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

Solar Facilities for the European Research Area

Thermal Energy Storage Performance Assessment

Pierre Garcia, CEA-LITEN

NETWORKING

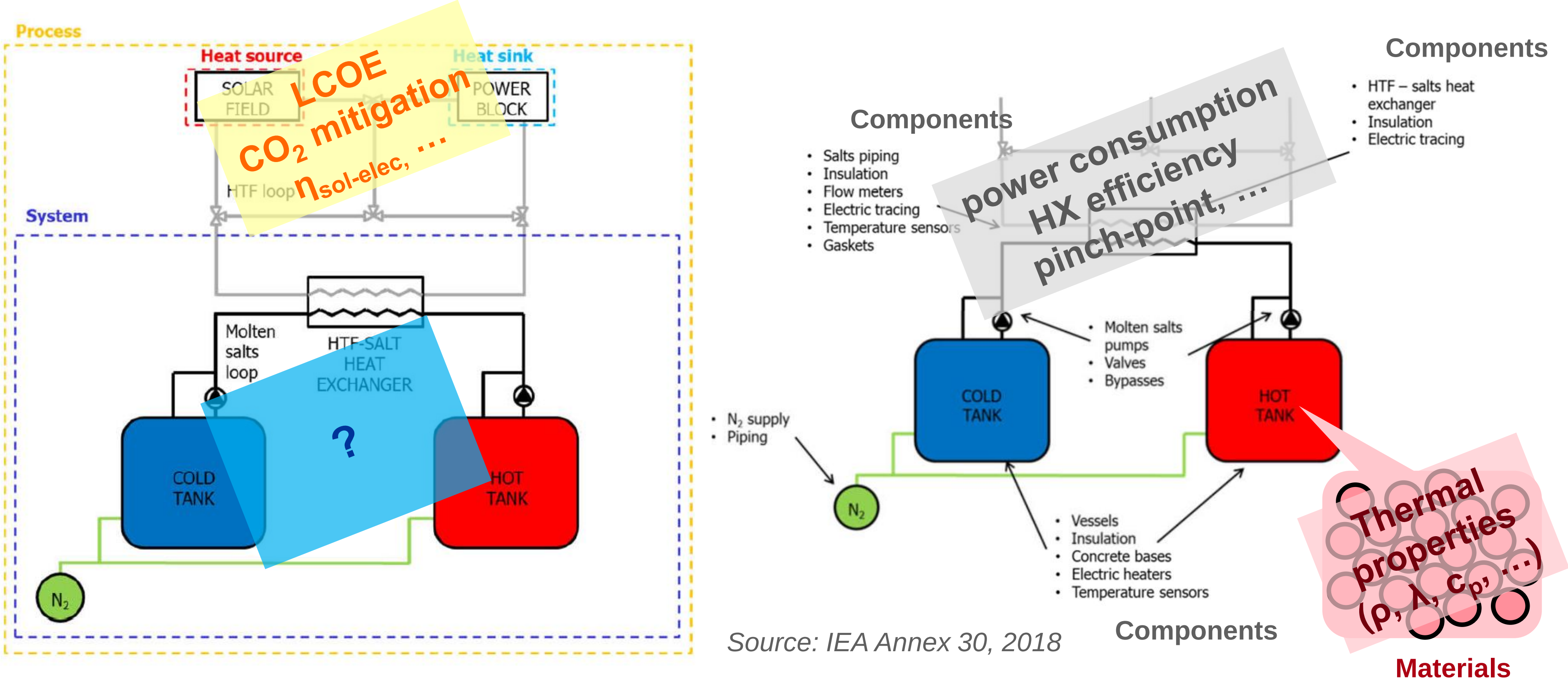
THIS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION’S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO **823802**

CONTENT

- Scope of this presentation
- KPI from the end-user perspective
- Technical performance indicators
- Case study: latent heat storage with PCM
- Durability issues

SCOPE

- Performance indicators are required everywhere
  - In research calls for proposal,
  - In CSP plants invitations to tender,…
- From process level to material level



LCOE
CO_2 mitigation
$\eta_{sol-elec}$, …

?

power consumption
HX efficiency
pinch-point, …

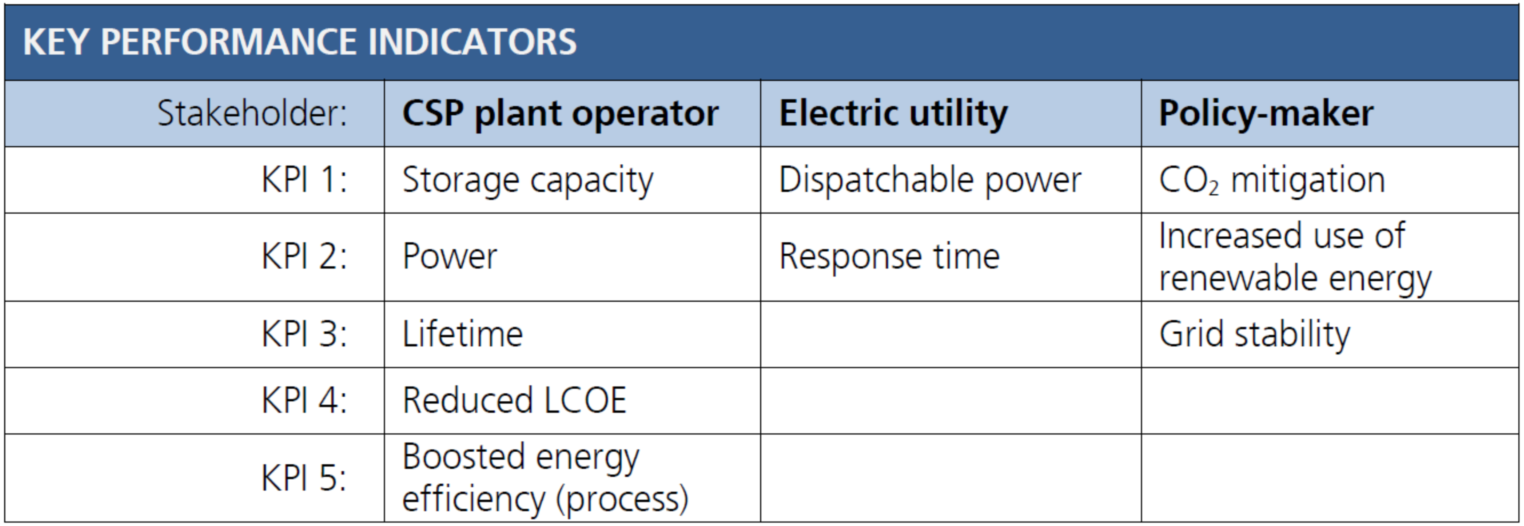
Thermal properties (ρ, λ, c_p, …)

Source: IEA Annex 30, 2018

- This presentation deals with performance indicators at **system** level

KEY PERFORMANCE INDICATORS

- Depend on the stakeholder perspective

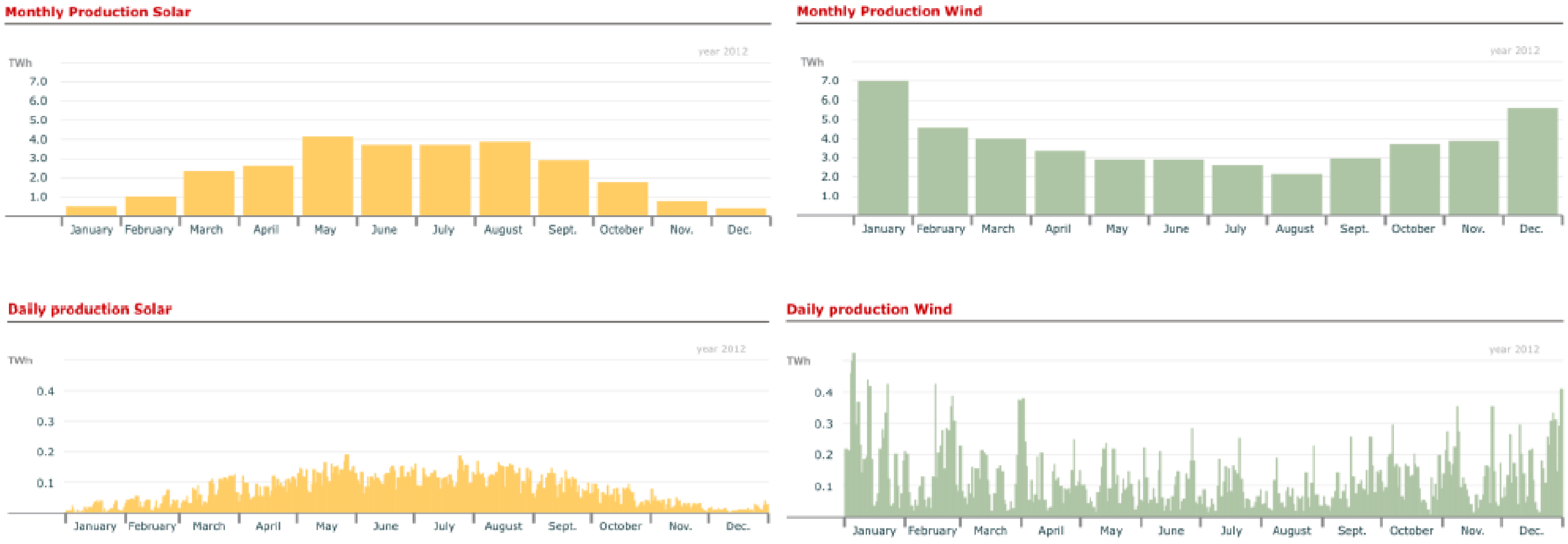


KEY PERFORMANCE INDICATORS			
Stakeholder:	**CSP plant operator**	**Electric utility**	**Policy-maker**
KPI 1:	Storage capacity	Dispatchable power	CO_2 mitigation
KPI 2:	Power	Response time	Increased use of renewable energy
KPI 3:	Lifetime		Grid stability
KPI 4:	Reduced LCOE		
KPI 5:	Boosted energy efficiency (process)		

KPI selection per stakeholder for integration of TES into a CSP plant (IEA Annex 30, 2018)

FROM THE UTILITY PERSPECTIVE…

- TES make CSP production **Dispatchable**
  - Dispatchable generation = sources of electricity that can be delivered on demand to grid operators
  - “Peak-shaving” ability (time-shifted operation)
  - Reduced need for peak-load fossil generating capacities



