for different CSP systems

- There is no single type of storage solution which is available for *all* different CSP systems
  → storage material depends on operation temperature

Oil parabolic trough	Two-tank molten salt storage Solid material storage Single tank thermocline molten salt storage
Direct steam generation parabolic trough / Linear Fresnel / Tower	Steam storage PCM storage
Solar tower with salt receiver	Two-tank molten salt storage Single tank thermocline molten salt storage
Solar tower with air receiver	Cowper storage (regenerator) Packed bed storage like a sand storage
Scheffler Dish	Solid block storage

Efficiency of sensible thermal energy storage
Molten salt energy storage

- Is rather a short term storage (15 hours)
- Large quantities of storage medium is required
- Nearly no losses in the storage itself
- Thermal losses due to the piping system, heat exchanger
- Overall efficiency > 90 %

Thermal Energy Storage: Summary

- CSP is the only solar technology that has large scale storage already today
- Implementation of storage leads to stable electricity production
  - Up to 24 hours a day
- Trend to direct storage systems
- Thermal energy storage makes CSP-plants dispatchable
  - Electricity on demand
- Thermal storage systems will become more efficient

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Evolution of molten salt storages
The path to lower cost

Two-tank **indirect**

- Temperature loss due two double HX
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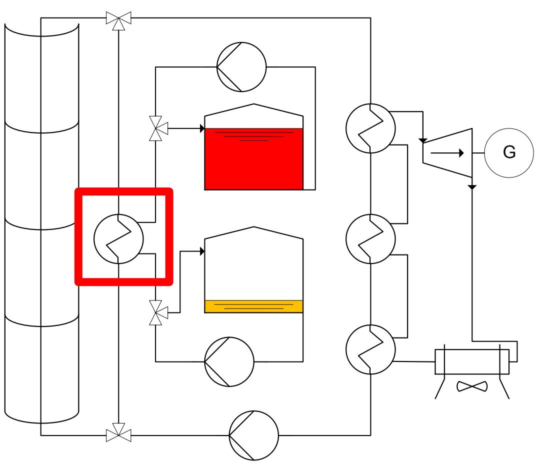
- One tank always empty



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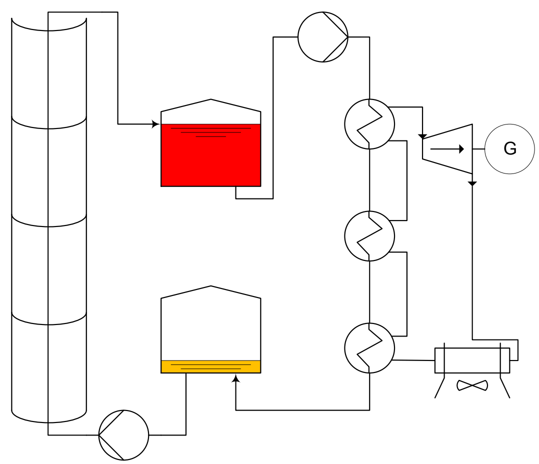

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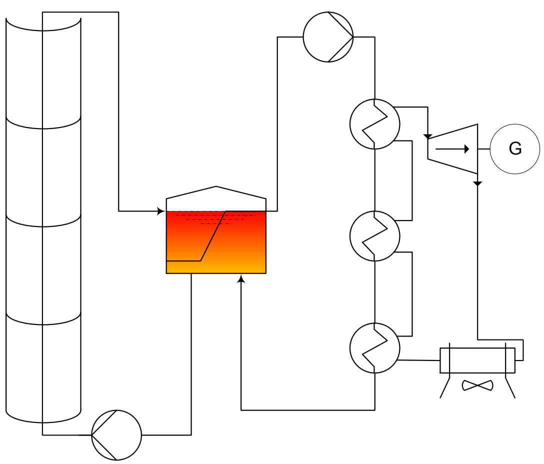


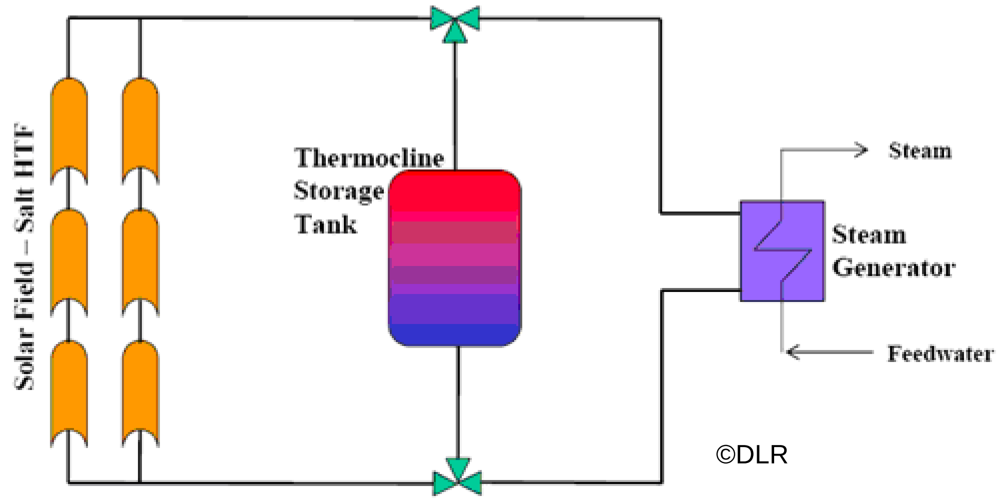
- Testing / Pilots

1-TANK THERMAL ENERGY STORAGE

- Introduction
- Sensible heat storage
- 1-Tank thermal energy storage with stratification
  - Basics
  - Example
  - Operational characteristic
- 1-Tank Storage: Prototype at Fraunhofer ISE

Possible Options for the Future – Thermocline Storage

- Molten salt is used as heat transfer fluid in the solar collectors as well as storage fluid in the TES
- Only ONE tank is used – system is well known from domestic solar water heating systems
- Relies on thermal buoyancy
- Saves costs for 2nd storage and one oil/molten salt heat exchanger



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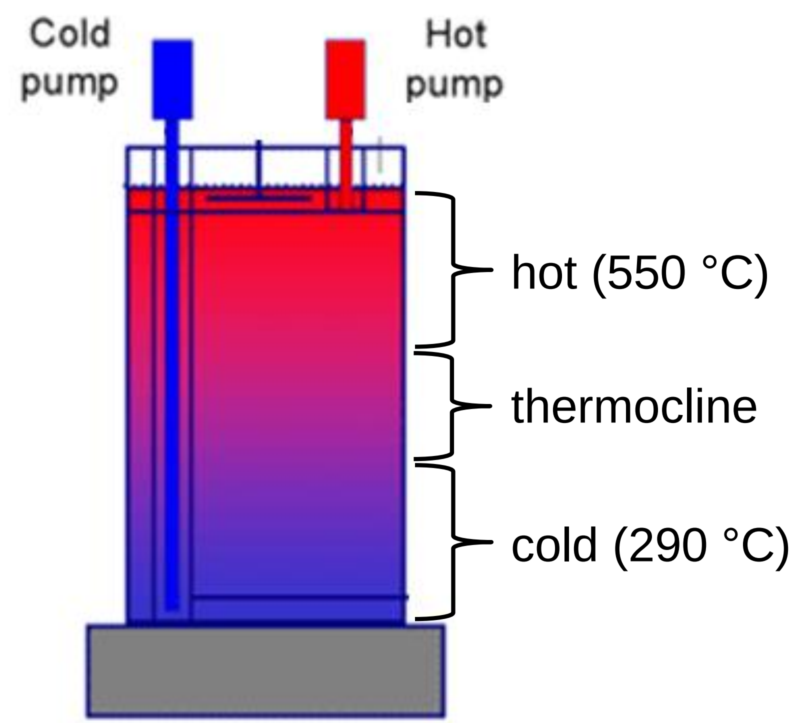
One Tank Molten Salt Storage With Stratification

