UNIVERSIDAD ADOLFO IBÁÑEZ
FACULTAD DE INGENIERÍA Y CIENCIAS

Thermal Storage (TES): key technical and economic component in Solar Thermal Plants

Professor
GUSTAVO CÁCERES

cigré COMITE CHILENO

Sexta Versión Congreso Bienal Internacional Cigré 2013 "Variabilidad del Costo del Suministro Eléctrico"

CHILE

Surface ~ 756.000 km^2

Population ~ 16,6 millones

PIB ~ US$19.000 per capita 2012 (growing > 5%)

No. 1 in Latin-America on Research of HTTES recognized by the IEA through his IA ECES
(Represented by Exp. Obs. Dr. Gustavo Cáceres)

No. 1 in Copper

No. 1 in Lithium

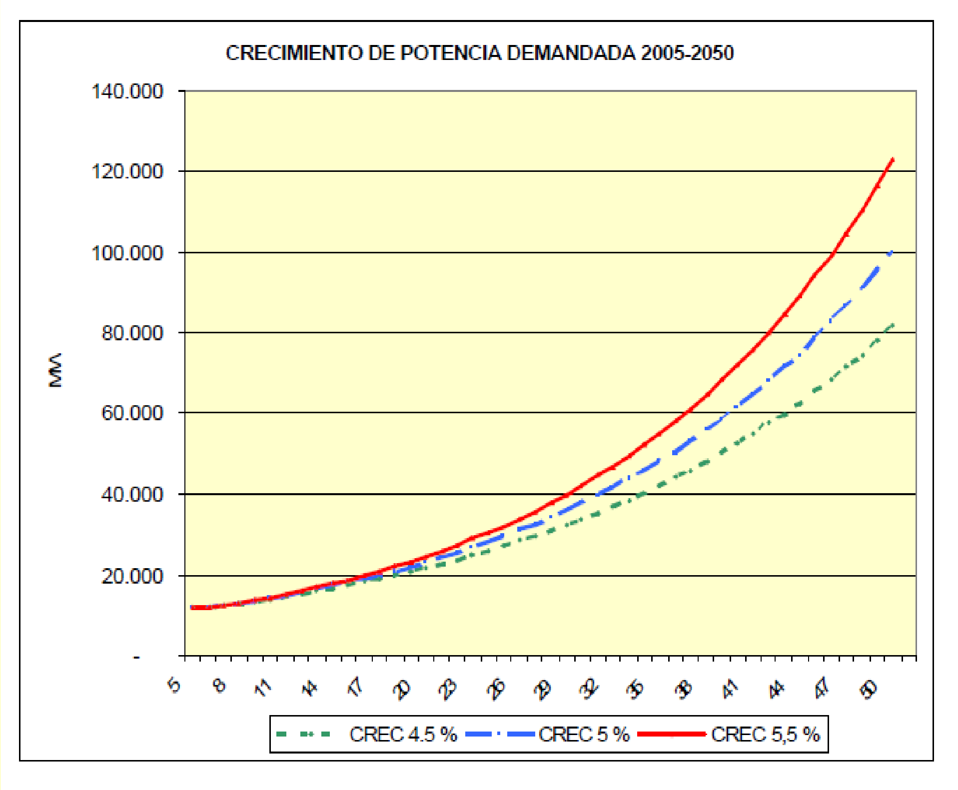
No. 1 in Rhenium

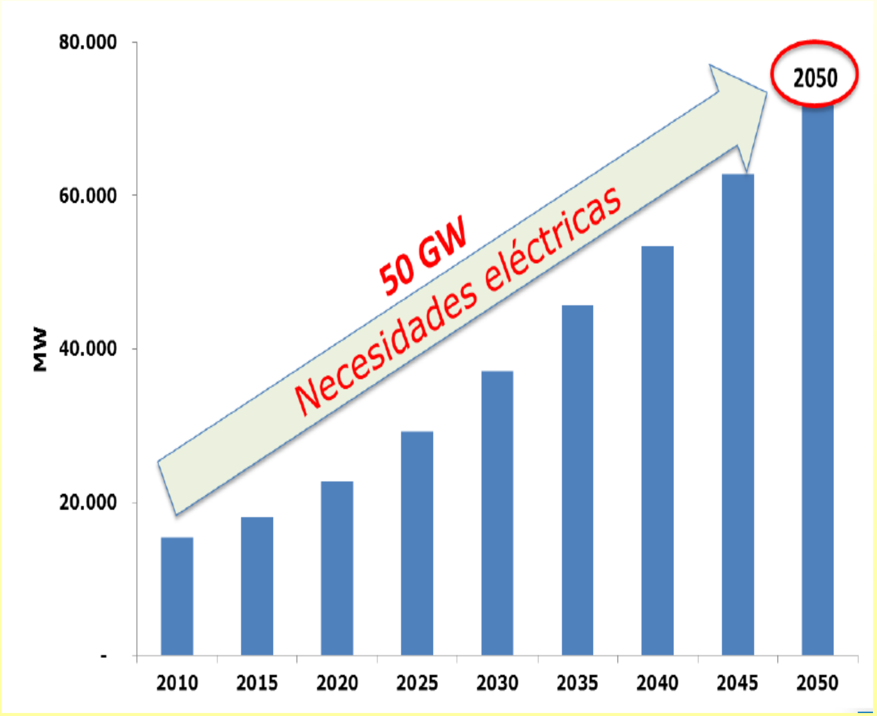
No. 1 in Nitrates

Chilean Economic Scope

Estimated Electricity Demand

- **Considering an annual GDP growth of 5%, in 2020 energy demand would reach more than 23,000 MW. This would imply high average annual increase of installed electricity capacity.**