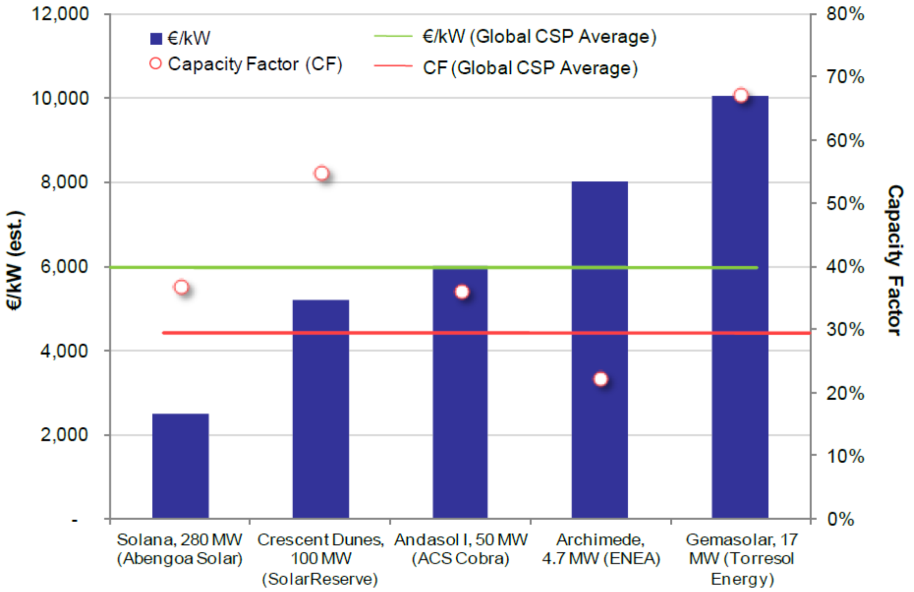
PV and wind power production in Germany (Burger, 2013)

FROM THE PLANT OPERATOR PERSPECTIVE…

- TES make CSP production **Reliable**
  - Increases plant utilization and capacity factor Fc

$$F_c = \frac{\text{power output during time t (MWh)}}{\text{t} \times \text{rated power (MW)}}$$

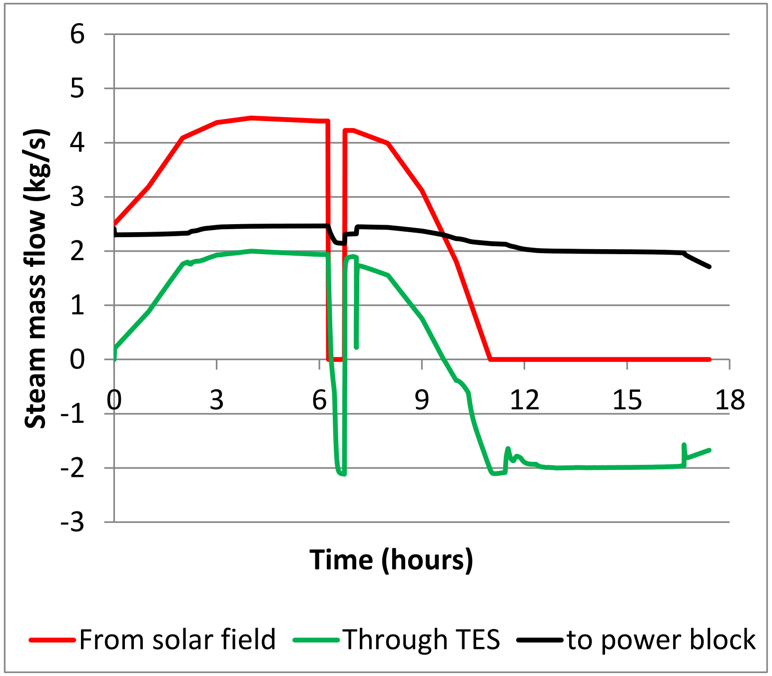
- Improves plant controllability and operability
  - expanding the range of possible operating strategies
- If adequately designed, improves
  - the value of the produced electricity
  - the profitability of the project



Reference capital costs and capacity factors of CSP plants with TES (Emerging Energy Research, 2010)

FROM THE GRID OPERATOR PERSPECTIVE…

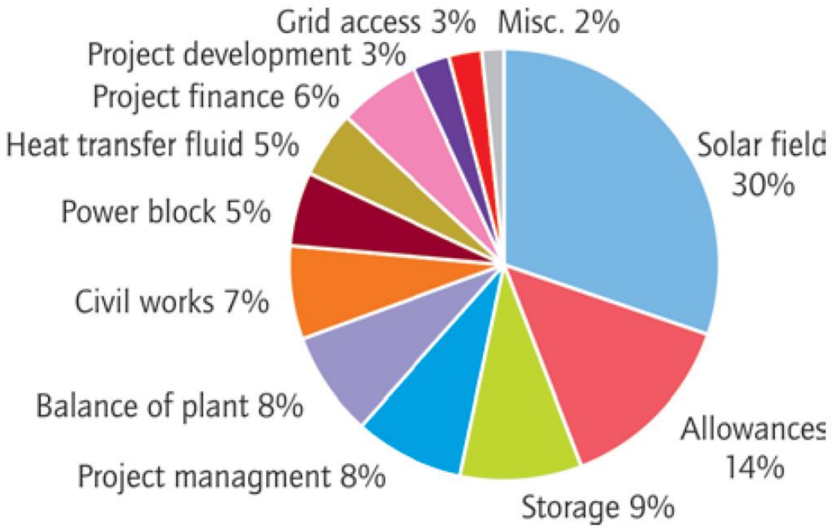
- TES make CSP production **Stable**
  - Smoothes load variation of the power block
    - Power generation kept almost constant during cloud transients
  - Part load operation and start-stop cycles are reduced
    - Improving thermal cycle efficiency
  - Extends lifetime of equipment
    - Reducing the number of start-stop cycles



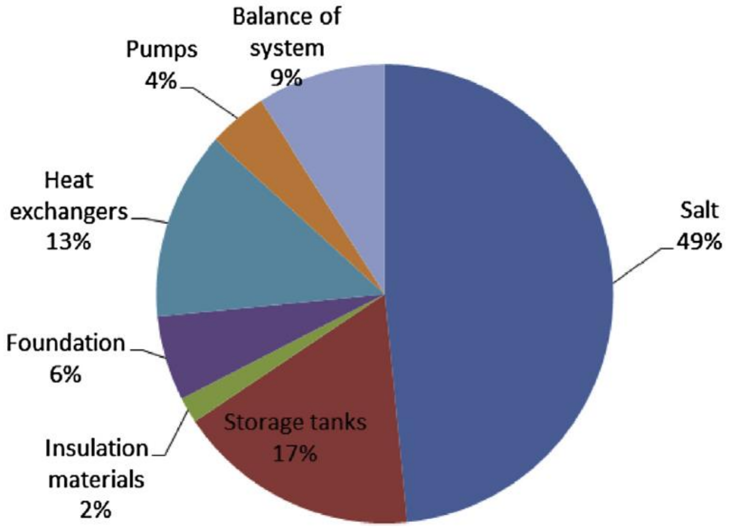
Simulated steam mass flow in a DSG plant with TES (CEA)

ECONOMIC PERFORMANCE INDICATORS

- Storage costs



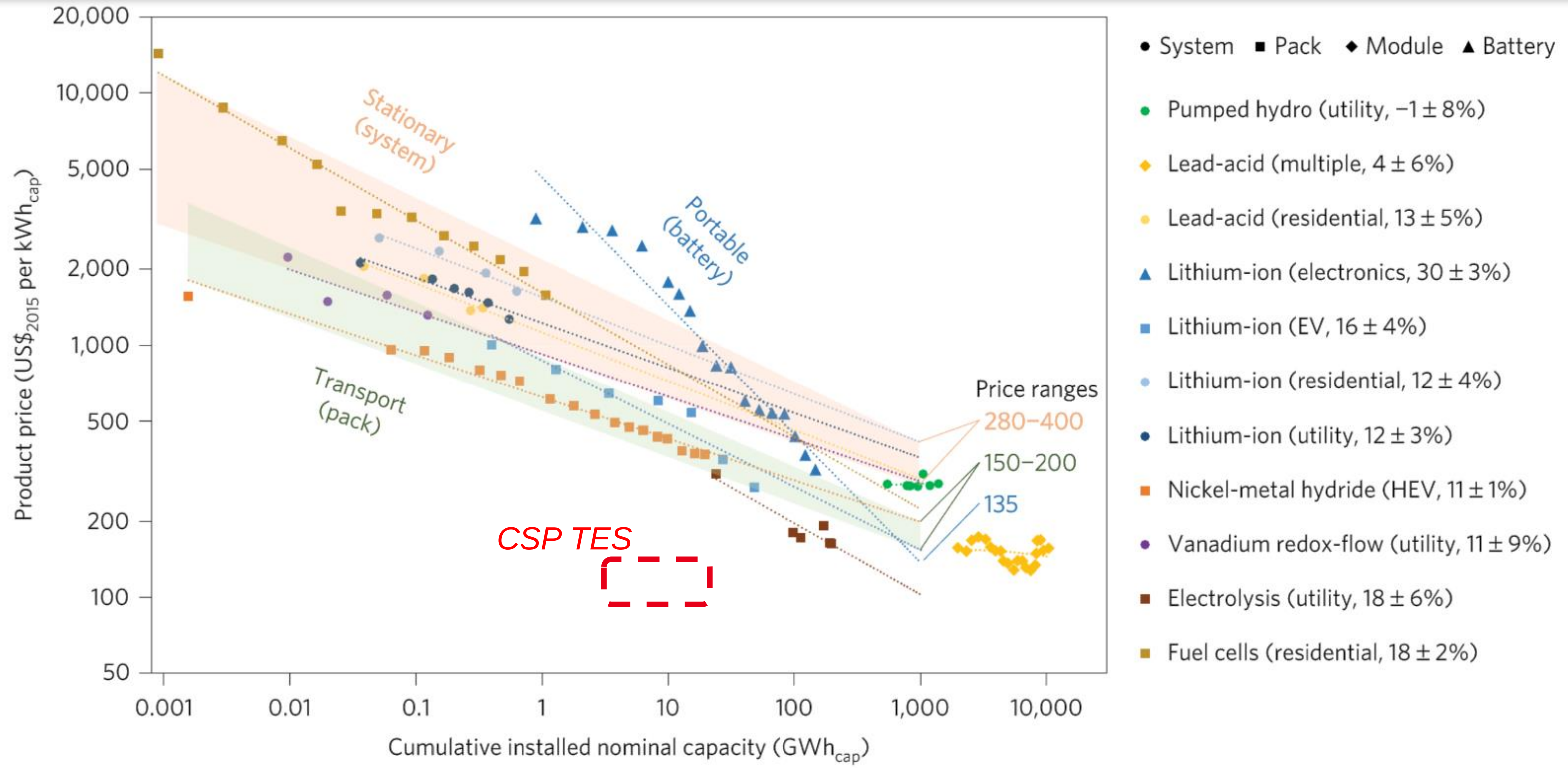
Investment costs breakdown of a 50 MWe PTC plant with indirect 7-hour storage (Source: IES STE roadmap 2010)



Detailed breakdown of the TES system (Source: IRENA 2012)

ECONOMIC PERFORMANCE INDICATORS

- Storage costs
  - From 20 to 33 USD/kWh$_{th}$ (NREL 2017) → about 100 USD/kWh$_{el}$
  - Lower than the other energy storage solutions