- Features
  - Separation due to density difference
  - Constant tank filling level
  - More than 2 temperatures
- Conventional design
  - Pumping with shaft untill the bottom of the tank
  - External steam generator



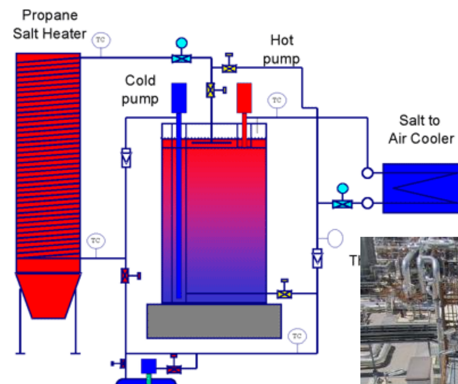
© Sandia

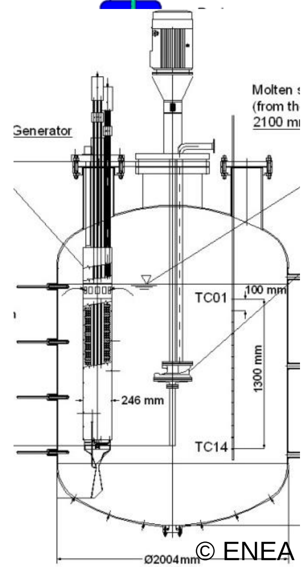
One Tank Storage: Basics

- Separation of hot and cold fluid due to density difference
  - Water: 20 °C – 90 °C ➔ 998 kg m^{-3} – 965 kg m^{-3} ➔ $\Delta\rho$ = 3.31%
  - Salt: 290 °C – 550 °C ➔ 1905 kg m^{-3} – 1740 kg m^{-3} ➔ $\Delta\rho$ = 8.66%
- The better the separation, the better the efficiency
- Parasitic effects for stratification
  - Mixing at the inlet (without filling material)
  - Heat exchange between molten salt and filling material

One Tank Storage: Examples

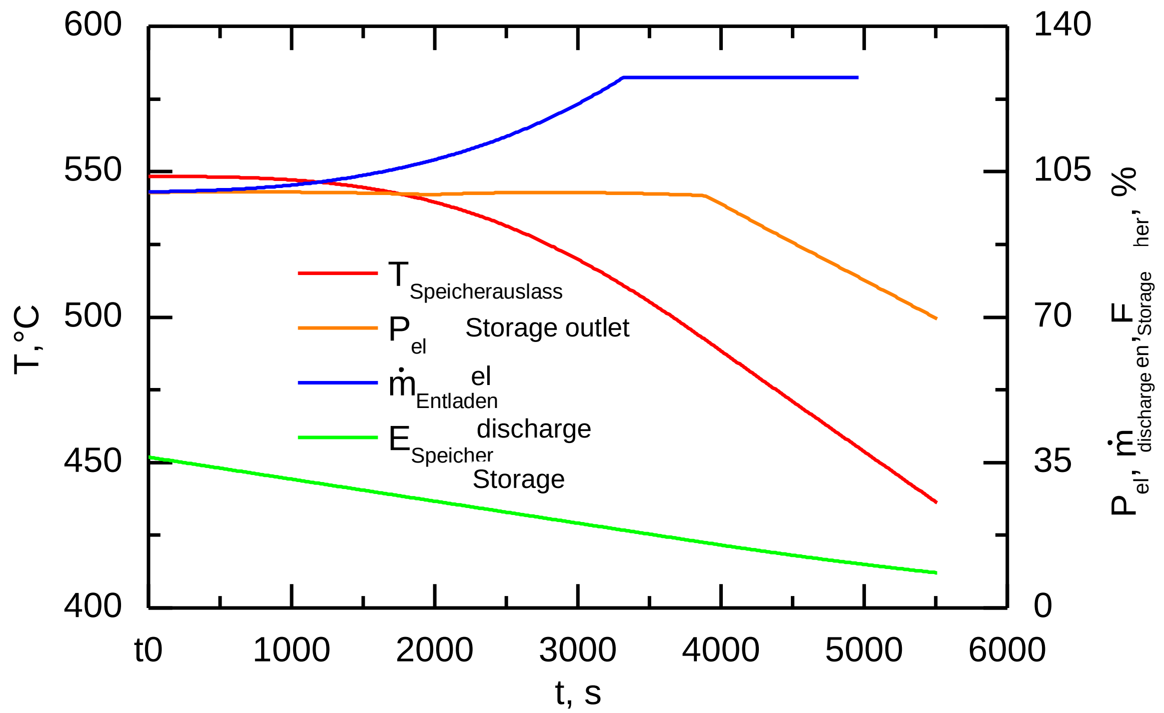
- Sandia, USA (2001): 2,3 MWh
  - T_{max} 390 °C
  - Filling material: Stone-Sand-Mixture
- Sener, Spain (2011): 24 MWh
  - T_{max} 390 °C
  - With separation barrier
- ENEA, Italy (2012): 1,2 MWh
  - T_{max} 520 °C
  - Internal steam generator





One Tank Storage: Operational Characteristics

- Behavior depends on stratification
- Discharge power lowers at the end of a cycle



1-TANK THERMAL ENERGY STORAGE

- Introduction
- Sensible heat storage
- 1-Tank thermal energy storage with stratification
- 1-Tank Storage: Prototype at Fraunhofer ISE
  - System Description
  - Qualitative Evaluation
    - Method
    - Result
  - Energetic Evaluation
    - Charging of Storage
    - Discharging of Storage
  - Conclusion and Outlook

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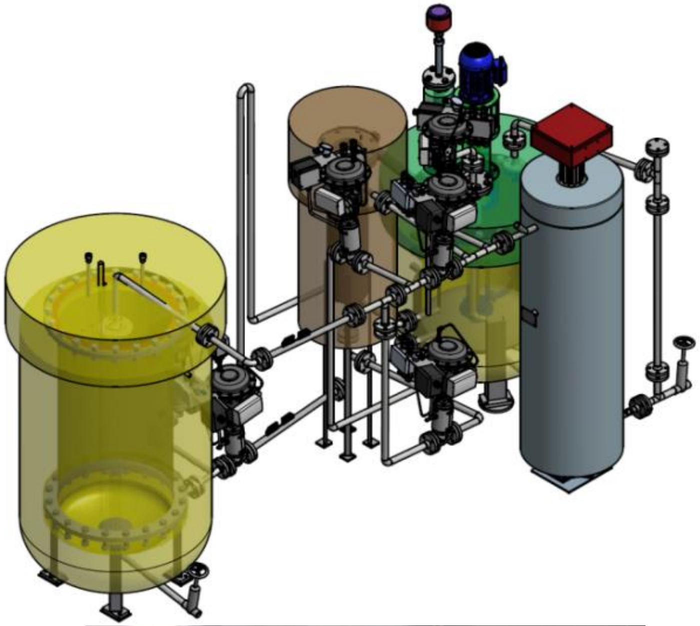
One Tank Storage: Prototype at ISE

- Stratified storage
  - Height 1,3 m / diameter 0,6 m
  - Capacity: 72 kWh
  - Temeperature: 290 °C – 550 °C
  - Heating and cooling power 60 kW
- Charge- and discharge experiments:
  - Temperature difference
  - Mass flow
- Next step: Filling material