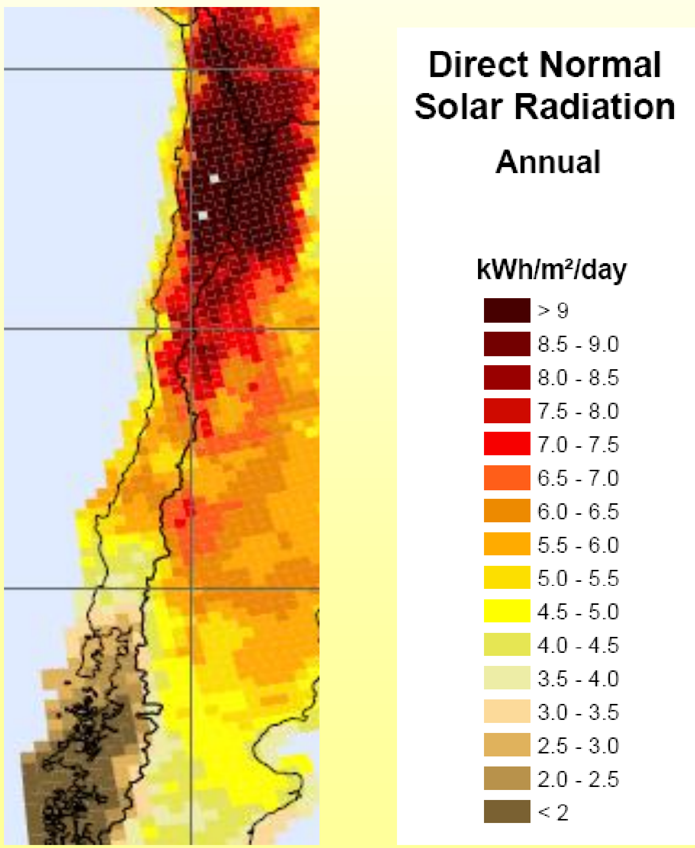


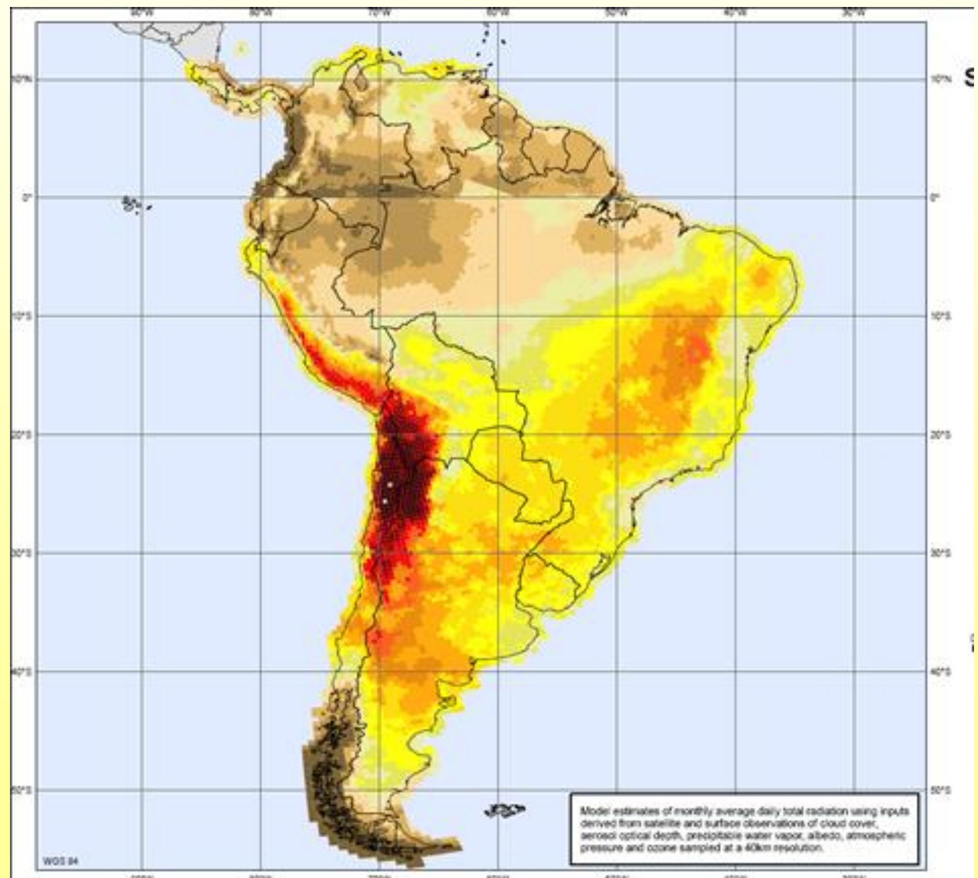


Chilean Solar Potential

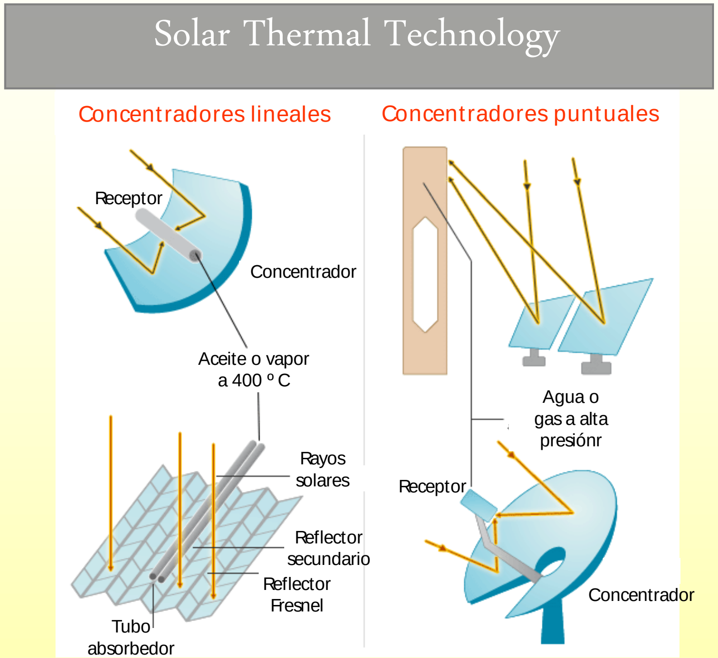
Northern Chile has the best conditions of solar radiation in the world with a potential estimated on 100,000 MW

- **Average Normal Radiation of 7 kWh/m^2/day**
- **On Atacama, radiation amounts to 3000 kWh/m2/year about 50% greater than, for example, Seville**
- **Large tracts of flat land ideal for solar power plants**

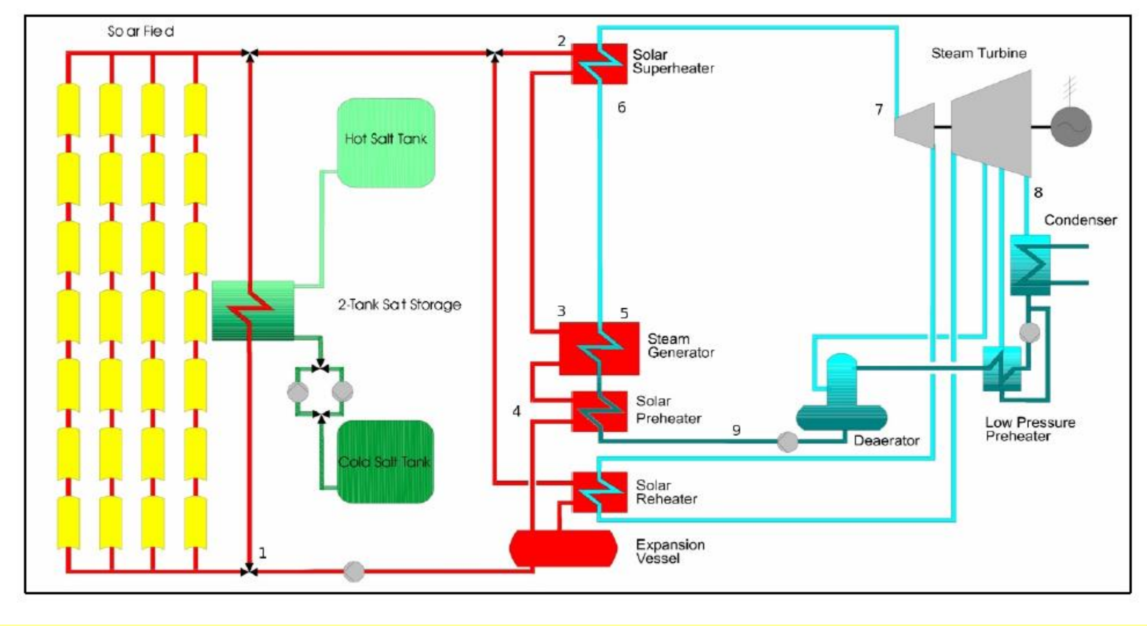




Solar Thermal or CSP Plants

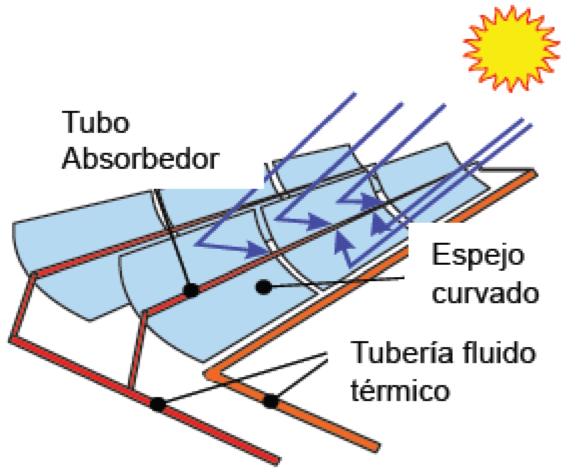


Operation: In general, concentrating solar power technology is based on the concept of concentration of solar radiation to produce steam or hot air, which can then be used in conventional power plants. For concentration, most systems use mirror due to its high reflectivity.

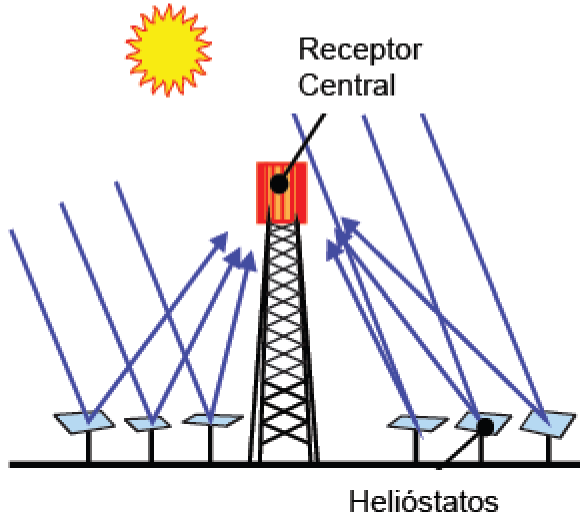


CSP

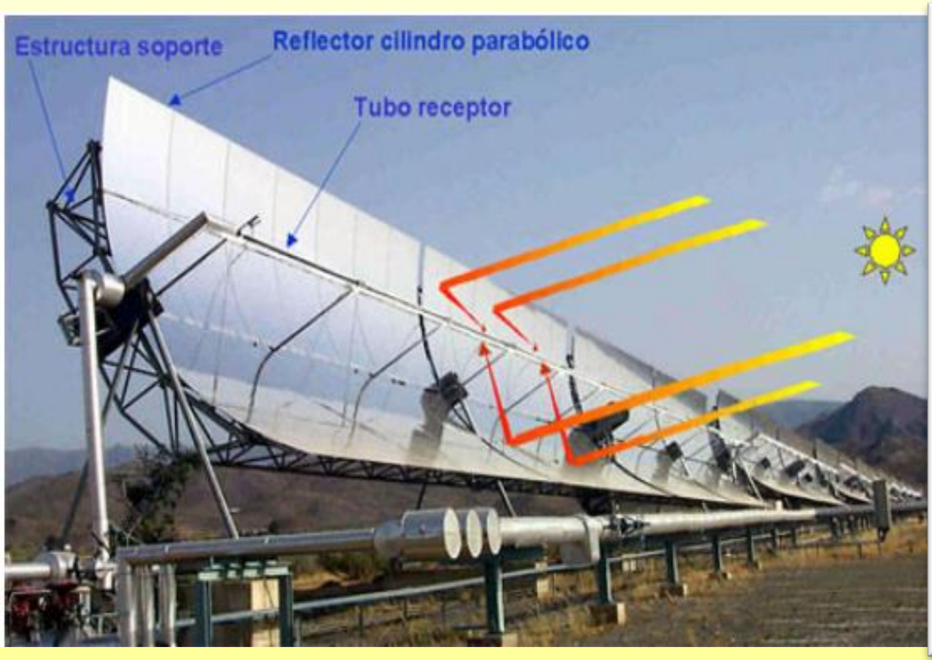
- **Sun provides the Earth in 1 hour more energy than the demanded by the planet in 1 year.**
- **4 types of technologies:**
  - **PTC (71%)– SPT (12.9%)– LFC (12.9%) – PDS (3.2%) [12]**
- **In the world:**
  - **8.5 GW under planning or development**
  - **7.5 GW installed or under construction**
    - **Spain has most of the installations**
    - **80% are PTC, followed by SPT [72]**
  - **Installed capacity from CSP ranges from 0.25 to 354 MW**
- **Commonly equipped with fuel BS and TES**
  - **98% of energy stored in TES can be recovered**
    - **Operation time extended up to 16 hrs. per day**
- **Working temperatures ranges from 93°C to 700°C (zhao, Tian, [12])**