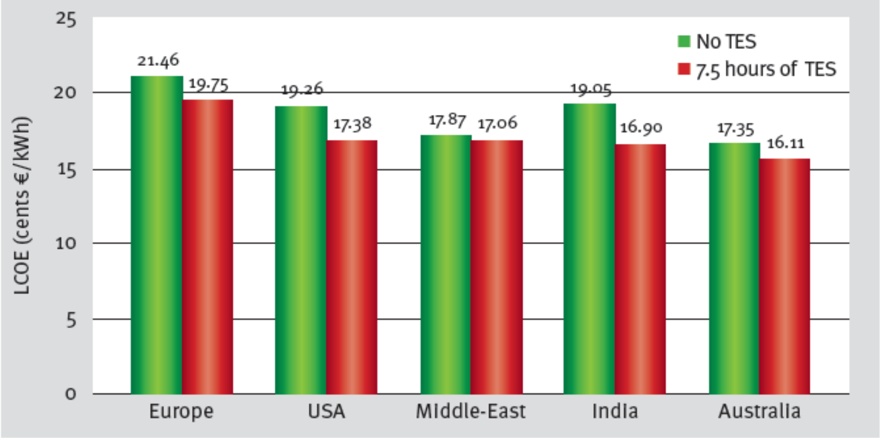
Future cost of electrical energy storage technologies at 1 TWh cumulative capacity (Schmidt, 2017)

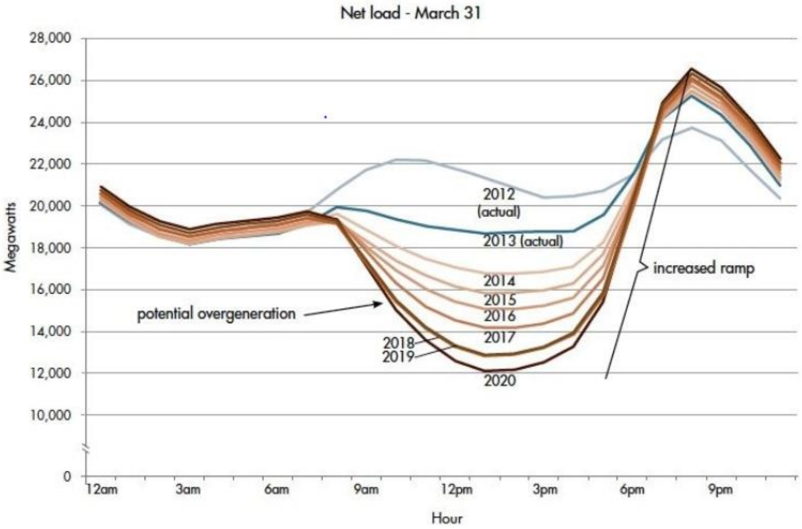
ECONOMIC PERFORMANCE INDICATORS

- Levelized Cost Of Electricity
- TES costs have low influence on LCOE
  - Extra investments → more $$
  - Extra production → more kWh

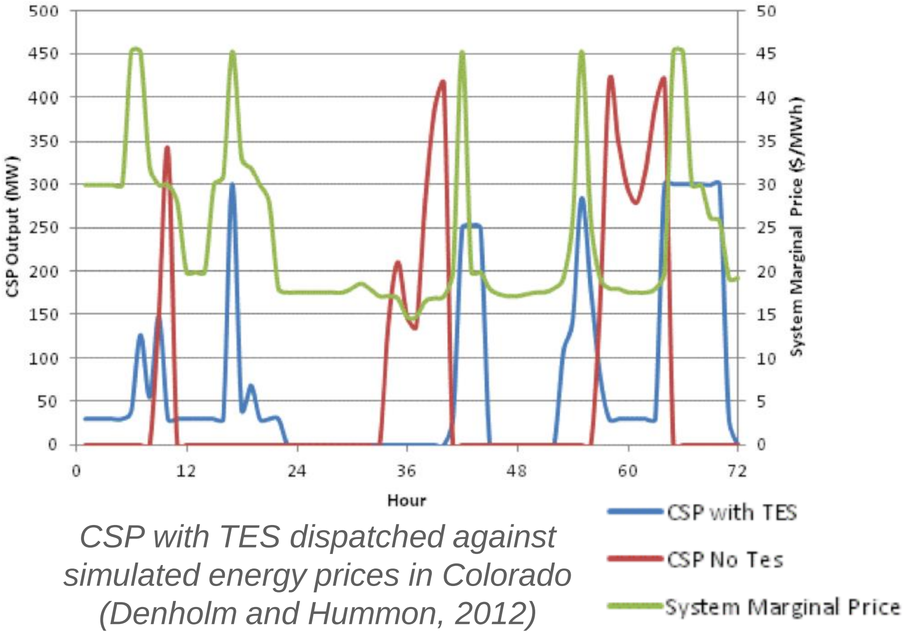
- TES Value
  - **+ \$6/kWh$_e$** compared to PV under 40% renewable penetration in California (NREL, 2017)

(NREL, 2017)





The Duck Curve (California Independent System Operator)



CSP with TES dispatched against simulated energy prices in Colorado (Denholm and Hummon, 2012)

TECHNICAL PERFORMANCE INDICATORS
TES SYSTEM

TECHNICAL PERFORMANCE INDICATORS

- Reference documents
  - IEE standard (draft)
  - AENOR standard (draft)
  - ASHRAE standards
  - Handbooks SFERA and SFERA III
  - SolarPACES Task III TES WG
  - Report of IEA ECES Annex 30

About 30 indicators proposed
Different definitions
Additional basic definitions needed!

- Basic principles
  - Measurements always done in HTF side
    - HTF may be different from the storage medium
  - Initial and final state are characterized by enthalpy levels
    - Temperature levels are only applicable to sensible storage

#	Indicators
1	Storage capacity
2	Utilization rate
3	Nominal Thermal power
4	Thermal losses
5	Storage efficiency
6	Stratification index degradation

+ Durability aspects

#1 - STORAGE CAPACITY (SC)

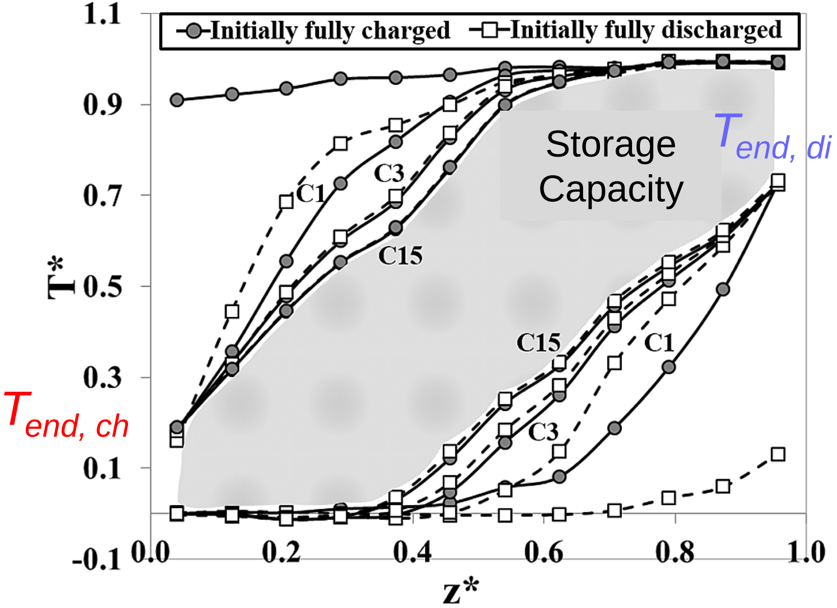
- Definition
  - Amount of **useful thermal energy** that the thermal storage system can supply by **full discharge** under certain starting and ending conditions.

$$SC = \int_{initial\ conditions}^{full\ discharge\ conditions} [\dot{m}(h_{outlet} - h_{in}]dt$$

Comments

- A charge capacity can also be defined ($SC_{ch} \neq SC$)
- SC depends on the initial conditions in the storage

Having a given value of $h_{HTF,out}$ does not ensure to have the same SC / SC_{ch}



Influence of storage initial state on thermocline cyclic behavior; Temperature profiles; "Cn" refers to the nth repetition of the cycle (Bruch, 2017)

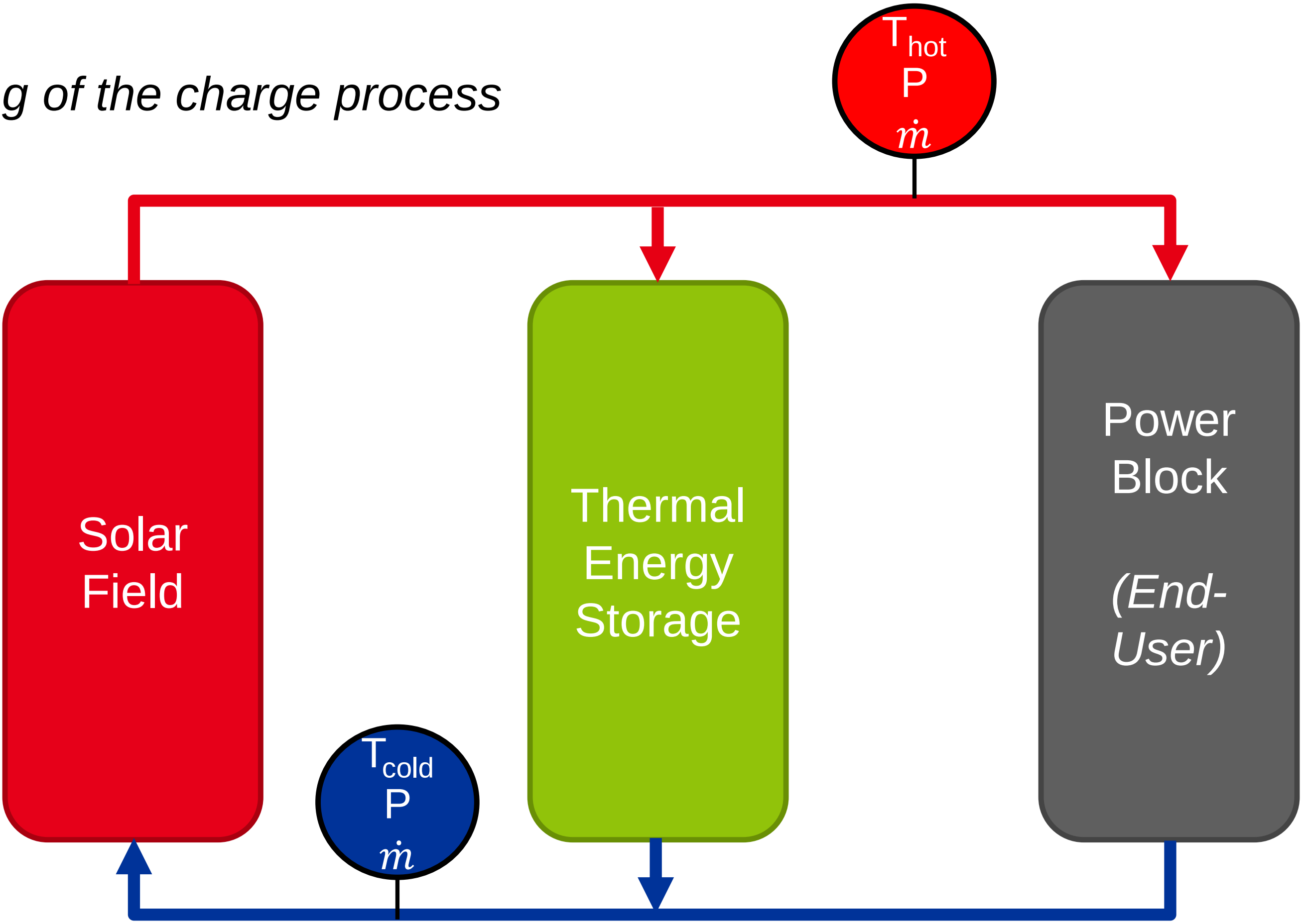
- $$\text{Storage level} = \frac{SC_{present\ conditions}}{SC_{nominal}}$$

- Test procedures (to assess $SC_{nominal}$)
  - Option A: Initial conditions with a given uniform temperature in the storage media
  - Option B: After a given number of charge-discharge cycles

END OF CHARGE CRITERIA

- **Full charge state**: after a charge process made under nominal conditions
  - End of full charge is obtained when the TES outlet HTF flow reaches the maximum solar field inlet conditions.