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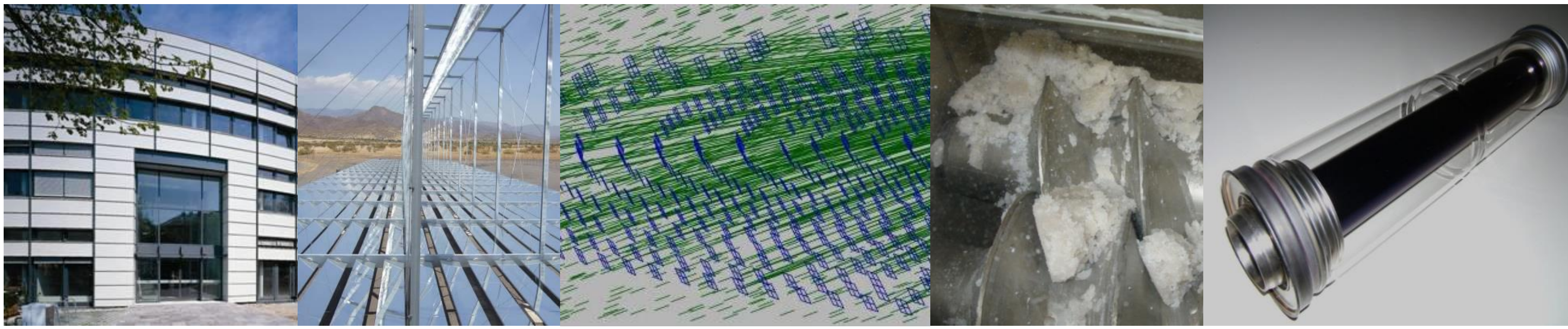

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Lessons learned from a lab-scale thermocline storage

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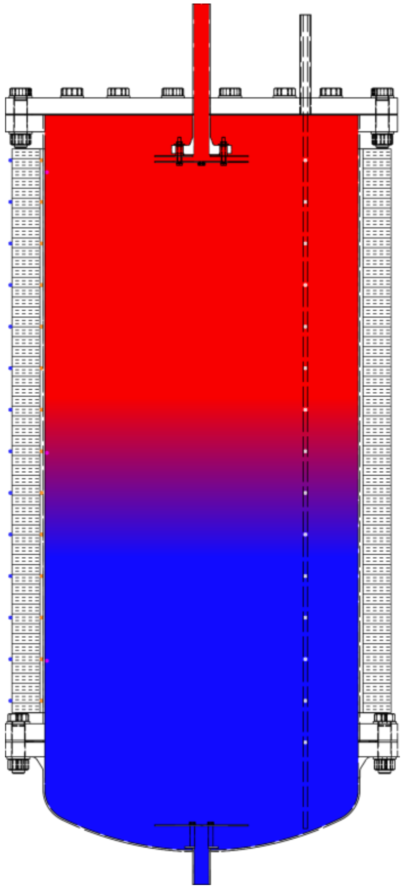
SFERA III summer school
CNRS/PROMES
September 09 – 11, 2019

EERA European Energy Research Alliance

Presentation Outline

1. Introduction
2. System Description
3. Qualitative Evaluation
   a) Method
   b) Result
4. Energetic Evaluation
   a) Charging of Storage
   b) Discharging of Storage
5. Conclusion and Outlook



Benefits of Single-Tank TES

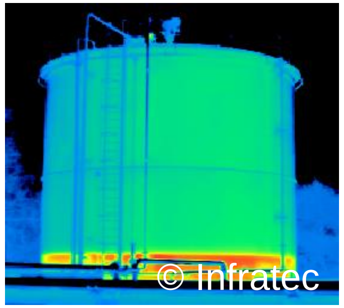
Only one tank

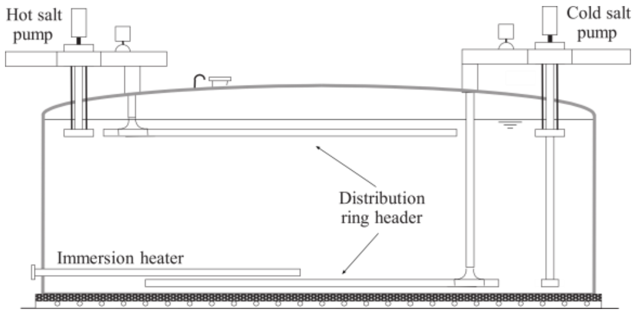
- Less material use
- Reduction of HTF volume
- Lower floor area demand
- Cold tank foundation
- Lower heat losses
- Reduced dead volume

Constant fill level

- Integration of filler material
- Short-shaft pumps
- Easier tank ullage gas management

→ Recent studies show that the CAPEX of storage systems could be reduced by up to 35 %





Drawback: Mixing of hot and cold layer →Loss of exergy

System Description

System Description

Main Features

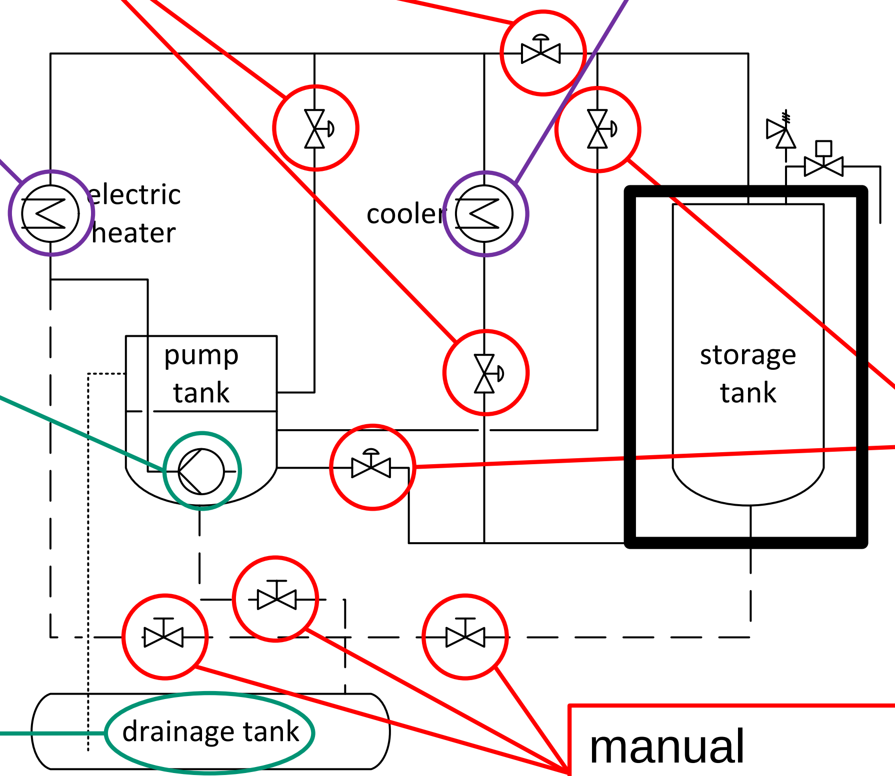
control valves DN 25

Q: 60 kW

T_{max}: 550 °C
Q: 60 kW

T_{max}: 600 °C
V: 4 m^3 h^{-1}

V: 0.6 m^3
p_{max}: 0.5 bar



shut-off valves DN 25

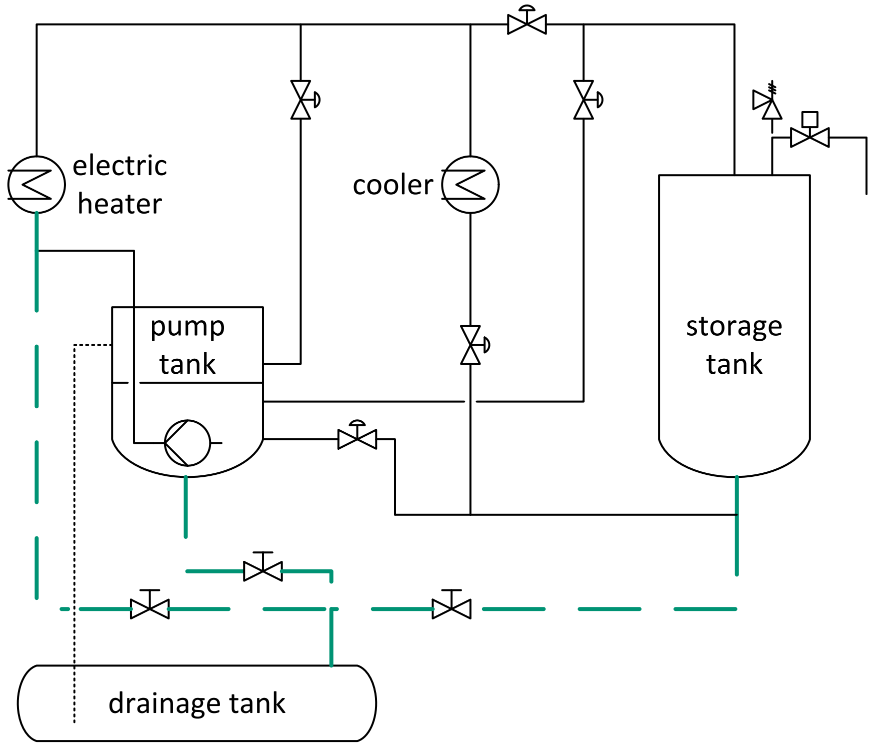
manual valves DN 25

$NaNO_3/KNO_3$ „Solar Salt“
60/40 wt.-%

System Description

Main Features

- Operating modes
  - Filling
  - Attemperation
  - Charging
  - Discharging
  - Draining