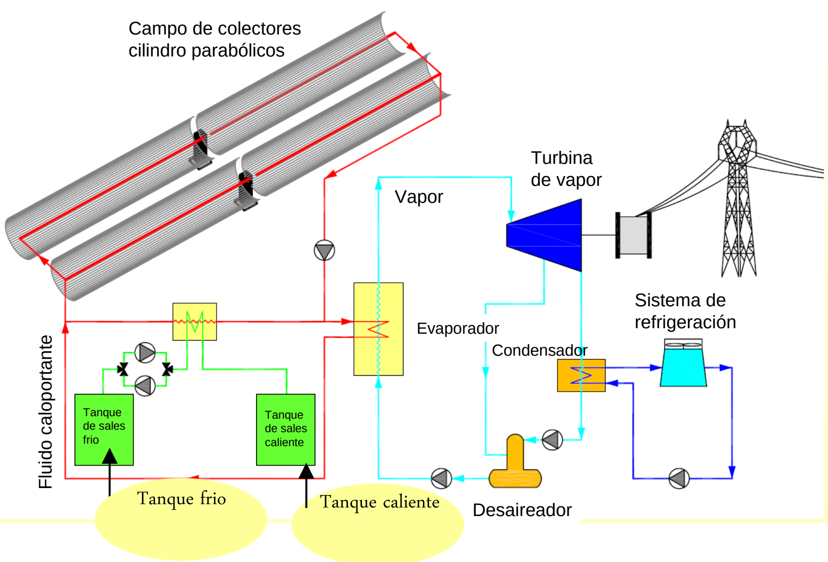
Cilindro-parabólicos



Receptor Central

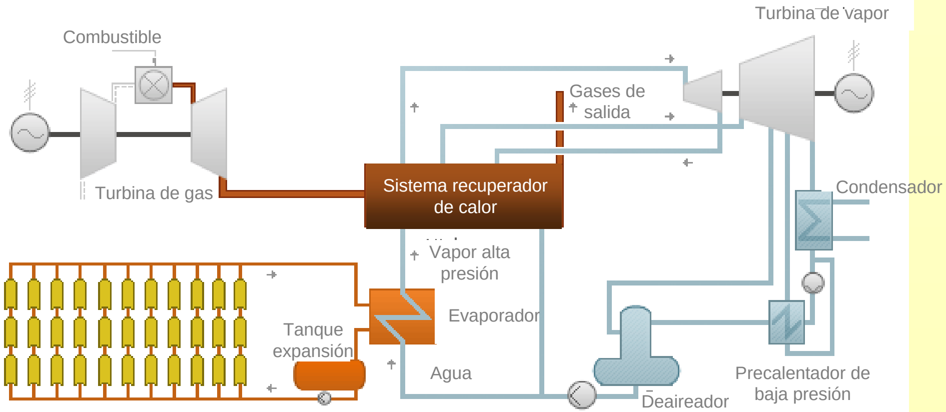


TECHNOLOGIES THAT GIVES STABILITY



Storage

The most common technology is salt storage

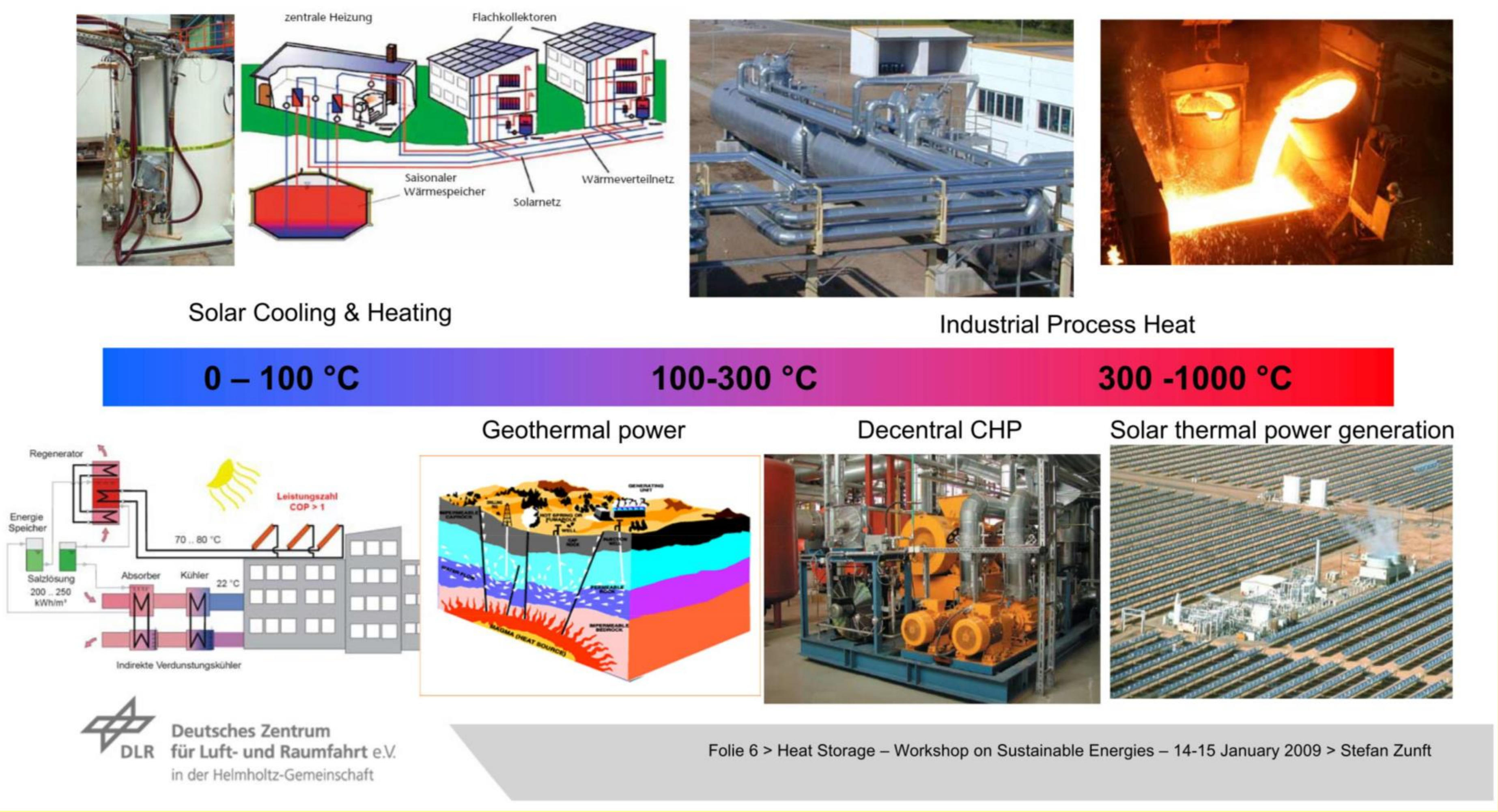


Hybridisation

The most common technology is: ISCC = Integrated Solar Combined Cycle

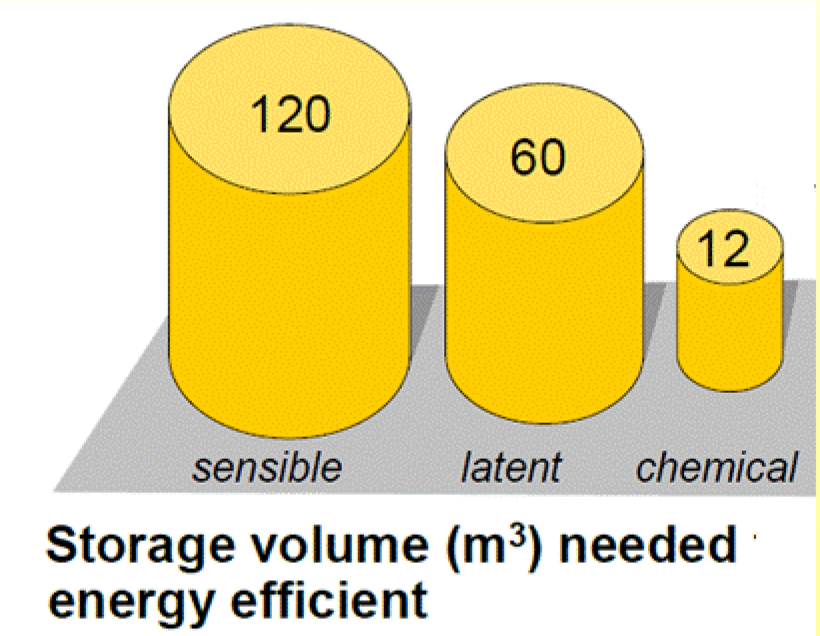
Thermal Energy Storage in CSP Plants

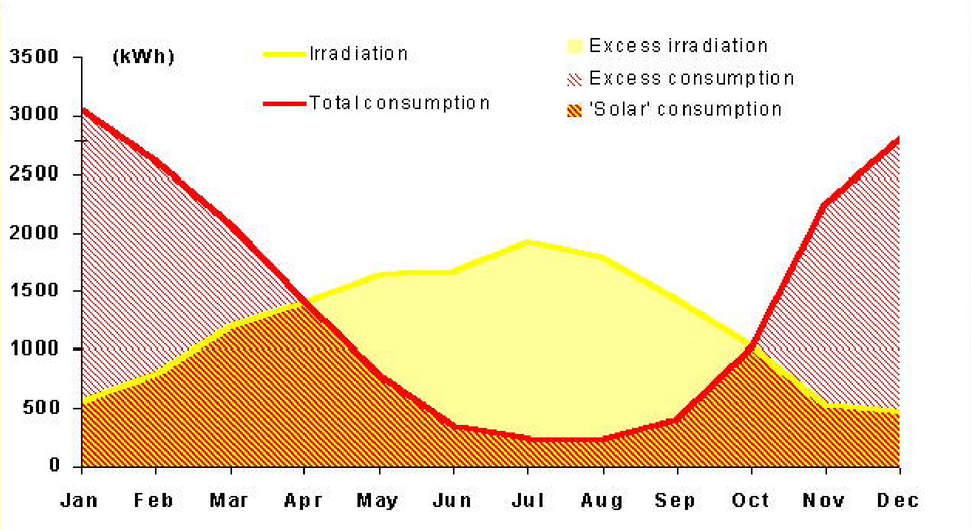
Thermal Energy Storage (TES)



Mechanisms of Thermal Storage

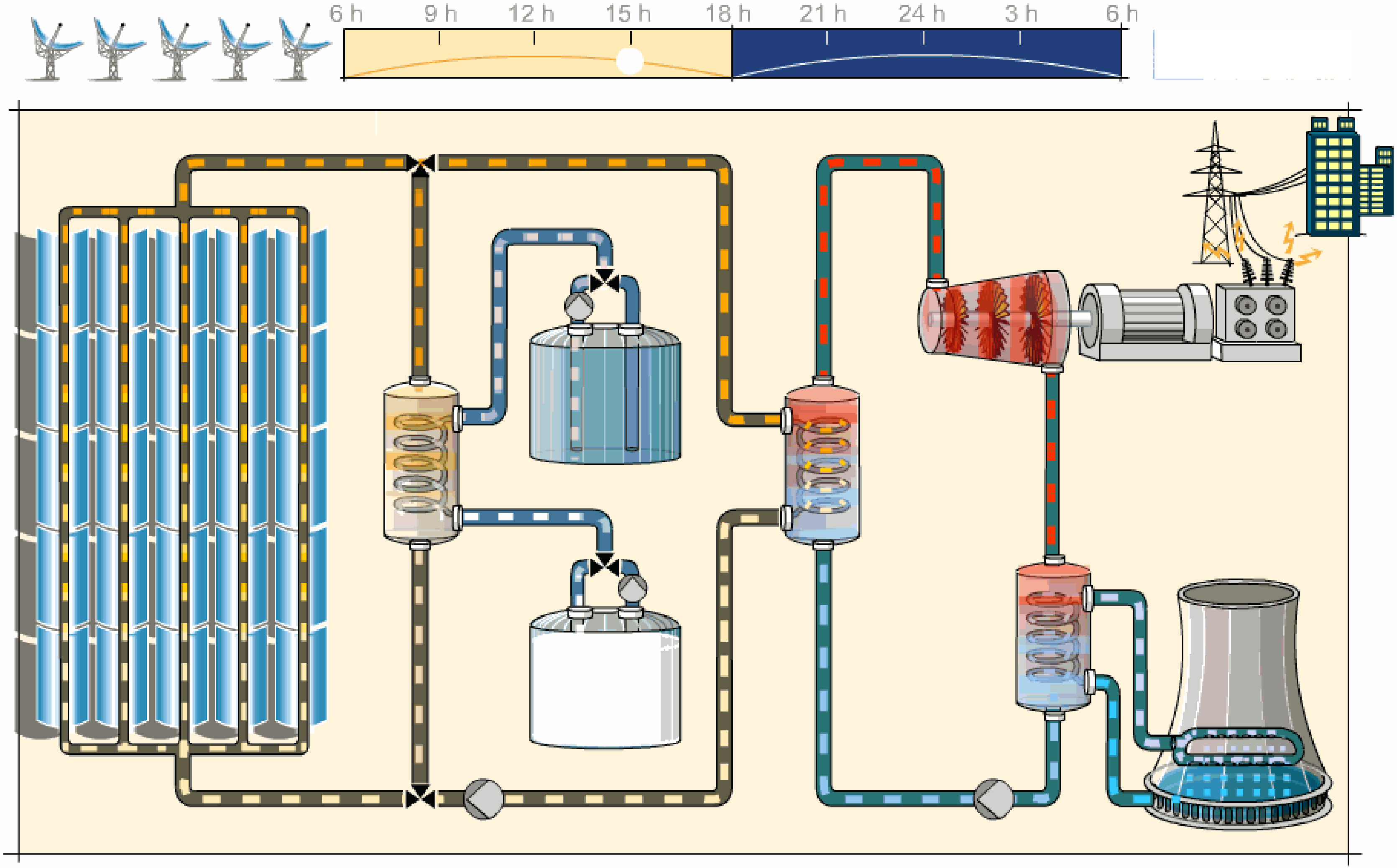