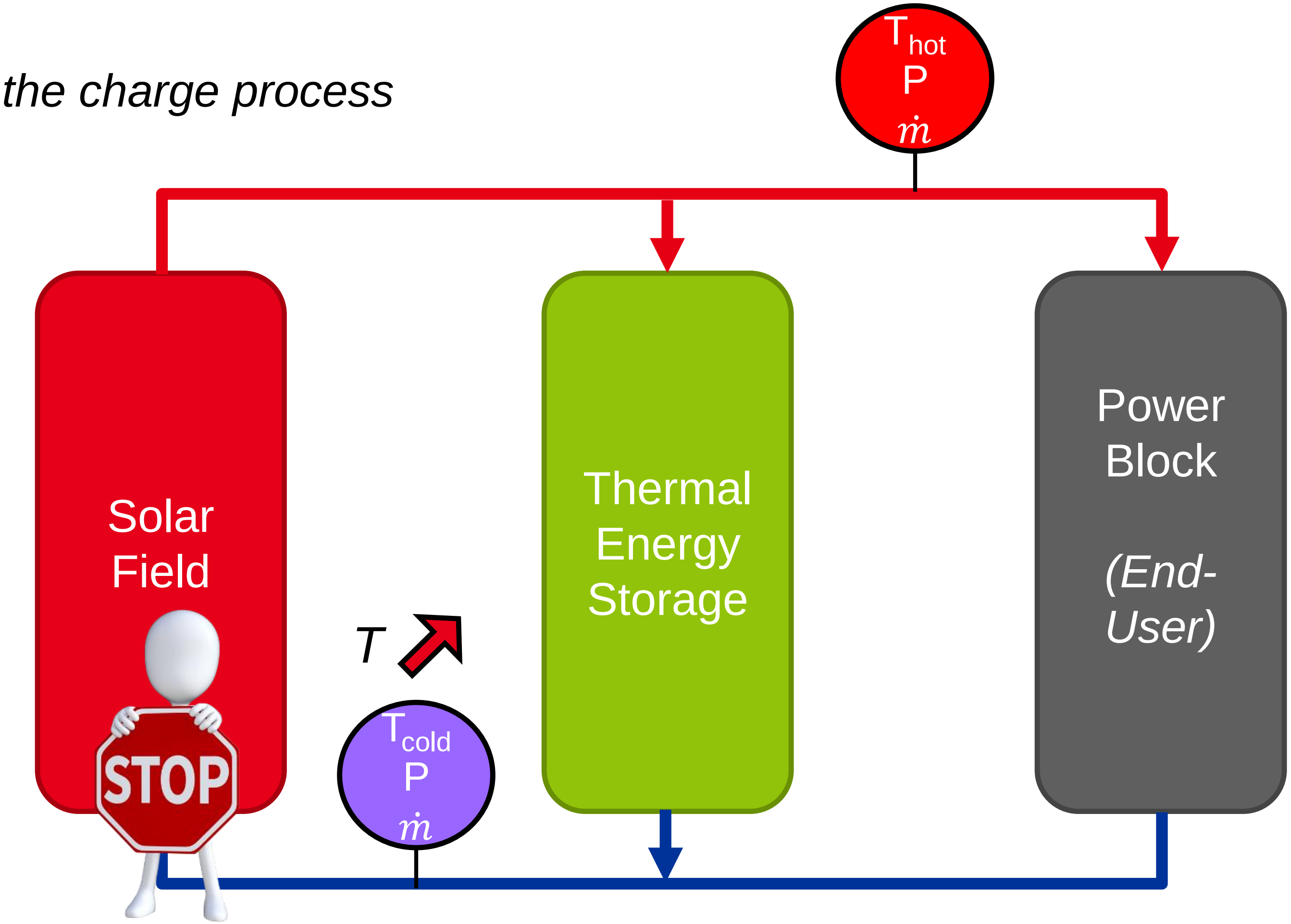
Beginning of the charge process



END OF CHARGE CRITERIA

- **Full charge state**: after a charge process made under nominal conditions
  - End of full charge is obtained when the TES outlet HTF flow reaches the maximum solar field inlet conditions.

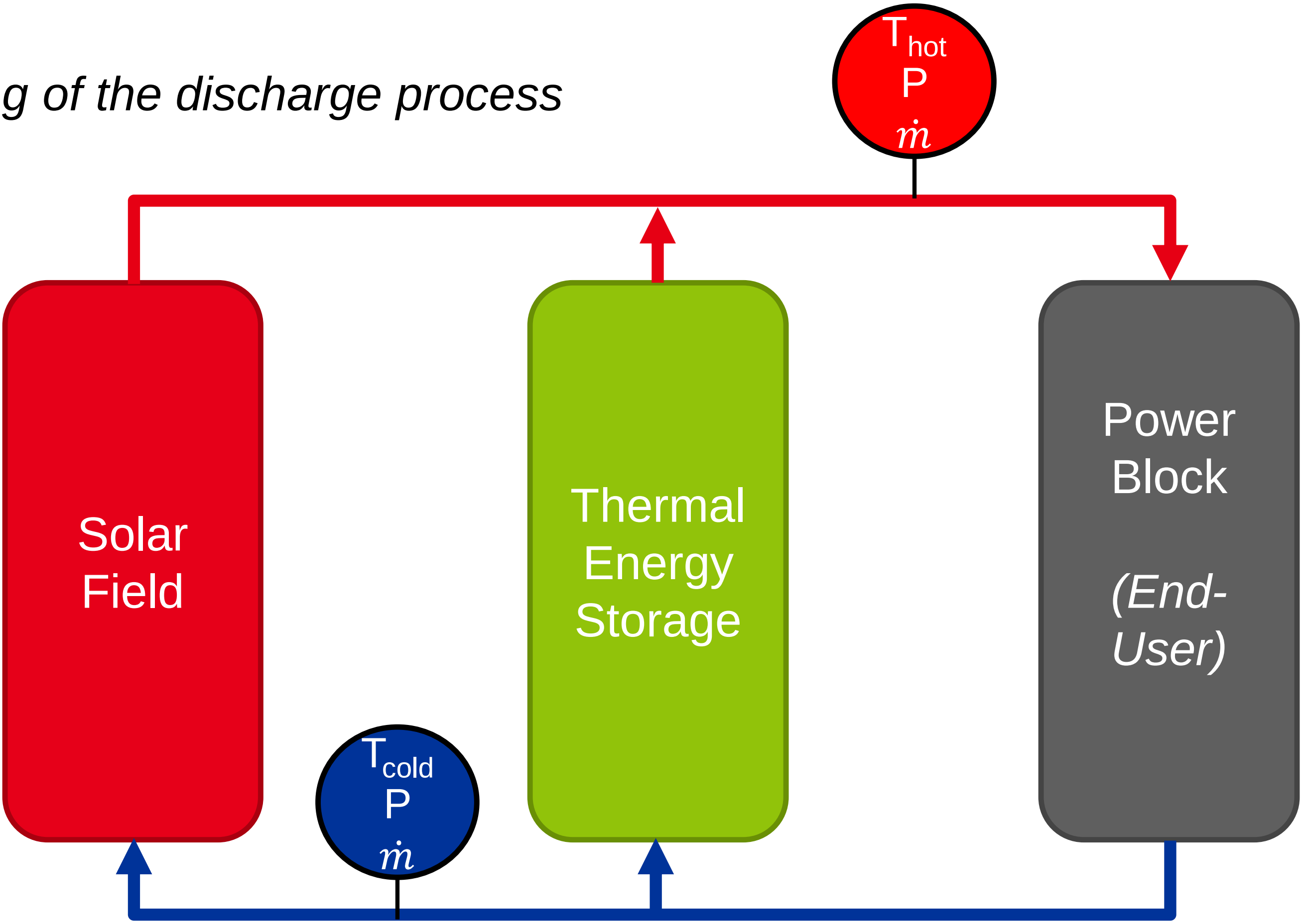
End of the charge process



END OF DISCHARGE CRITERIA

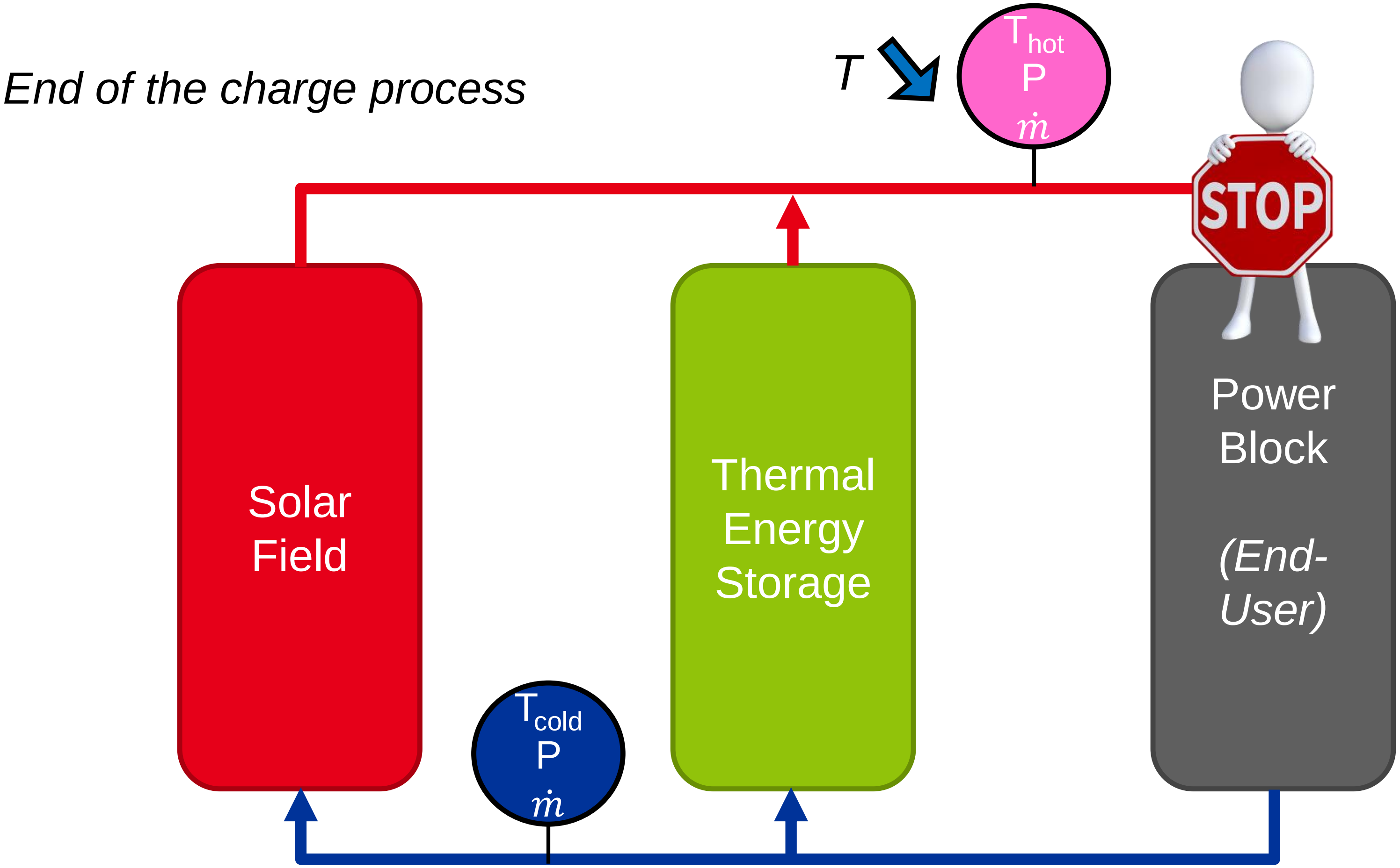
- **Full discharge state**: after a discharge process made under nominal conditions
  - End of full discharge is obtained when the TES outlet HTF flow reaches the minimum power block inlet conditions.