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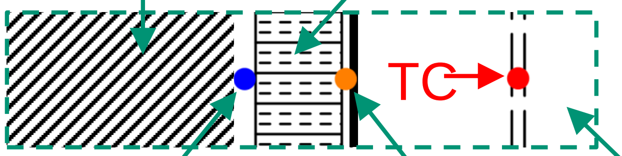
STAGE STE EERA

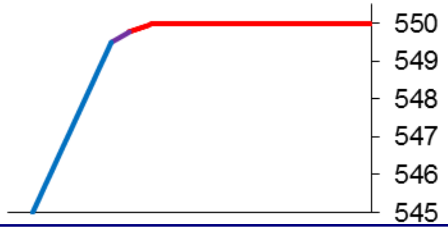
15 x thermocouples (TC) for measurement of stratification

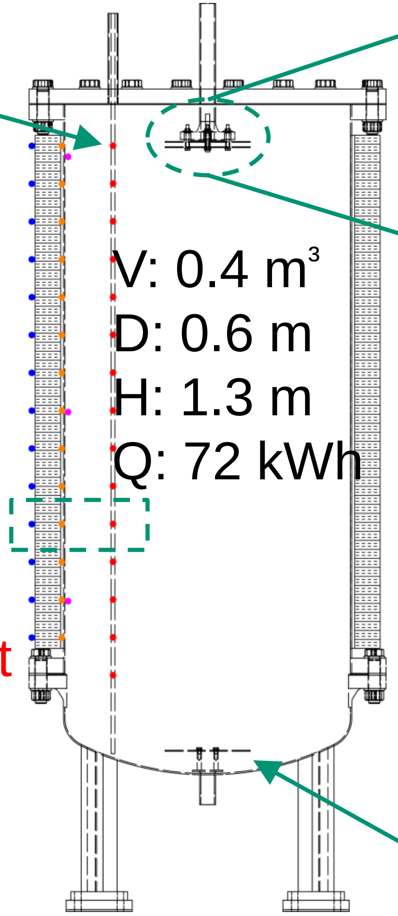
secondary/main insulation

primary insulation

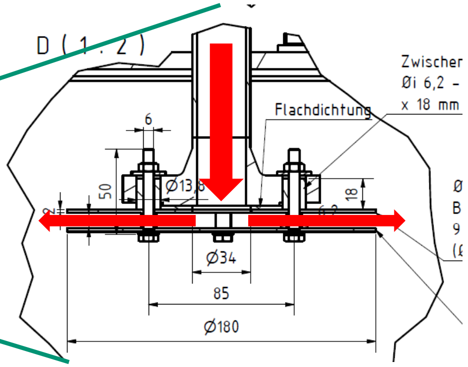


heating cable wall molten salt





V: 0.4 m³
D: 0.6 m
H: 1.3 m
Q: 72 kWh



double-plate radial diffuser
A_{inlet}: 0.0051 m^2
u_{inlet}: 0.02 m s^{-1} (@ 0.4 m^3 h^{-1})

Unfavorable surface-area-to-volume-ratio -> prone to edge effects

single-plate radial diffuser

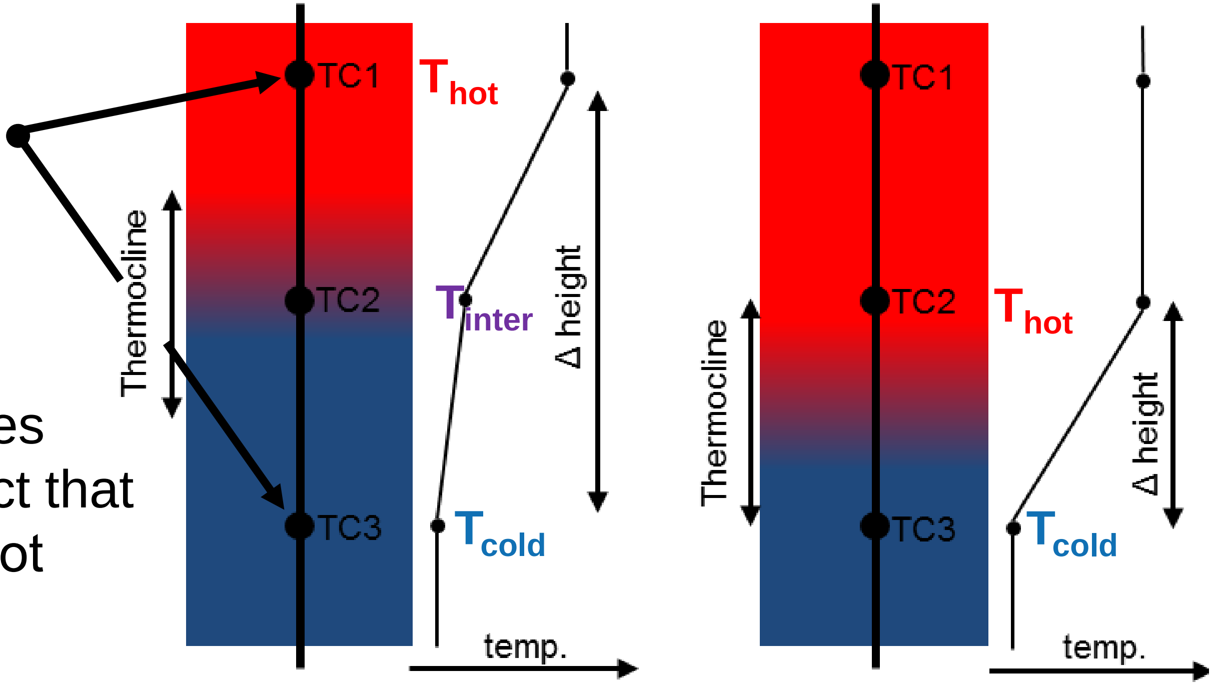
Qualitative Evaluation Method

Qualitative Evaluation

Method to Measure the Thickness of the Thermocline

- Temperature measured by the thermocouples gives indication about the separation of cold and hot fluid → Stratification
- Only measurement values at certain vertical locations available
- The position of the thermocline changes