- **Sensible heat:** storage energy by increasing temperature in a single phase (solid or liquid phase)
- **Latent heat:** storage energy by phase change
- **Thermochemical:** heat from chemical reaction





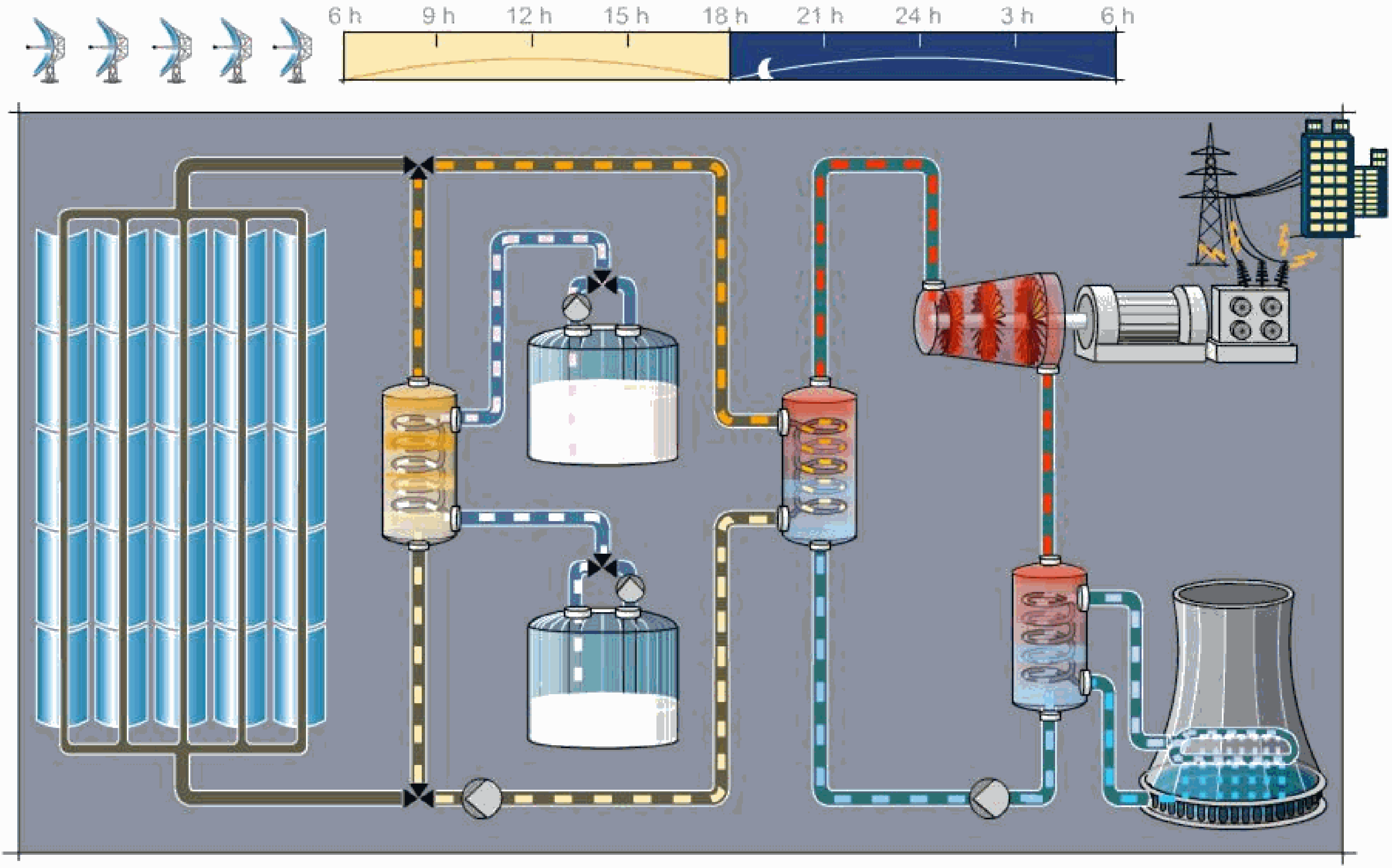
TES for CSP Plants

- Active Thermal Energy Storage
  - ➢ Convection or circulation of fluid storage
  - ➢ One or Two Tank Systems
    - a) Direct system: HTF is also the storage medium
    - b) Indirect system: HTF and storage medium are different
- Passive Thermal Energy Storage
  - ➢ Not circulation of fluid storage
  - ➢ One or more exchangers modules