Beginning of the discharge process



END OF DISCHARGE CRITERIA

- **Full discharge state**: after a discharge process made under nominal conditions
  - End of full discharge is obtained when the TES outlet HTF flow reaches the minimum power block inlet conditions.

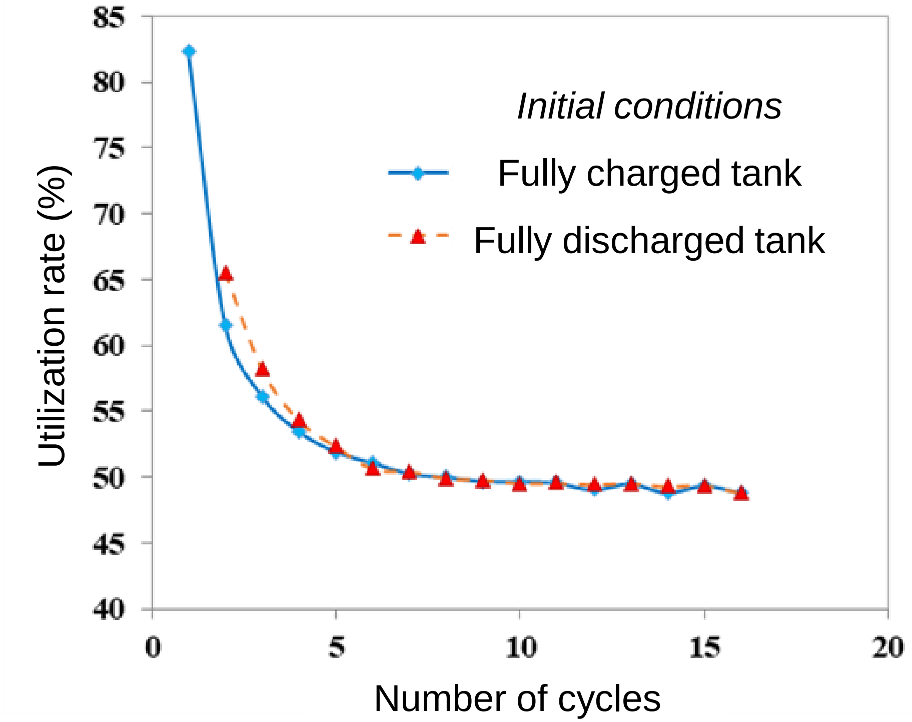


#2 - UTILIZATION RATE

- Definitions
  - **Theoretical storage capacity (SC_{th})**: amount of energy that can be accumulated by the storage medium
  - $SC_{th} = \sum_{storage\ materials} m\,(h_{charge,,nominal} - h_{discharge,nominal})$
  - $\textbf{Utilization Rate} = \frac{SC}{SC_{th}}$

- Comments
  - Like SC, UR depends on TES initial state and evolves from cycle to cycle.
  - Alternative definition for sensible heat storage (Bruch 2017):

$$UR = \frac{\left(\int_{L_{tank}} T dz\right)\Big|_{charge} - \left(\int_{L_{tank}} T dz\right)\Big|_{discharge}}{\left(T_{charge} - T_{discharge}\right) L_{tank}}$$



Influence of storage initial state on thermocline cyclic behavior: Utilization rate

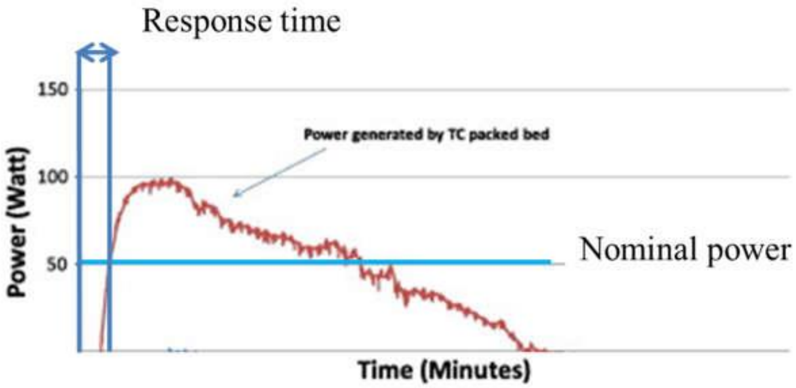
- Test procedure
  - SC_{th} is calculated from literature material characteristics.
  - The utilization rate can be evaluated from any storage capacity test.

#3 - NOMINAL / DESIGN THERMAL POWER

- Definition
  - P_{nom} is the nominal thermal power of the discharge. If relevant for the TES system, the nominal power of the charge ($P_{nom, ch}$) can be indicated next to the discharge value, clearly stating which belongs to charge and which to discharge.

- Comments
  - It is a mean value all over the discharge process
  - P_{nom} can be limited by
    - The maximum mass flow rate of the storage pumps
    - The maximum allowable pressure drop in the TES system
    - The heat transfer rate between the HTF and the storage material (ex PCM)
  - Directly linked to the nominal discharging time ($t_{discharge}$) and charging time (t_{charge})
    - $t_{discharge} = \frac{SC}{P_{nom}}$ & $t_{charge} = \frac{SC_{ch}}{P_{nom,ch}}$

- Test procedure
  - P_{nom} can be estimated from SC and $t_{discharge}$ under nominal discharge conditions



#4 - THERMAL LOSSES

- Definition
  - Energy lost by the thermal storage system during time "t" from the instant at which it is at storage level A, without charging or discharging.

- Comments
  - Thermal losses can hardly be extrapolated from small to large systems.
  - Difficult to estimate
  - Order of magnitude:
    - A few degrees decrease per hour for lab-scale TES
    - A few degrees decrease per day for industrial-scale TES

- Test procedures (examples)
  - Isothermal test
    - Losses offsetting with heat tracing
    - No fluid flow
  - Energy balance at constant temperature
    - Balance between inlet and outlet enthalpies at constant inlet conditions after temperature stabilization
  - Comparison between two standardized charging-discharging tests
    - With and without idle time between end of charge and beginning of discharge

#5 - STORAGE EFFICIENCY

- Definition
  - In consecutive charge and discharge: $$\eta_{TES} = \frac{E_{discharge}}{E_{charge}}$$
  - When considering full discharge conditions: $$\eta_{TES} = \frac{SC}{SC_{ch}}$$

- Comments
  - η_{TES} depends on TES initial state and varies from cycle to cycle in case of repetitive cycles.
  - This is a 1st law of thermodynamics approach.
    - Energy quality (exergy) degradation is not taken into account.

- Test procedure
  - Derived from SC and SC_{ch} values obtained from consecutive charge and discharge cycles

#6 - STRATIFICATION INDEX (1/2)

- Definition
  - Indicates the degree of thermal stratification in a storage device.
  - Generated entropy ΔS can be a representative value of the thermal stratification

$$\Delta S_{fully-mixed} > \Delta S_{real} > \Delta S_{stratified}$$

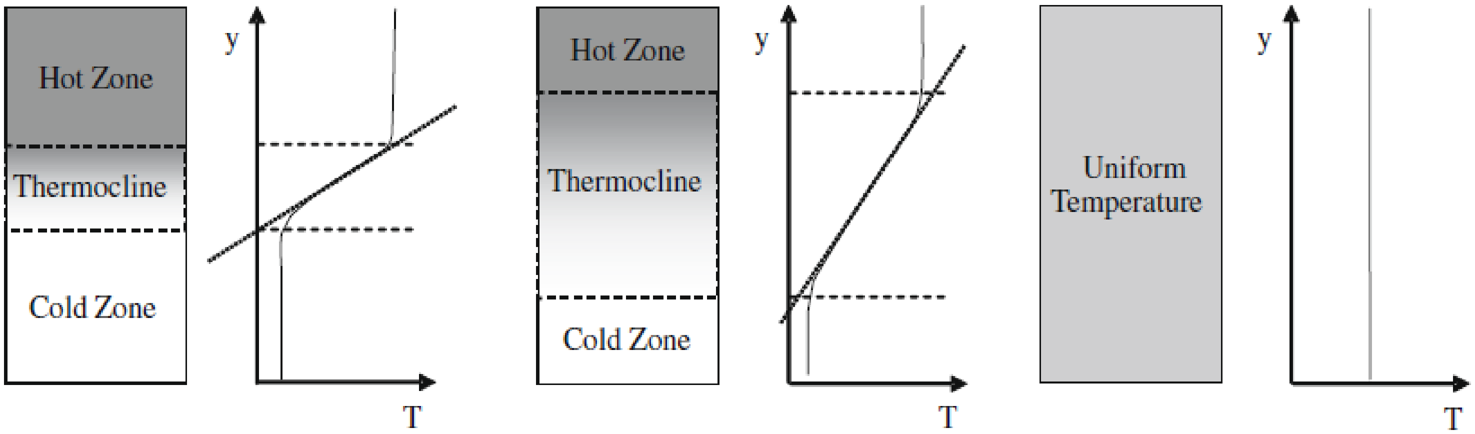
  - No agreed definition for this concept