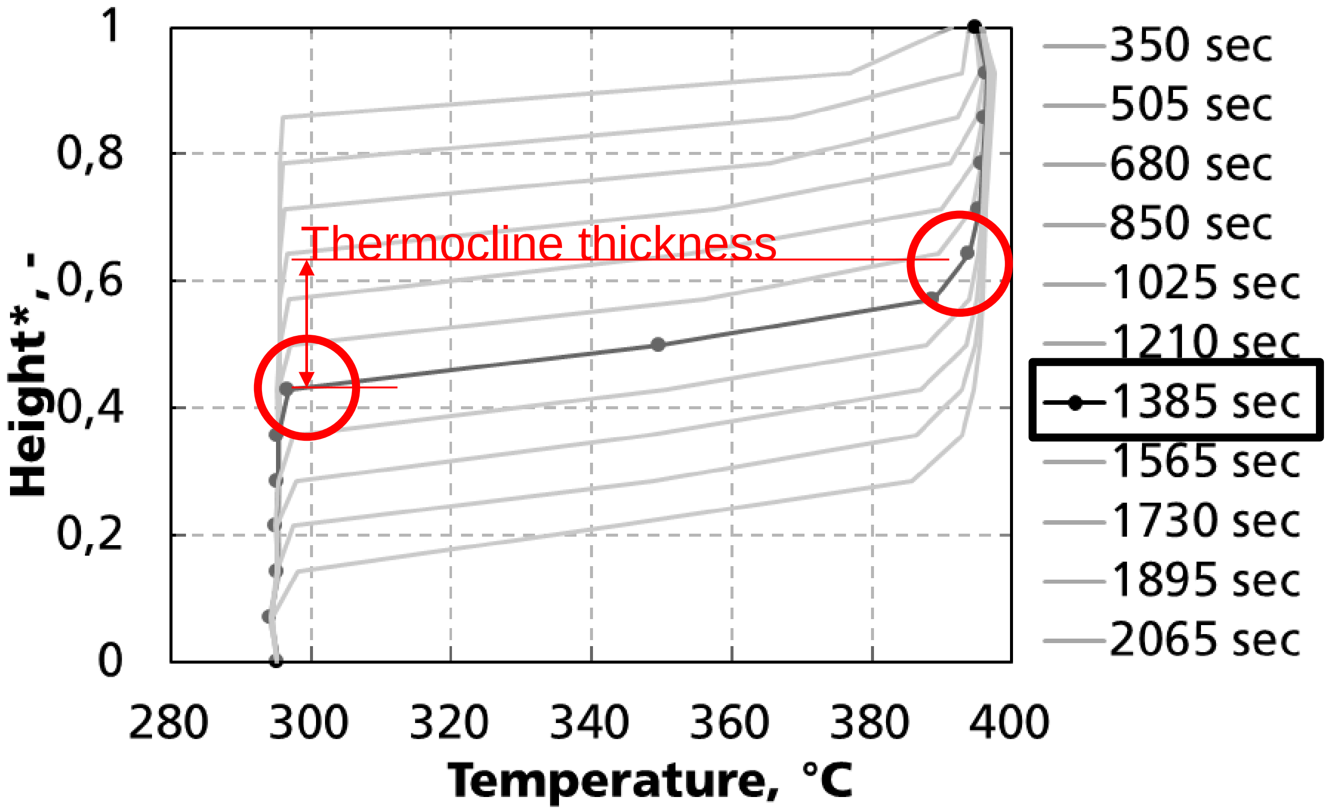
  → The derived thickness varies periodically, despite the fact that the "real" thickness does not change in this way



- Determination of thermocline thickness based on experimental data
  → more complex than from numerical data / simulation models
  → interpolation for thermocline thickness calculation at individual positions