Solar fields **TES 2 tanks** **Steam power block**

Solar plant: charging TES



Solar fields TES 2 tanks Steam power block

Solar plant: discharging TES

ACS-COBRA (TECNOLOGIA CCP)

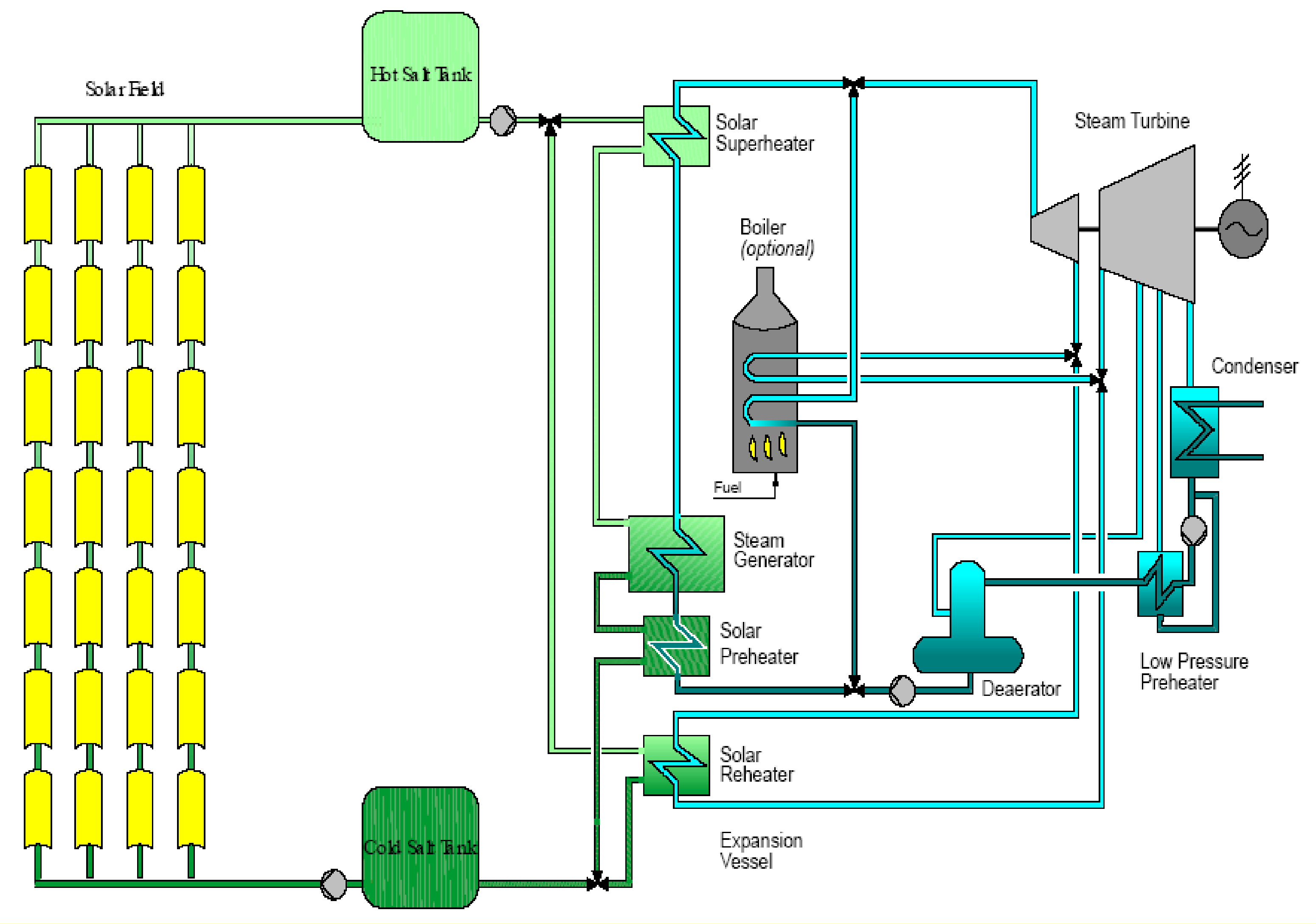
ANDASOL 1, 2, 3 (Aldeire, Granada, España). DNI: 2136 kWh/m² year

- Solar Field 510.120m² Parabolic through collectors
- Thermal Storage for 7,5 hours with molten salts
- Annual production of 176 GWh, with12% Gas
- Cost (EPC) ≈ 260 M€/plant

UNIVERSIDAD ADOLFO IBÁÑEZ
FACULTAD DE INGENIERÍA Y CIENCIAS

SERC CHILE
SOLAR ENERGY RESEARCH CENTER

Active TES: 2-Tank Salt Storage (Direct System)