- Comments

Only for thermocline or regenerative storage

Measured on storage media side

  - Thorough instrumentation of the tank is needed

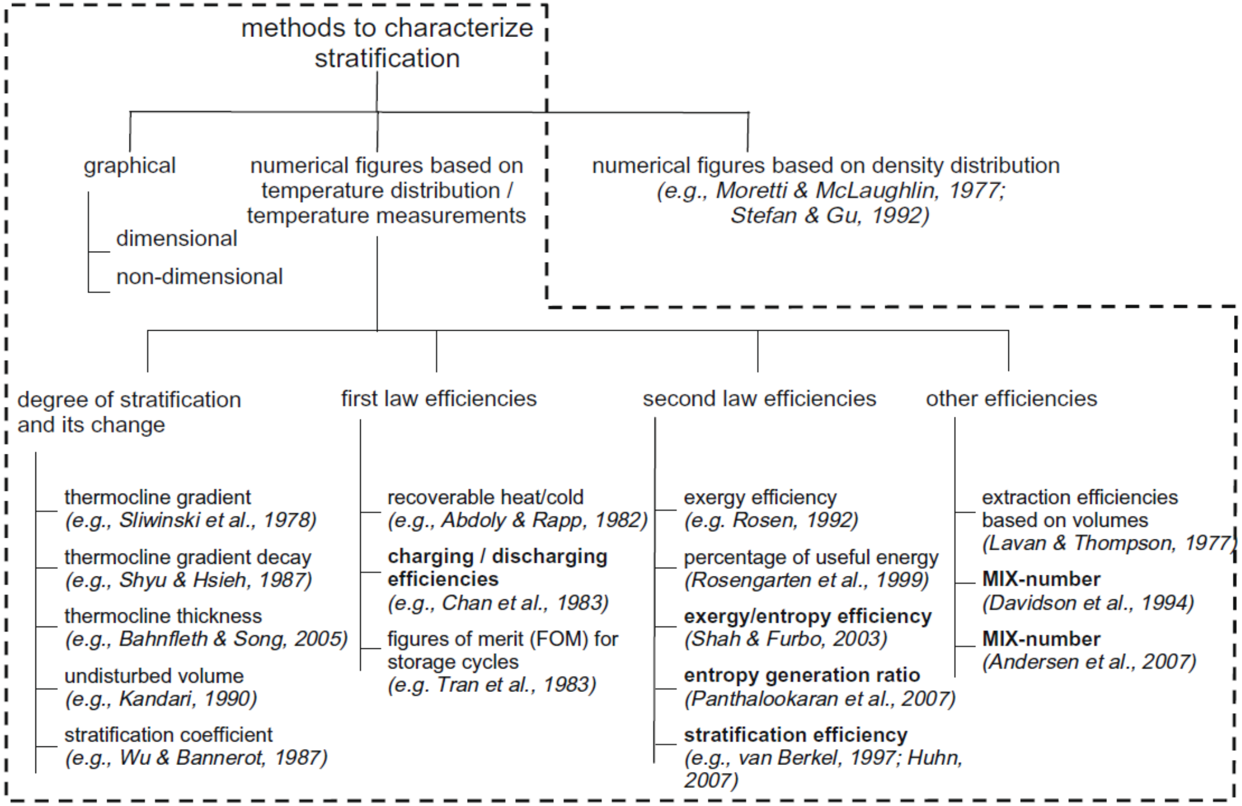


very stratified *moderately stratified* *fully-mixed.*

Different stratification degrees in a tank with the same energy content (Haller et al., 2009)

#6 - STRATIFICATION INDEX (2/2)

- Possible test procedures
  - Thermocline thickness evaluation (Bahnfleth, 2005)
  - MIX-number (Andersen, 2009)
  - Stratification efficiency (Huhn 2007, Haller 2010): $\eta_{strat} = 1 - \frac{\Delta S_{irr*}^{exp}}{\Delta S_{irr*}^{mix,0}}$



methods to characterize stratification

- graphical
  - dimensional
  - non-dimensional
- numerical figures based on temperature distribution / temperature measurements
  - degree of stratification and its change
    - thermocline gradient *(e.g., Sliwinski et al., 1978)*
    - thermocline gradient decay *(e.g., Shyu & Hsieh, 1987)*
    - thermocline thickness *(e.g., Bahnfleth & Song, 2005)*
    - undisturbed volume *(e.g., Kandari, 1990)*
    - stratification coefficient *(e.g., Wu & Bannerot, 1987)*
  - first law efficiencies
    - recoverable heat/cold *(e.g., Abdoly & Rapp, 1982)*
    - **charging / discharging efficiencies** *(e.g., Chan et al., 1983)*
    - figures of merit (FOM) for storage cycles *(e.g. Tran et al., 1983)*
  - second law efficiencies
    - exergy efficiency *(e.g. Rosen, 1992)*
    - percentage of useful energy *(Rosengarten et al., 1999)*
    - **exergy/entropy efficiency** *(Shah & Furbo, 2003)*
    - **entropy generation ratio** *(Panthalookaran et al., 2007)*
    - **stratification efficiency** *(e.g., van Berkel, 1997; Huhn, 2007)*
  - other efficiencies
    - extraction efficiencies based on volumes *(Lavan & Thompson, 1977)*
    - **MIX-number** *(Davidson et al., 1994)*
    - **MIX-number** *(Andersen et al., 2007)*
- numerical figures based on density distribution *(e.g., Moretti & McLaughlin, 1977; Stefan & Gu, 1992)*

(Haller, 2009)

OTHER PERFORMANCE INDICATORS

- Is **storage density** a KPI for CSP plants?
  - Area needed for storage << Area needed for solar field

  - Storage density is critical for other applications
    - In buildings
    - If heat must be transported

Density of the storage media < Density of the storage tank < Density of the storage system

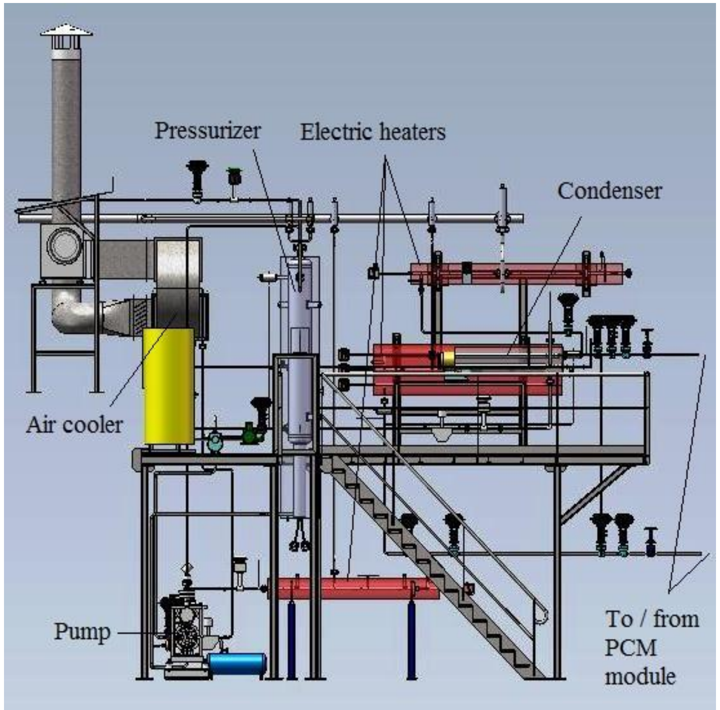
- Response time
- Auxiliary energy ratio
- Minimum cycle length
- Partial load suitability

CASE STUDY

LATENT HEAT STORAGE PERFORMANCE ASSESSMENT

TEST FACILITY

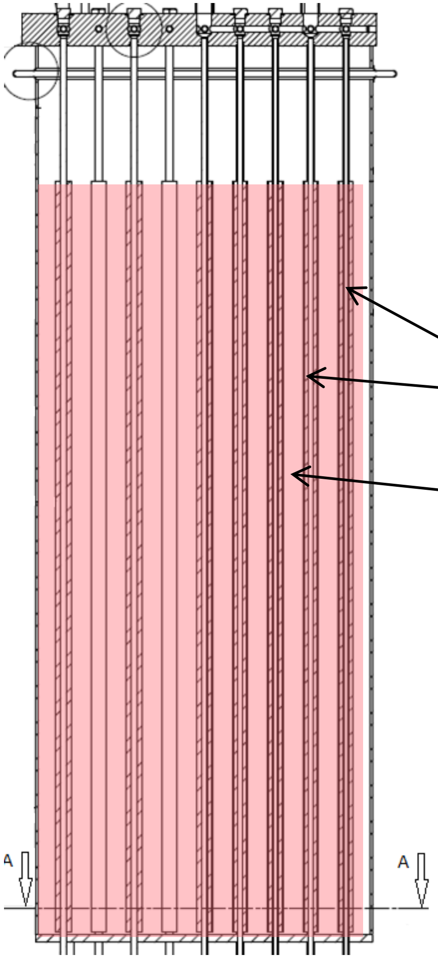
- LHASSA experimental facility at the CEA Grenoble
  - operating conditions similar to those of commercial CSP DSG plants (145 bar, 350 °C)
  - high pressure water-steam closed loop
  - wide range of charge and discharge transients



LHASSA test facility

PCM module

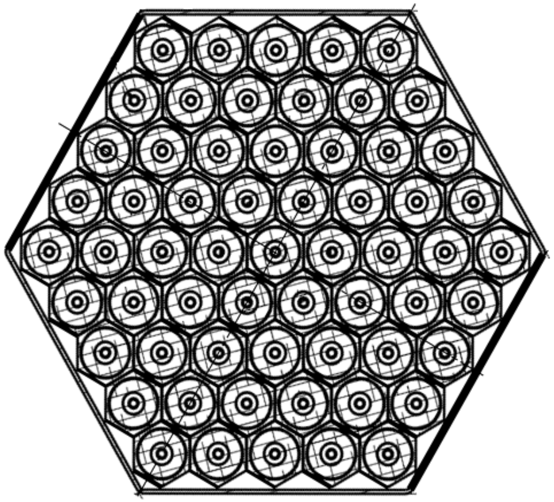
PCM STORAGE DESCRIPTION



Vertical bundle of parallel tubes with high pressure steam/water inside and a static PCM volume outside

Finned tubes

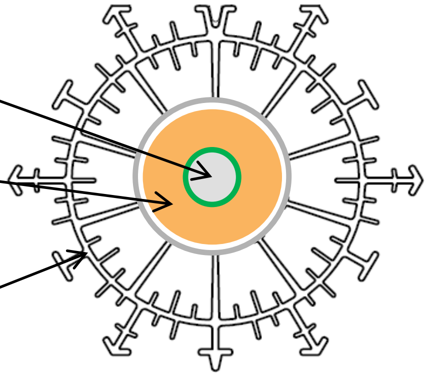
PCM volume



A-A section

Tubes

Fins



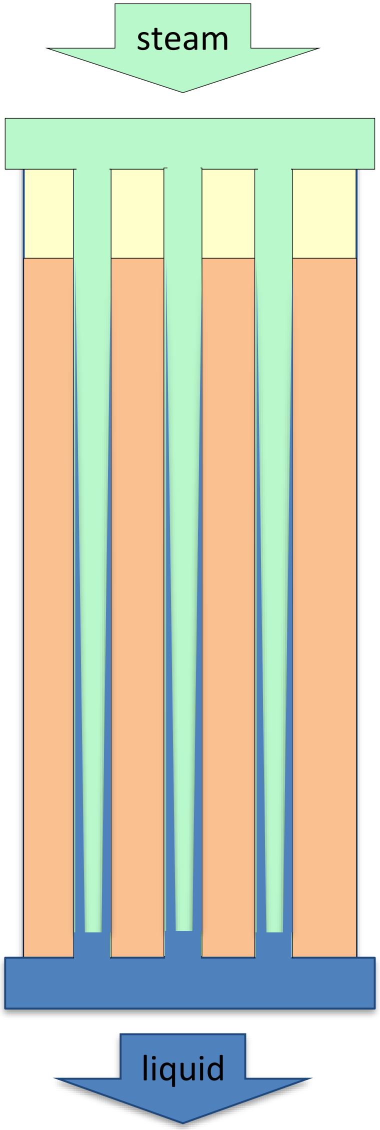
Heat transfer enhancement by aluminum inserts around the vertical finned tubes