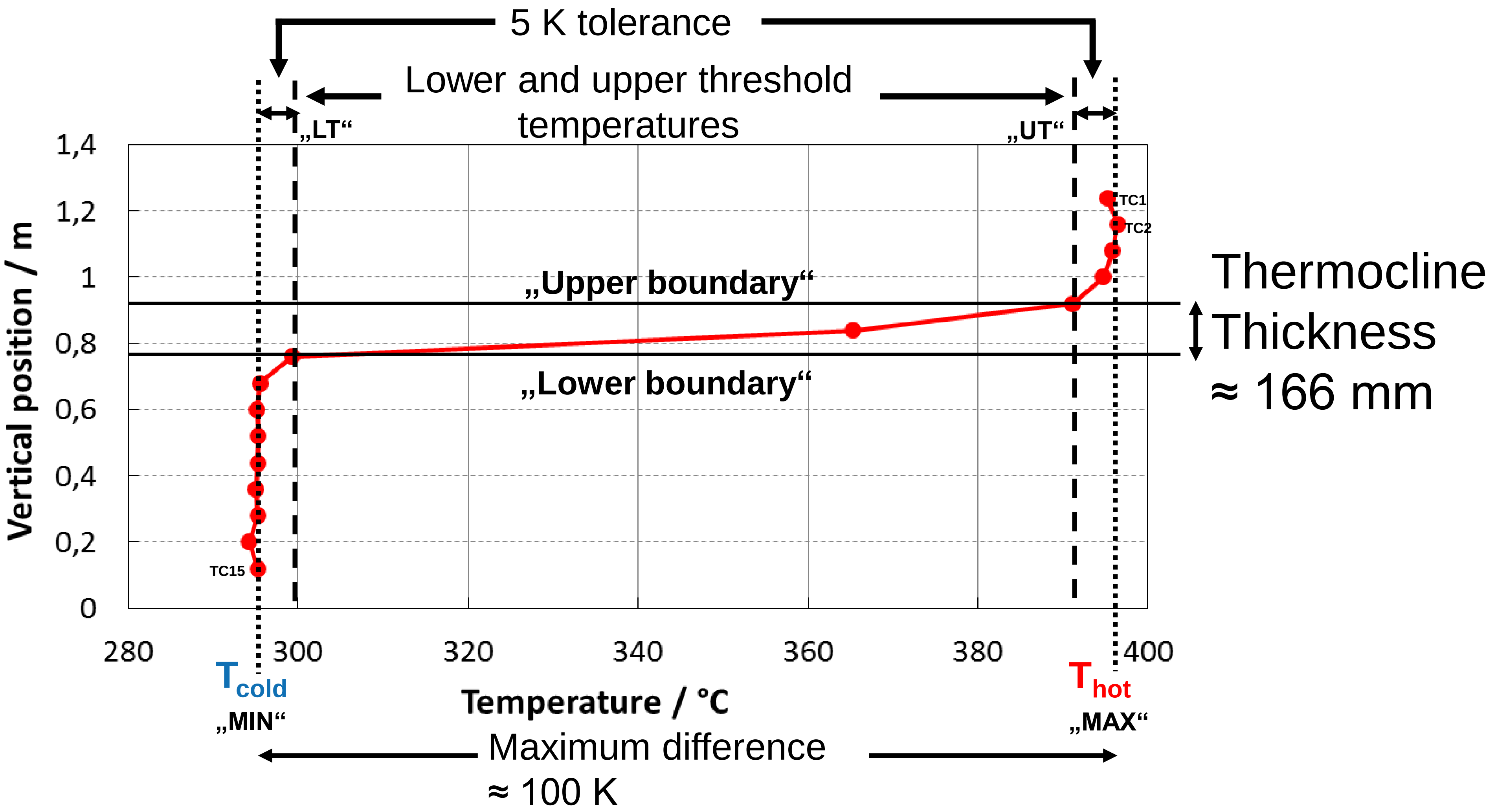
Qualitative Evaluation

Method to Measure the Thickness of the Thermocline



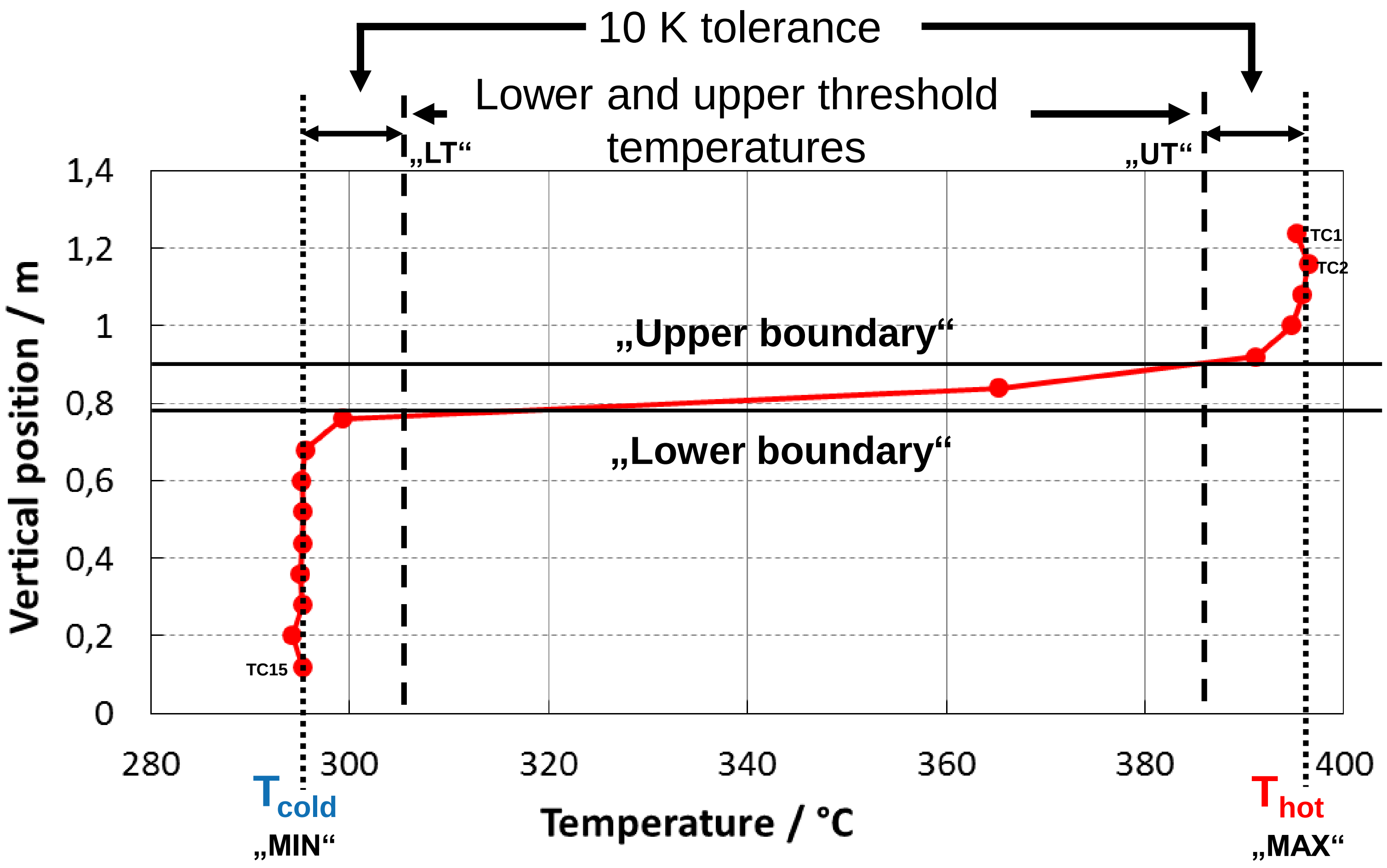
Qualitative Evaluation

Method to Measure the Thickness of the Thermocline



Qualitative Evaluation

Method to Measure the Thickness of the Thermocline

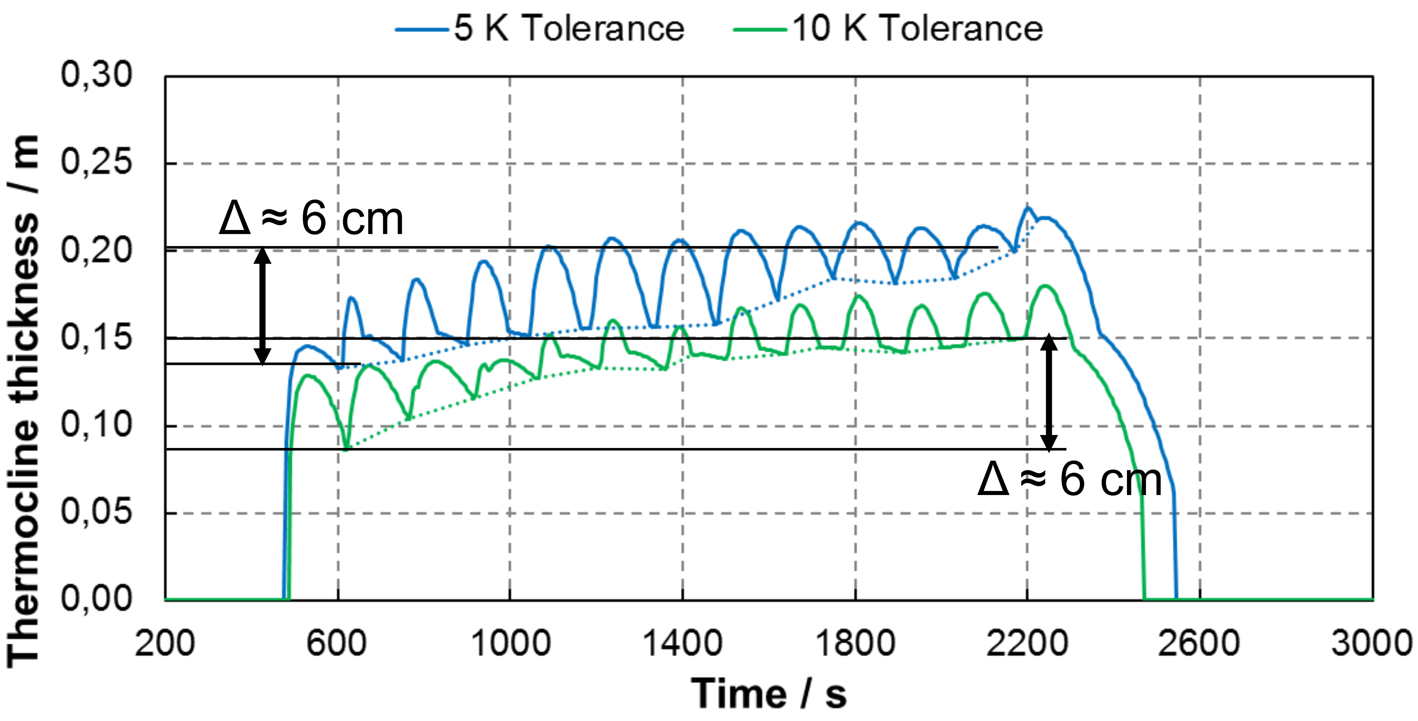


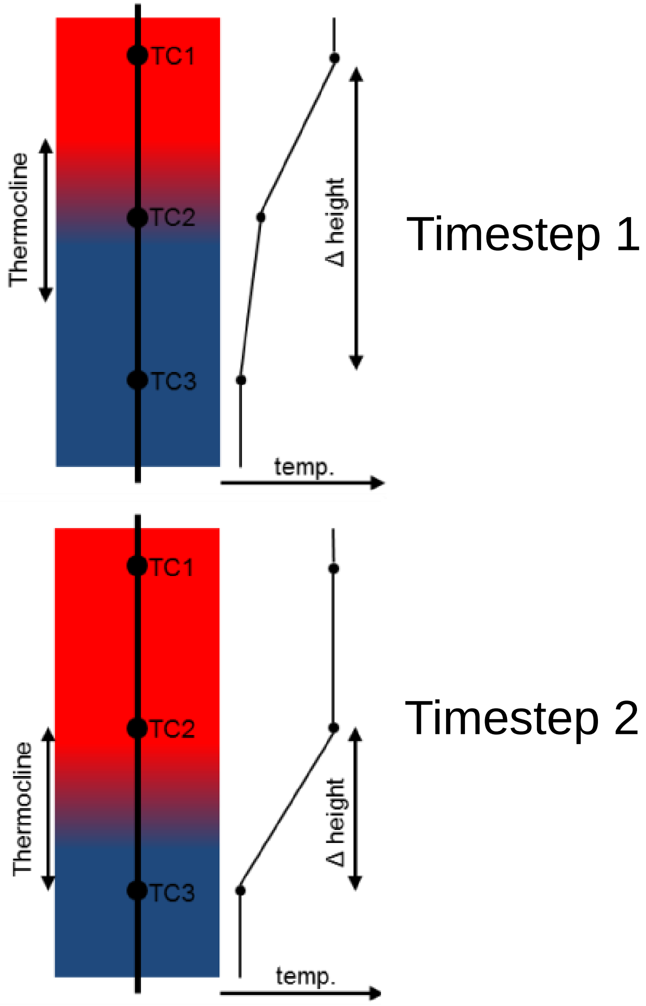
Thermocline Thickness ≈ 139 mm

Qualitative Evaluation Results

Qualitative Evaluation

Measurement Result of Thermocline Thickness





- TC thickness varies between 14 and 20 cm for 5 K tolerance (blue dotted line ---)
- .. and 9 and 15 cm for 10 K tolerance (green dotted line ---)
- → Thermocline thickness increases about 6 cm