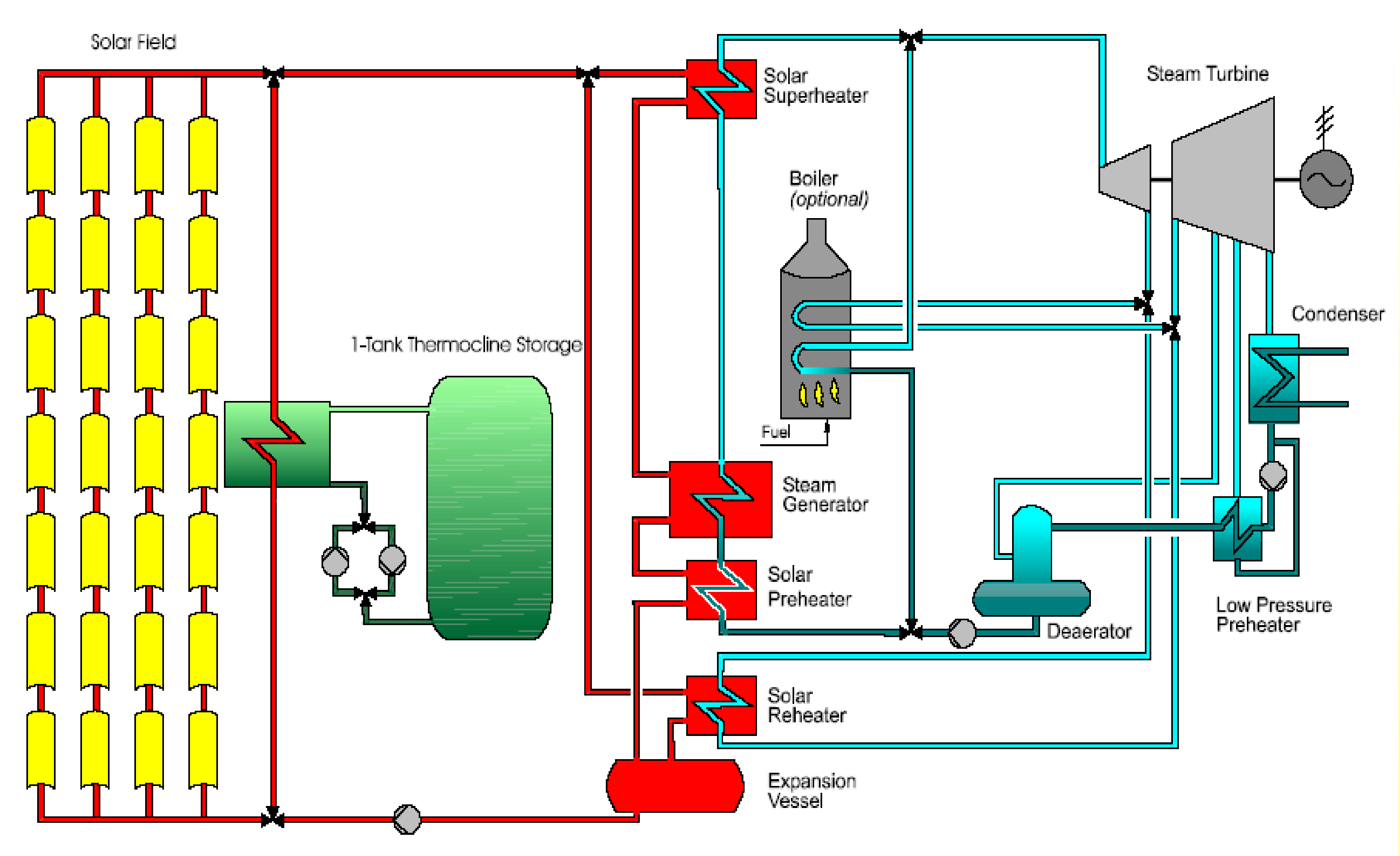


UNIVERSIDAD ADOLFO IBÁÑEZ
FACULTAD DE INGENIERÍA Y CIENCIAS

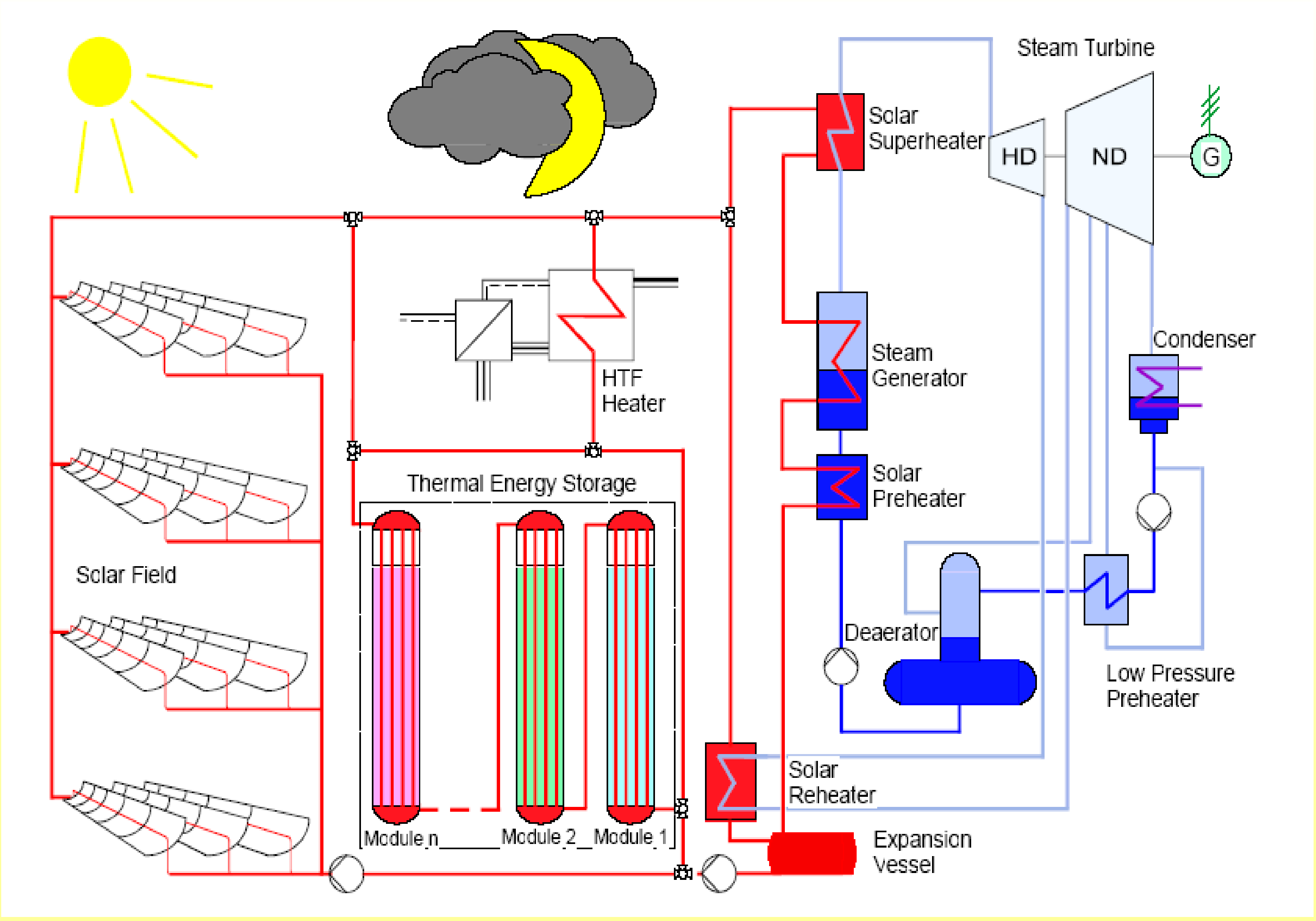
SERC CHILE
SOLAR ENERGY RESEARCH CENTER

GEMASOLAR (TORRESOL ENERGY)

Active TES: 1-Tank Thermocline Storage

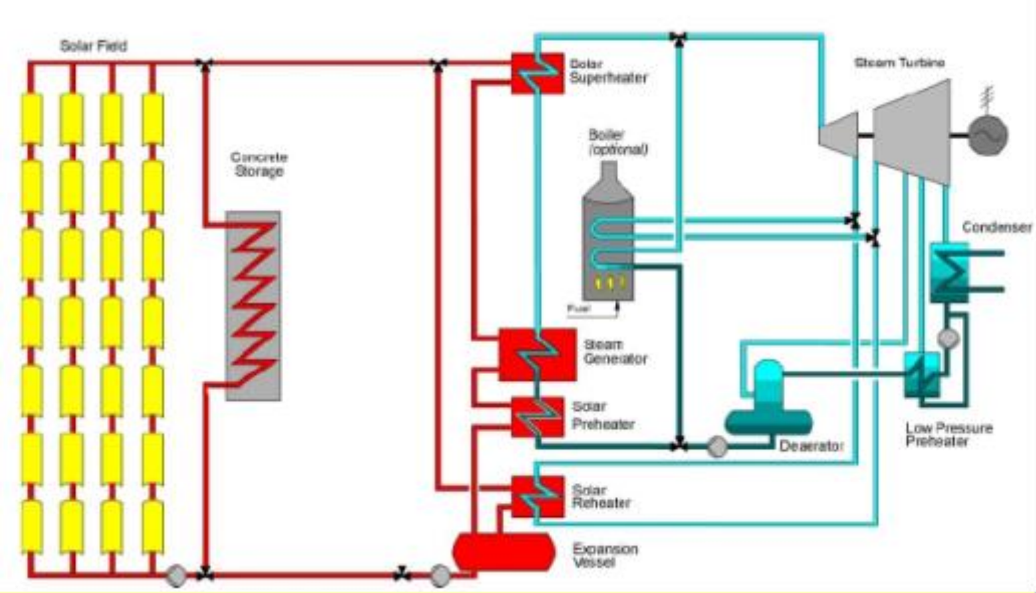


Passive TES: PCM Storage



Passive TES: Concrete

Solar plant: HT concrete



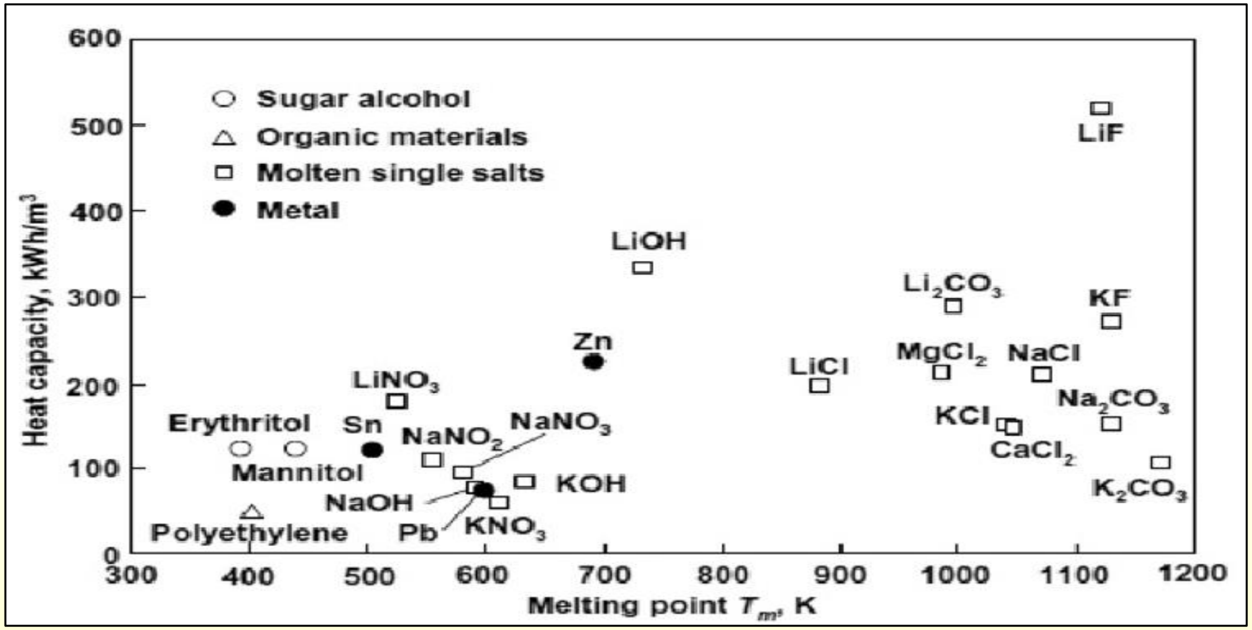
Scheme of a parabolic through plant, with concrete (or castable ceramics) storage system (Herrmann, 2006