(Garcia 2015)

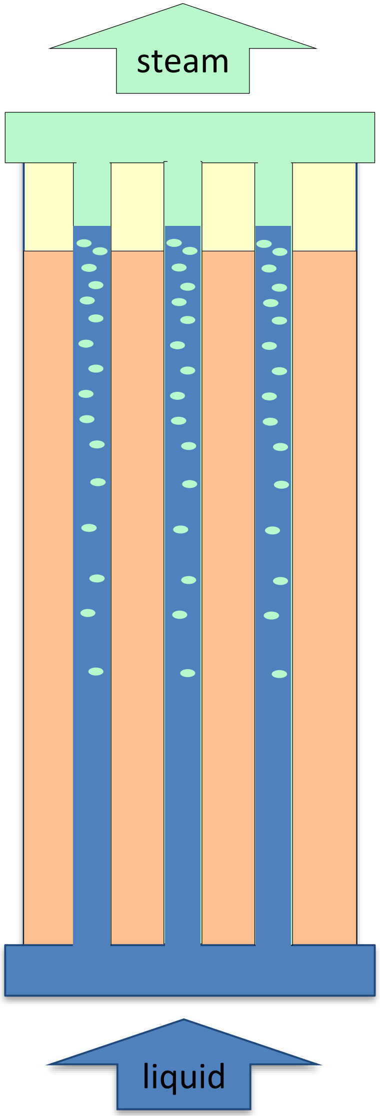
TEST PROCEDURES

- Objectives : validating the thermo-hydraulic behavior of the storage module under realistic operating conditions
  - Inlet mass flow is set by the operator
- Two control strategies
  - Sliding pressure
    - Controlled pressure to keep water level constant
  - Fixed pressure (in charge)
    - With variable water level in the tubes
- In charging mode
  - Low liquid water level in the test section
  - Steam condenses causing the melting of the PCM

Full charge process compatible with the storage charging time of a commercial CSP plant on summer days



TEST PROCEDURES



- Objectives : validating the thermal performances of the storage module under realistic operating conditions
  - Inlet mass flow is set by the operator
- Two control strategies
  - Sliding pressure
    - Controlled pressure to keep water level constant
  - Fixed pressure (in charge)
    - With variable water level in the tubes
- In discharging mode
  - High liquid water level in the test section
  - Liquid PCM solidifies causing the evaporation of the liquid water

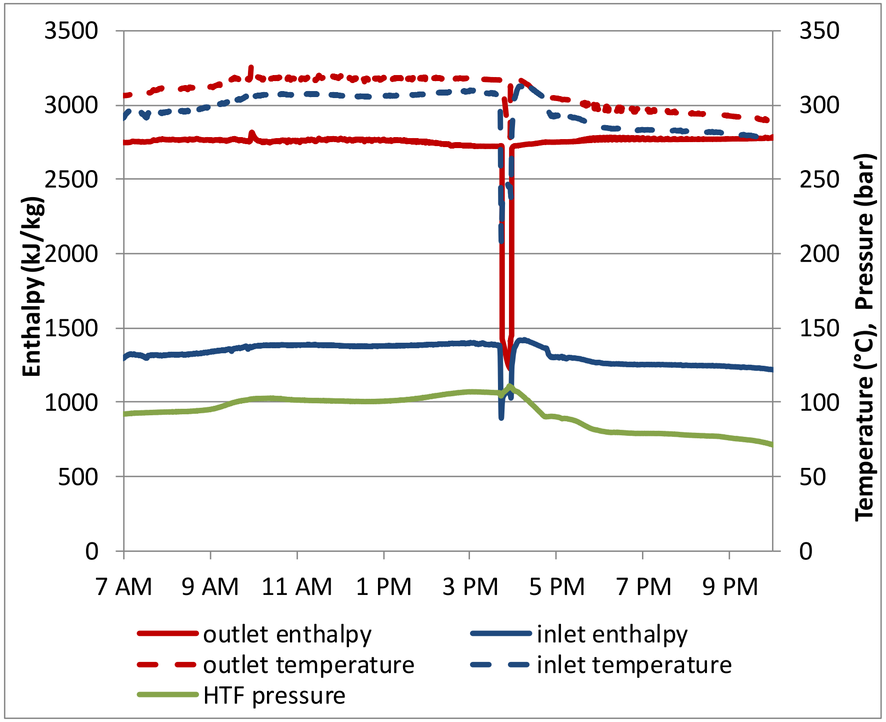
Full discharge process corresponds to a typical discharging time when storage is used during peak loads after sunset

PERFORMANCE INDICATORS – CASE STUDY STORAGE CAPACITY

- Calculated on HTF side
  - $SC = \int_{initial\ conditions}^{full\ discharge\ conditions} [\dot{m}(h_{outlet} - h_{in}]dt$
  - Inlet: liquid water
    - h_{in} = enthalpy(T_{in}, P_{in})
  - Outlet: steam
    - If $T_{out} > T_{sat}$ +2°C, h_{out} = enthalpy(T_{out}, P_{out})
    - Else, h_{out} is calculated thanks to an energy balance at the condenser boundaries

- Discharge
  - Initial state: T_{PCM} ~ 310°C
  - Inlet temperature: T_{sat} – 10°C

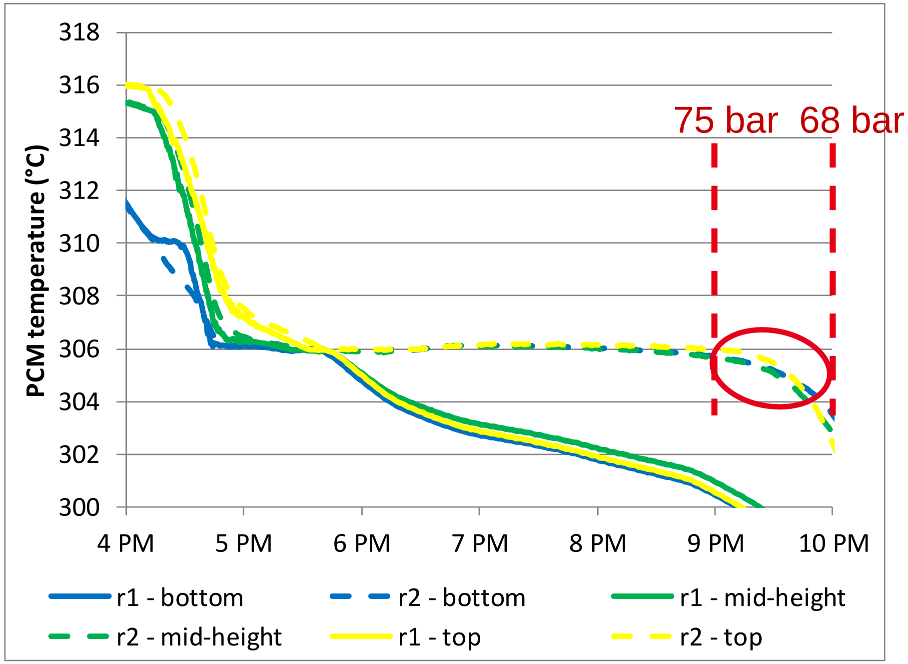
- SC results
  - End of discharge @ 75 bar
    255,6 kWh
  - End of discharge @ 68 bar
    316,5 kWh



PERFORMANCE INDICATORS – CASE STUDY
UTILIZATION RATE

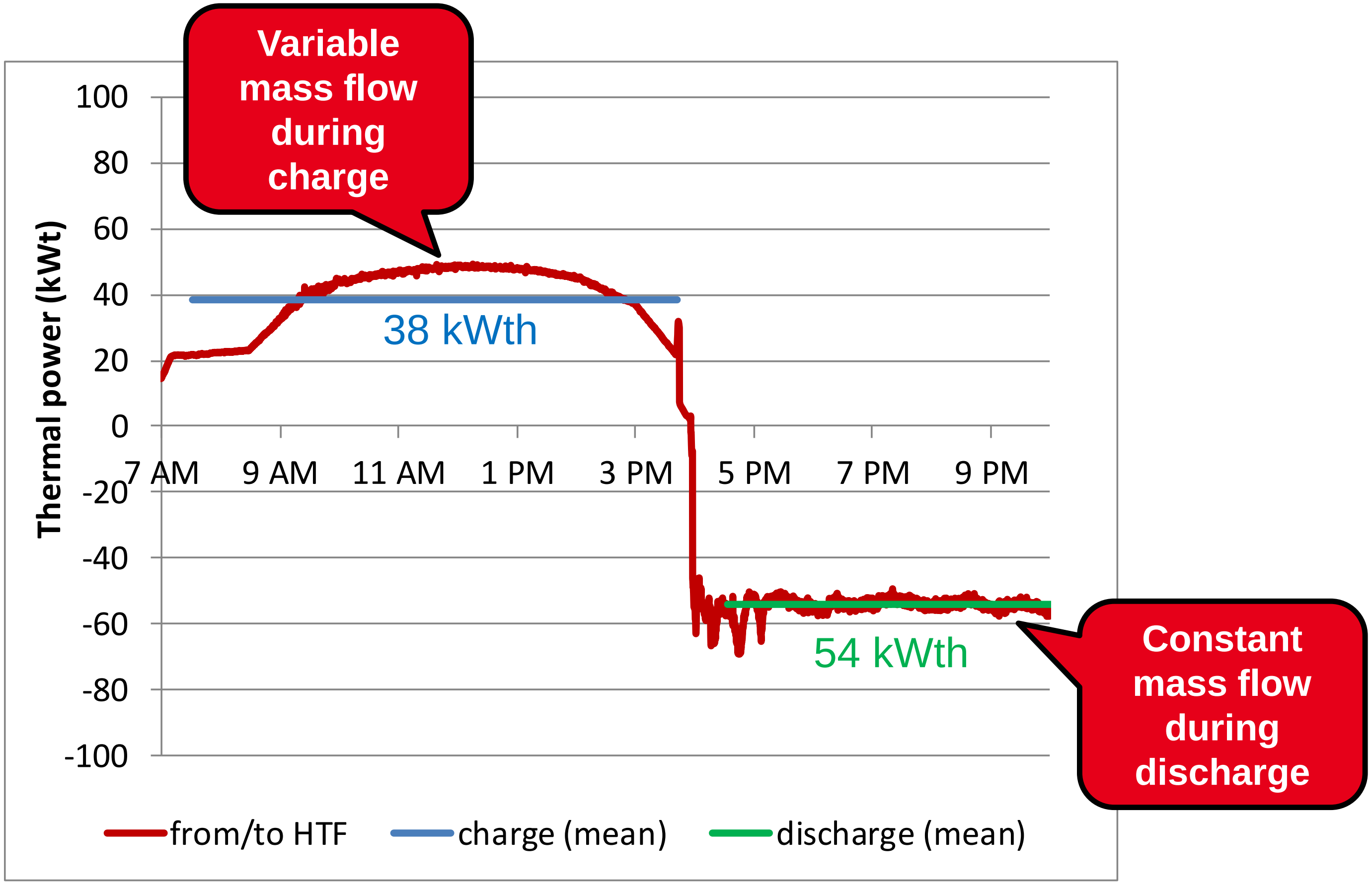
- Theoretical storage capacity (SCth)
  - Depends on temperature references!