Energetic Evaluation

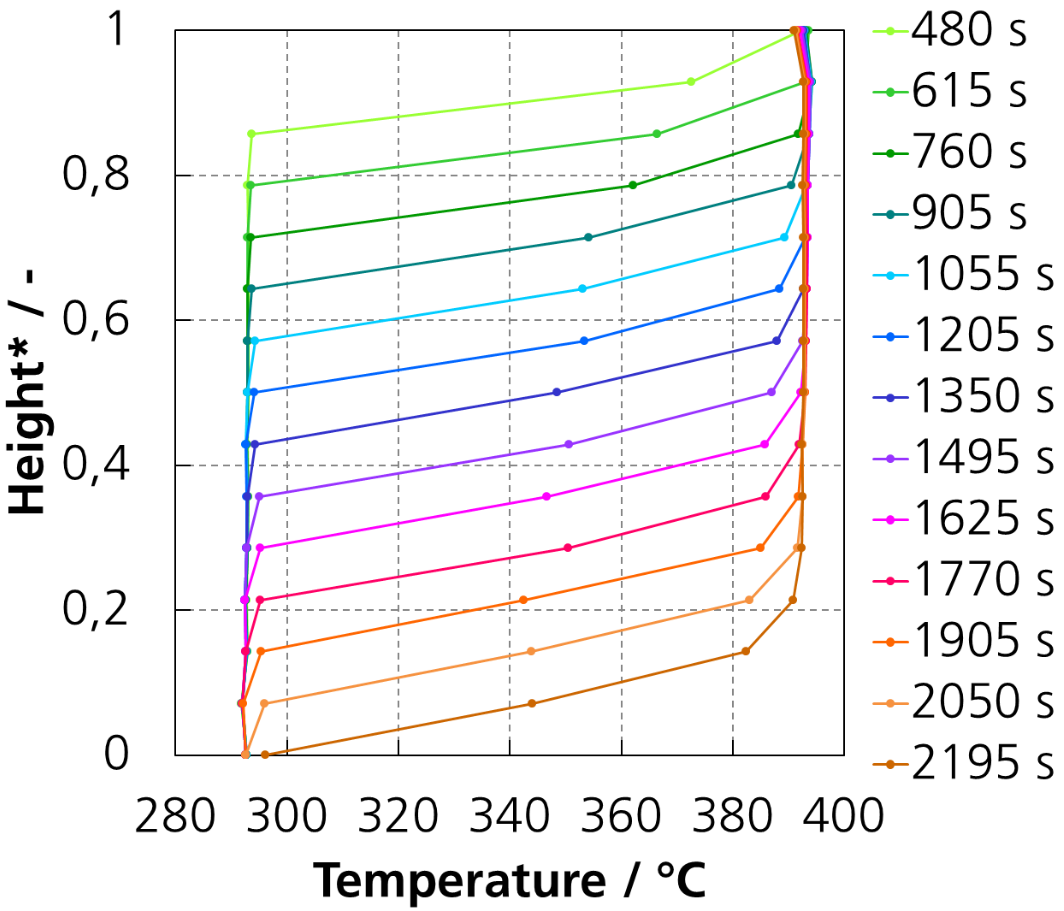
Energetic Evaluation
Approach

- Thermal power for charging and discharging of the storage by mass flow as well as inlet and outlet temperature
- Introduction of a boundary condition for charging / discharging:
  "Theoretical threshold temperature"
- Storage charging / discharging limited to outlet temperature of the storage
  - Charging: Maximum inlet temperature of the solar field
  - Discharging: Minimum inlet temperature of the power block
  - Remaining heat could be used (e.g. for freeze protection or preheating)
- Comparison of actual storage capacity (charging and discharging) with theoretical values

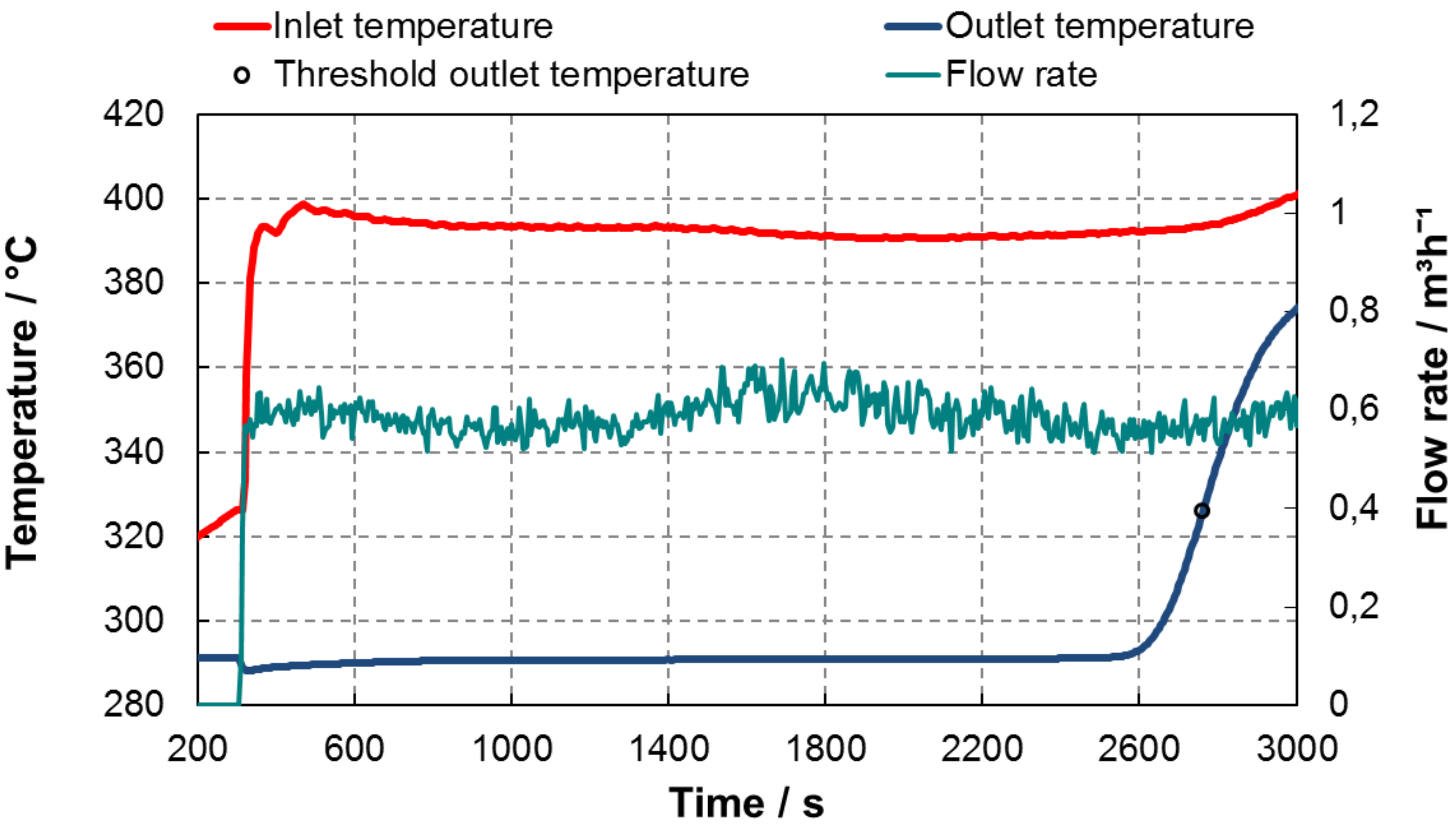
Energetic Evaluation

Charging of Storage

Parameter	Value	Unit
Average inlet temperature	392.3	°C
Average initial tank temperature	292.9	°C
Temperature difference	99.5	K
Theoretical thermal capacity	29.8	kWh
Threshold outlet temperature (t_{th})	326.0	°C
Thermal capacity at t_{th}	27.94	kWh
Utilization ratio	93.8	%
Average flow rate	0.59	m³ / h
Average charging power	38.2	kW