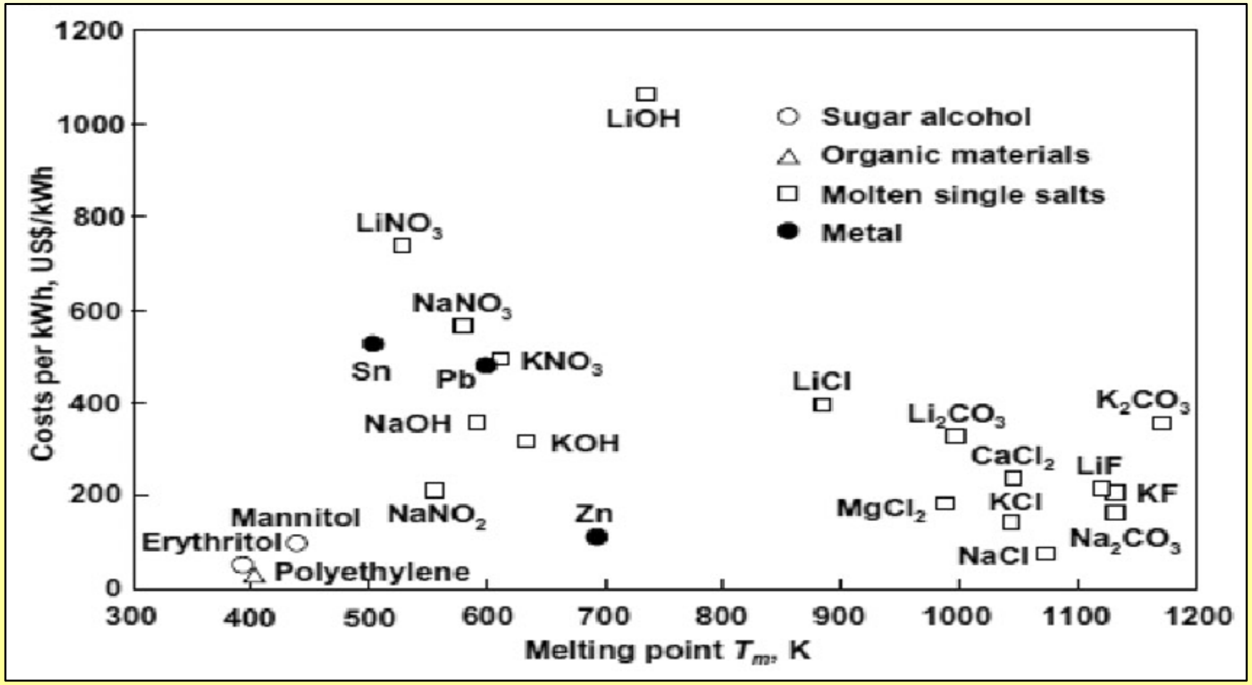
High temperature concrete storage system (Tamme 2003)

Preliminary ECONOMIC ANALISYS

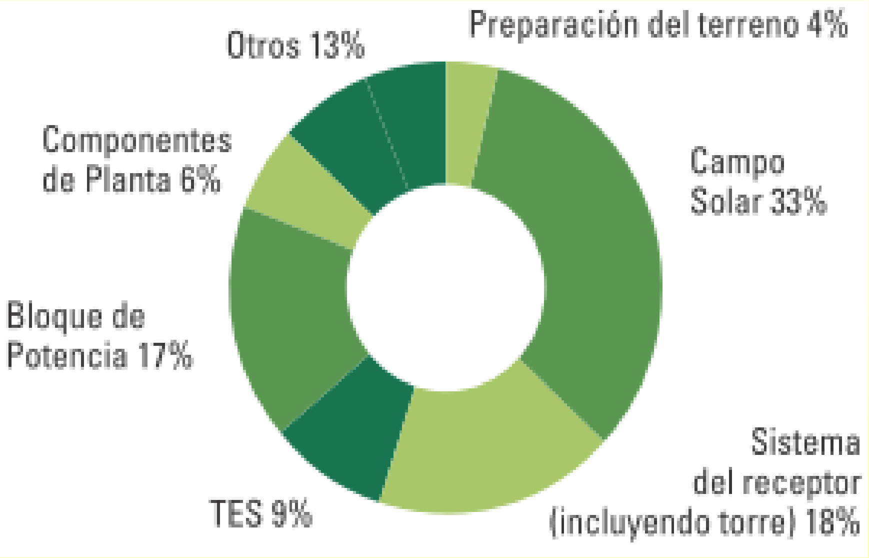
UNIVERSIDAD ADOLFO IBÁÑEZ
FACULTAD DE INGENIERÍA Y CIENCIAS

TES Materials

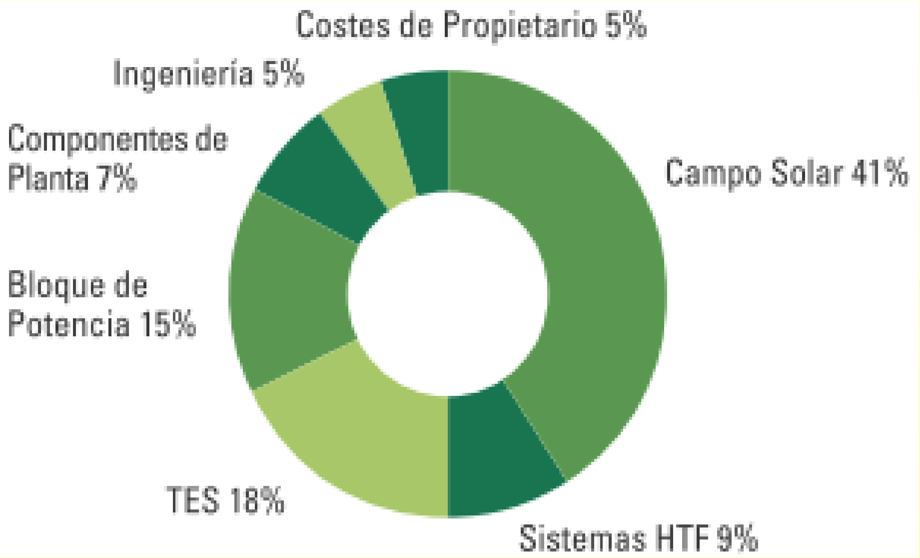




Costs of TES System



SPT



PTC

UNIVERSIDAD ADOLFO IBÁÑEZ
FACULTAD DE INGENIERÍA Y CIENCIAS

SERC CHILE
SOLAR ENERGY RESEARCH CENTER

Costs of TES System

Item	$1,000	Contingency	$1,000
Land	2,671	0%	2,671
Structures and Improvements	3,273	15%	3,763
Collector System	513,420	5%	539,091
Thermal Storage System	94,944	5%	99,691
Heat Transport Fluid System	60,173	10%	66,190
Electric Power Generation System	98,570	10%	108,428
Master Control System	2,270	15%	2,610
	---------	------	---------
Total Field Cost	775,321	6%	822,445
Engineering, Procurement, and Home Office	12,750	15%	14,662
Construction Management and Field Procurement	5,005	15%	5,756
Startup and Checkout	2,296	15%	2,640
Contractor Fee (3 percent)	23,861	0%	23,861
	--------	------	--------
	43,911	7%	46,919
Total Overnight Construction Cost	819,232	6%	869,363

Estimate Summary 250 MWe Plant with 3 Hours of Thermal Storage .(Kelly 2005)

Table 2

Comparison for 50 MW_{el} CSP plants with TES.

H.L. Zhang [a,*], J. Baeyens [b], J. Degrève [a], G. Cacères [c]

Renewable and Sustainable Energy Reviews 22 (2013) 466–481

Parameters	PTC with oil, without storage and back-up	SPT with steam, without storage and back-up	SPT with molten salt, TES storage and back-up system
Mean gross efficiency (as % of direct radiation)	15.4	14.2	18.1
Mean net efficiency (%)	14	13.6	14
Specific power generation (kW h/m^2-year)	308	258	375
Capacity factor (%)	23–50	24	Up to 75
Unitary investment (€/kW h_{el})	1.54	1.43	1.29
Levelized electricity cost (€/kW h_{el})	0.16–0.19	0.17–0.23	0.14–0.17