PCM total mass	kg	6330		
PCM latent heat	kJ/kg	172		
Total latent heat	**kWht**	**302**		
Phase change temperature	°C	306		
Design hot temperature	°C	315	310	310
Design cold temperature	°C	295	294	301
Total sensible heat (PCM)	**kWht**	**58**	**48**	**26**
Total sensible heat (metal)	**kWht**	**16**	**13**	**7**
Theoretical storage capacity	**kWht**	**376**	**363**	**336**
% sensible heat		*20%*	*17%*	*10%*



- Utilization rate
  - End of discharge @ 75 bar
    mean T_{PCM} ~ 301°C
    UR = 76%
  - End of discharge @ 68 bar
    mean T_{PCM} ~ 294°C
    UR = 87%

PERFORMANCE INDICATORS – CASE STUDY NOMINAL THERMAL POWER



Variable mass flow during charge

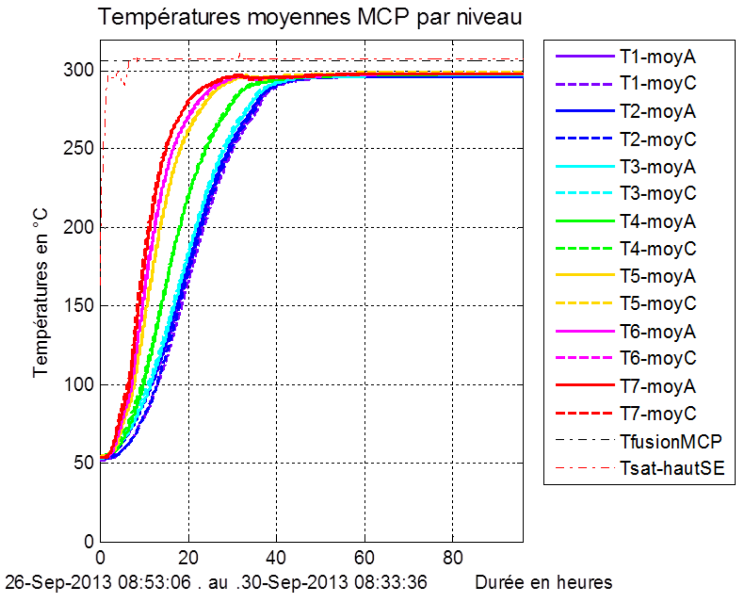
Constant mass flow during discharge

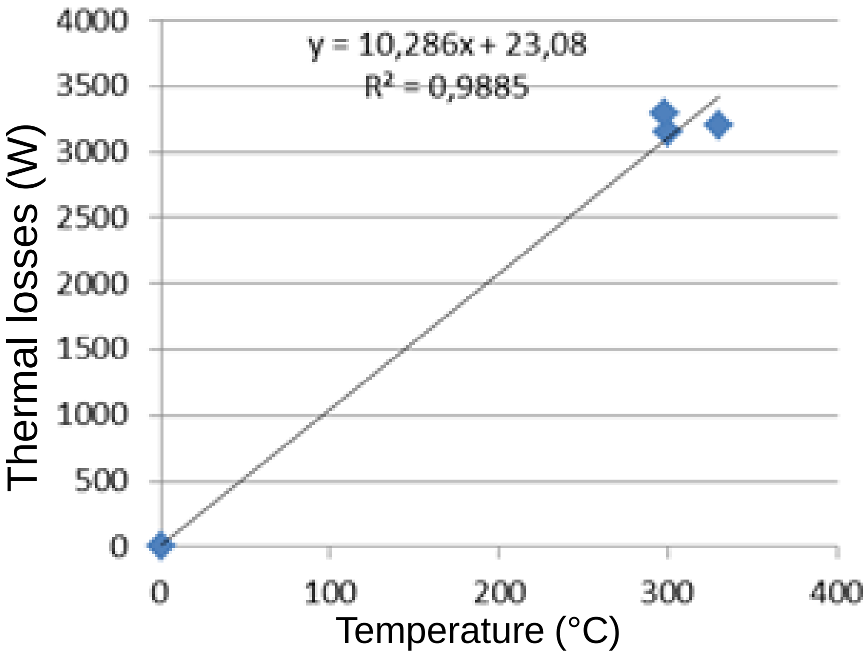
PERFORMANCE INDICATORS – CASE STUDY THERMAL LOSSES

- Repeated isothermal tests
  - Temperature maintained constant
  - Thanks to electrical heat tracing

    $P_{losses} = P_{elec}$

- Results
  - 2,88 kW_{th} at 300 °C
  - About 5% of P_{nom}





PERFORMANCE INDICATORS – CASE STUDY STORAGE EFFICIENCY

TEST	CHARGE				DISCHARGE			
	Mass flow	Charge state (E_c/E_{latent})	Duration	Final pressure (bar)	Mass flow	Storage efficiency (E_d/E_c)	Duration	Final pressure (bar)
Partial load	Variable	49,9%	4h18	94,1	Constan 	90,1% 100,0%	3h06 3h23	75,0 73,6
Partial load	Constant	28,4%	1h46	101,6	Constant	89,5%	1h38	75,0
Complete load	Variable	107,5%	8h11	104,8	Constant	75,7% 94,2%	4h44 5h51	75,0 68,1

- η_{TES} should be estimated in « cycling conditions »
  - With storage conditions at the end of discharge equal to those at the beginning of charge
  - If not respected, storage efficiency may > 100%

SOME CONCLUSIONS

- **TES performance depends strongly on the end-user!**
  - Basic technical KPI cannot be defined independently from the whole process

- **Many KPI vary depending on the initial state of the TES system**
  - e.g. for thermocline TES, the initial state depends on previous charge-discharge cycles until stable initial conditions are reached

- **Calculation on the HTF side, but you need information from inside the tanks…**

- **Test procedures for KPI estimation should be thoroughly described**
  - Initial and final conditions
  - Inlet and outlet flow conditions (mass flow, pressure, temperatures, …)

DURABILITY ISSUES

ABOUT DURABILITY

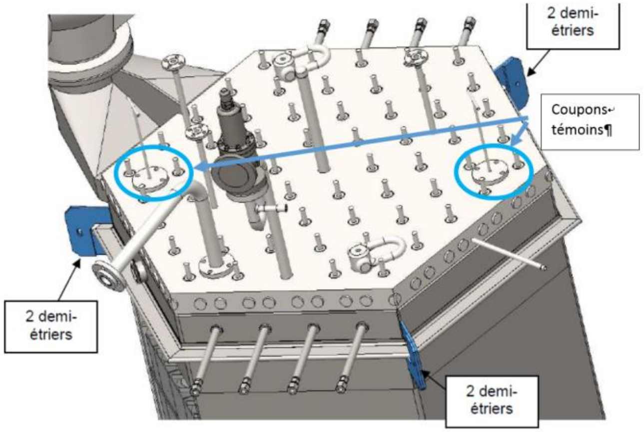
- TES Lifetime is another KPI
  - Expected lifetime in CSP plants is about 20 to 30 years
  - Difficult to demonstrate
  - Durability and corrosion tests must be performed

- Issues
  - Performance degradation
  - Safety issues: risk of failure

- Specific indicators
  - Degradation of the above-mentioned performance indicators
  - Corrosion mechanisms of metals by HTF and storage media
    - Passivation
    - Intergranular / Pit corrosion
  - Composition and thermo-physical properties of the storage media

CASE STUDY: PCM STORAGE

- Direct measurement on tubes and fins: *corrosion rate*
- From a representative sample removed when the salt is liquid
- Metal loss rate assessment (weighting, thickness measure)
- SEM and XRD measurements



- Indirect measurement on PCM: *Fe release due to corrosion and salt purity*
- ICP analysis for Fe release
- Calorimetry measurement ($NaNO_3$ Vs $NaNO_2$)

- Indirect measurement on gases: *initial composition and composition evolution*
- O_2 / N_2 measurements to monitor chemical equilibriums

MERCI POUR VOTRE ATTENTION

THANKS FOR YOUR ATTENTION

Commissariat à l'énergie atomique et aux énergies alternatives
17 rue des Martyrs | 38054 Grenoble Cedex
www-liten.cea.fr

Établissement public à caractère industriel et commercial | RCS Paris B 775 685 019

REFERENCES

- IEA Solar Thermal Electricity Technology Roadmap, OECD/IEA, Paris, 2014.
- P. Denholm, Y.-H. Wan, M. Hummon and M. Mehos, "An Analysis of Concentrating Solar Power with Thermal Energy Storage in a California 33% Renewable Scenario," NREL Report No. TP-6A20-58186, National Renewable Energy Laboratory, Golden, CO, 2013.
- IEA Technology Roadmap: Concentrating Solar Power, OECD/IEA, Paris, 2010.
- W.-D. Steinmann, Thermal energy storage systems for concentrating solar power (CSP) technology, in Advances in Thermal Energy Storage Systems. In Woodhead Publishing Series in Energy, Woodhead Publishing, 2015, Pages 511-531.
- NREL, Survey of Thermal Storage for Parabolic Trough Power Plants, NREL/SR-550-27925, 2000.
- Goldstern, Walter Steam storage installations. Springer-Verlag OHG, Berling / Göttingen / Heidelberg, 1970.
- NREL website, https://www.nrel.gov/csp/solarpaces.
- IRENA Renewable energy technologies: cost analysis series, Concentrating Solar Power, June 2012.
- NREL Technical Report, Concentrating Solar Power Gen3 Demonstration Roadmap, TP-5500-67464, January 2017.
- P. Denholm and M. Hummon, Simulating the Value of Concentrating Solar Power with Thermal Energy Storage in a Production Cost Model. Technical Report NREL/TP-6A20-56731, November 2012.
- U. Herrmann and D. W. Kearney, Survey of thermal energy storage for parabolic trough power plants, J Sol Eng, 124:145, 2002.
- P. Garcia, M. Olcese, S. Rougé, Energy Procedia 69, 842 – 849 (2015).
- Laing D, Bahl C, Bauer T, Lehmann D, Steinmann WD. Thermal energy storage for direct steam generation. Solar Energy 85; 2011. p. 627–633.
- M. Haller, C Cruickshank, W. Streicher, S. Harrison, E. Andersen, S. Furbo: Methods to determine stratification efficiency of thermal energy storage processes - Review and theoretical comparison. In: Solar Energy 83 (2009), Oct, Nr. 10, S. 1847–1860. – ISSN 0038–092X
- Zavattoni, S.A., Barbato, M.C., Zanganeh, G., Pedretti, A., High temperature thermocline TES – Effect of system pre-charging on thermal stratification. AIP Conference Proceedings Volume 1734, 31 May 2016, 21st International Conference on Concentrating Solar Power and Chemical Energy Systems, SolarPACES 2015; Cape Town; South Africa.
- Andersen E., Furbo S., Fan J., Multilayer fabric stratification pipes for solar tanks. Solar Energy 81 (2007) 1219–1226.
- A. Bruch, S. Molina, T. Esence, J.F. Fourmigue, R. Couturier, Experimental investigation of cycling behaviour of pilot-scale thermal oil packed-bed thermal storage system, Renewable Energy 103 (2017) 277-285
- Applications of Thermal Energy Storage in the energy transition, benchmarks and developments: Public Report of IEA ECES Annex 30, September 2018