Energetic Evaluation
Charging of Storage



✓ Outlet temperature remains rather constant

Energetic Evaluation

Discharging of Storage

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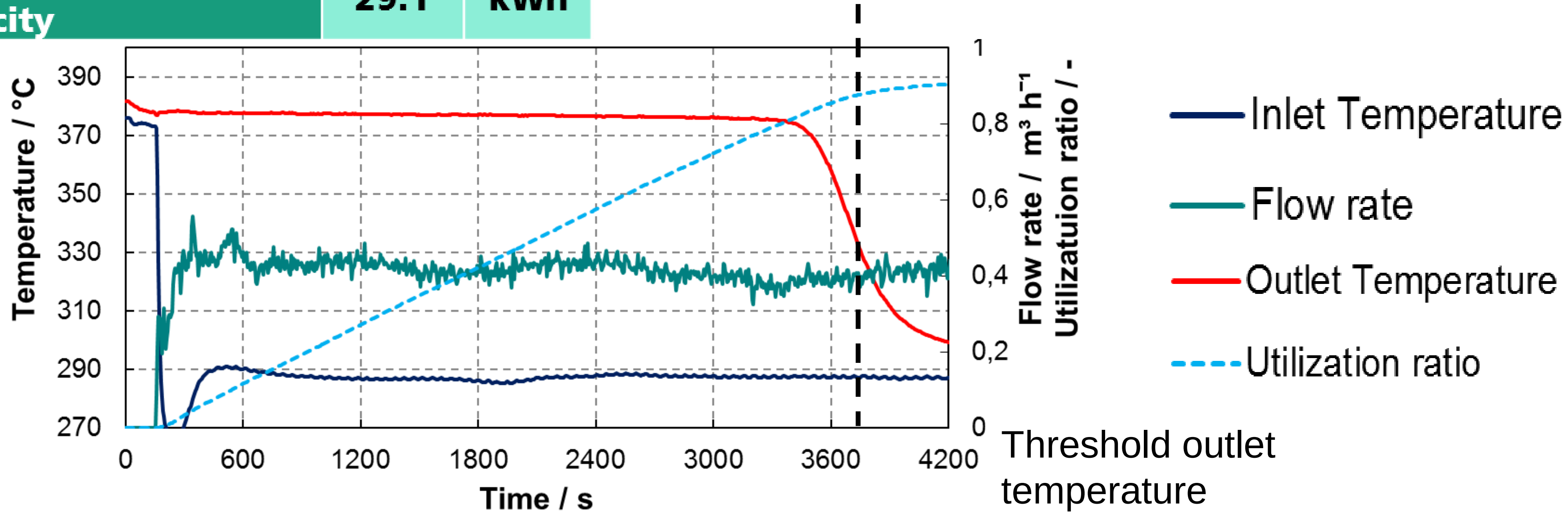
STAGE STE EERA

Parameter	Value	Unit
Average inlet temperature	287.0	°C
Average initial tank temperature	380.7	°C
Temperature difference	93.7	K
Theoretical thermal capacity	29.1	kWh

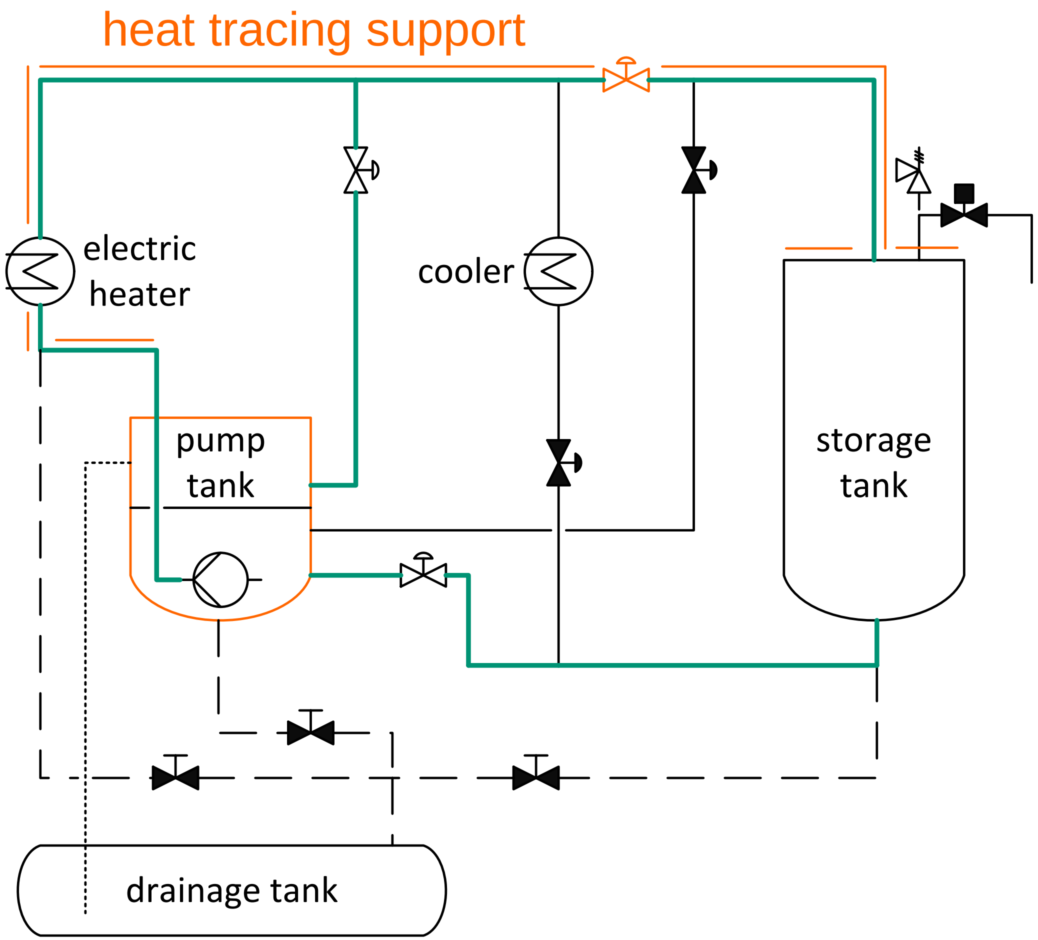
Parameter	Value	Unit
Threshold outlet temperature (t_{th})	349.5	°C
Thermal capacity at t_{th}	25.0	kWh
Utilization ratio	86.2	%
Average flow rate	0.42	m³ / h
Average discharging power	-26.0	kW



Conclusion & Outlook

Lessons Learned

- Heat tracing support for charging process
- Effect of heat loss during charging
- Good heat tracing equipment is essential in molten salt systems



Conclusion

- Demonstration of a stable outlet temperature of a thermocline storage with molten salt
  - → Good stratification
  - However, thermocline zone increases during charging / discharging
  - Design of diffusor and wall temperature management (for small prototype vessels) crucial for stratification
- Introduction of a method to determine the thickness of the thermocline zone at variable height positions despite fixed measurement points

Outlook

- Compare introduced evaluation method with other approaches and numerical models
  → refine approach
- Performance evaluation of consecutive charging / discharging cycles
- Increase of maximum temperature and thus the temperature difference
- Investigation of different salt mixtures
- Introduction and analysis of different filler materials using a packed-bed storage tank

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Thanks for Your Attention

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