CSP: CAPACITY FACTOR

Reference Equivalent hours for solar thermal technology facilities

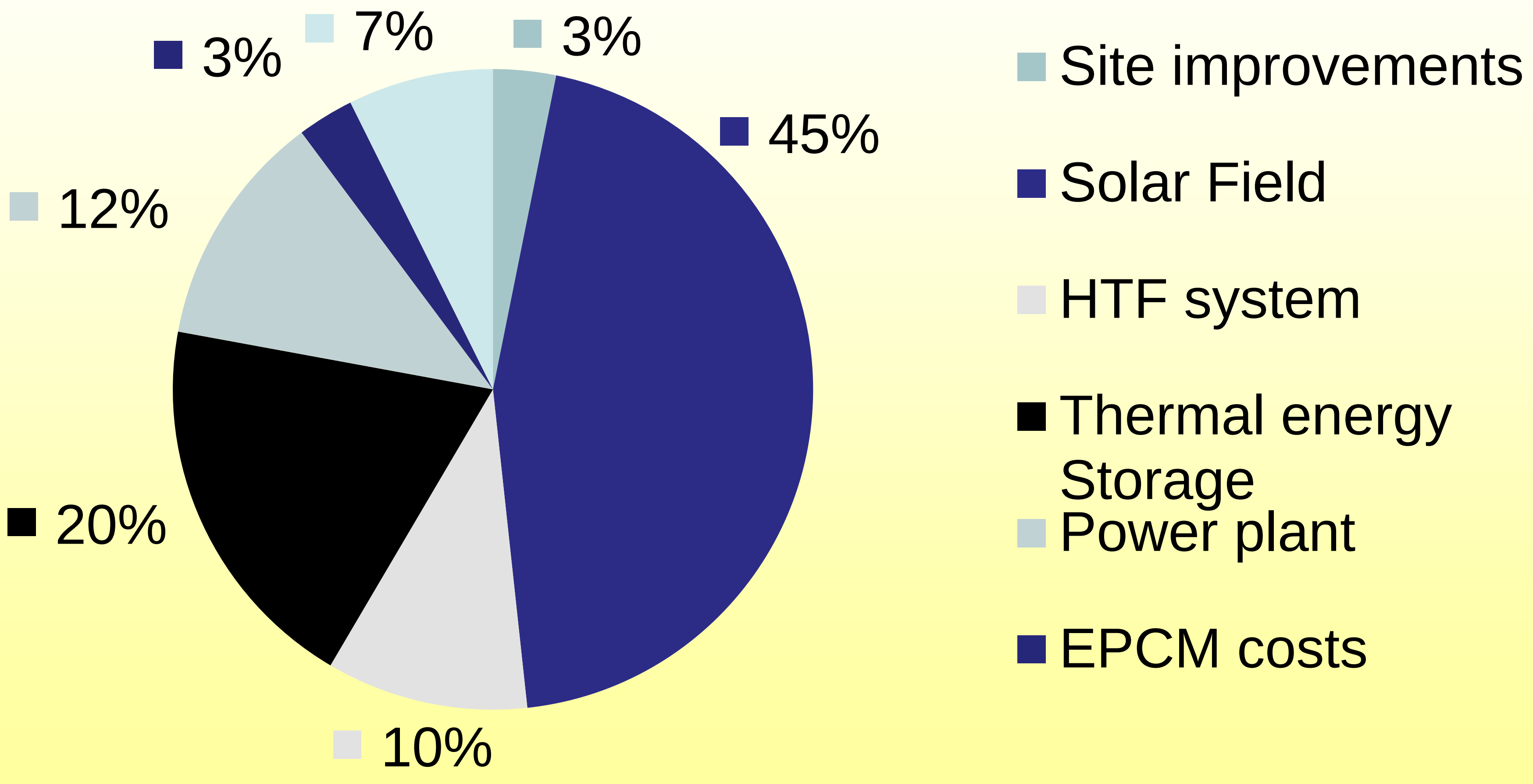
Tecnología	*Horas equivalentes de referencia / año*	*Factor de capacidad*
Torre sales con almacenamiento de15h	6.450	73,63%
Cilindro parabólico con 9h almacenamiento	4.000	45,66%
Cilindro parabólico con 7h almacenamiento	3.950	45,09%
Cilindro parabólico con 4h almacenamiento	3.450	39,38%
Cilindro parabólico sin almacenamiento	2.855	32,59%
Torre vapor saturado	2.750	31,39%
Fresnel	2.450	27,97%
Stirling	2.350	26,83%

Economic analysis in USA 2010

- **Parabolic Trough Reference Plant**
  - Worley Parsons - C. Turchi, NREL (2010)

Parabolic Trough CSP Characteristics	
Capacity	100 (MWe)
TES	6.3 (hours)
TES size	1988 (MWth)
Capacity Factor	47%
Annual net generation	426,717 (MWh)
Life	30 (years)

Cost structure



Worley parsons – NREL

- Total installed cost 8 (MMUSD/MWe)
- LCOE 180 (USD/MWh)

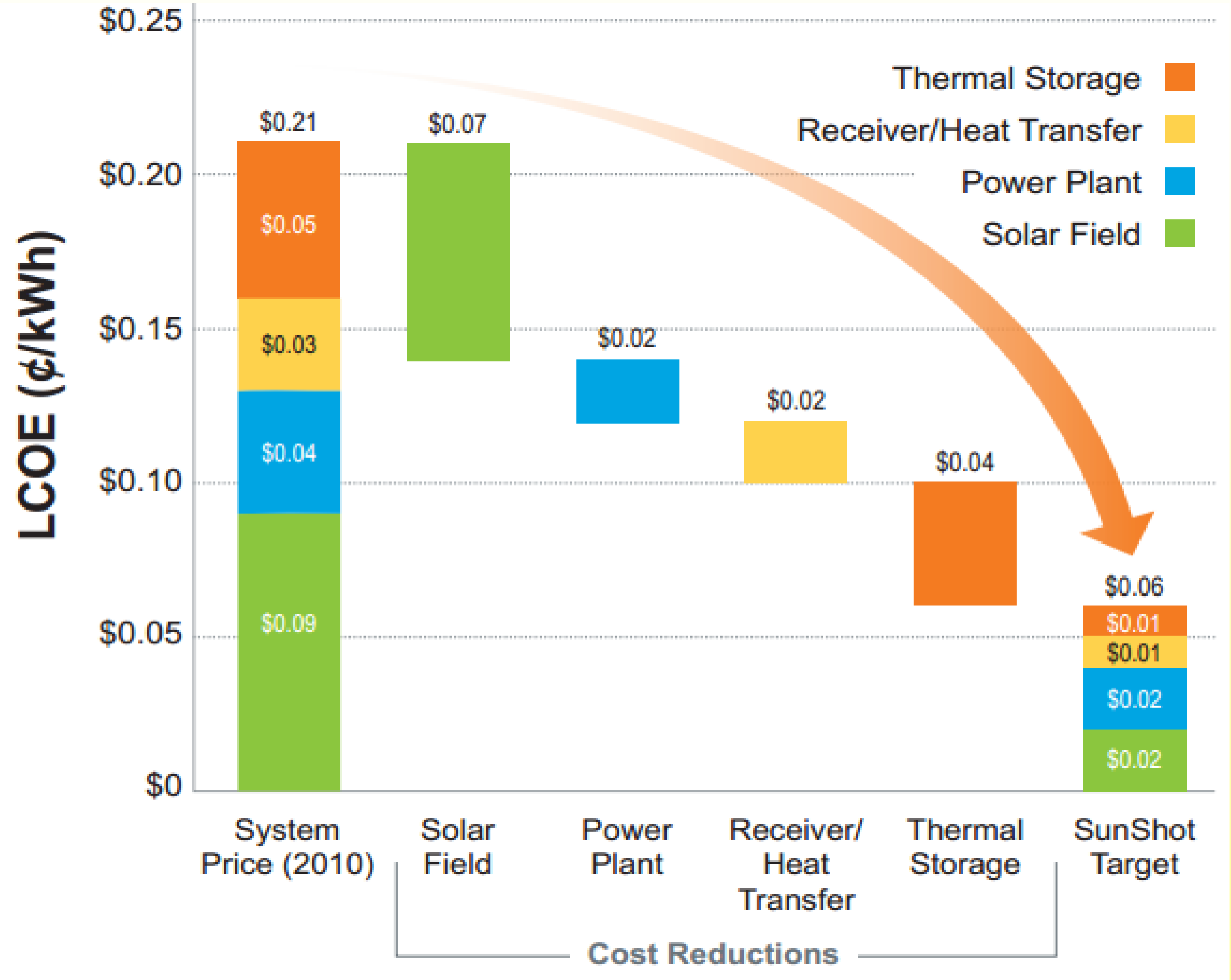
LCOE results 2012

	Installed cost (2010 USD/kW)	Capacity factor (%)	O&M (2010 USD/kWh)	LCOE (2010 USD/kWh)
Parabolic trough			0.02 to 0.035	0.14 to 0.36
No storage	4 600	20 to 25		
6 hours storage	7 100 to 9 800	40 to 53		
Solar tower				0.17 to 0.29
6 to 7.5 hours storage	6 300 to 7 500	40 to 45		
12 to 15 hours storage	9 000 to 10 500	65 to 80		

CSP costs and performance in 2011 (IRENA, June, 2012)

CSP

- LCOE
- SunShot CSP Program (DOE)



Conclusion

Thermal Energy Storage (TES) is a key technical and economic component for CSP Plants

- **Can reduce the LCOE**
- **Improve Capacity Factor**
- **Give stability to electricity generation**
- **Is low carbon emitions and can replace currents fossils back-up**

UNIVERSIDAD ADOLFO IBÁÑEZ
FACULTAD DE INGENIERÍA Y CIENCIAS

Acknowledgements of Chilean National Projects

SERC CHILE
SOLAR ENERGY RESEARCH CENTER

Solar Energy Research Center
CONICYT/FONDAP/15110019

CONICYT
Ministerio de Educación
Gobierno de Chile

Proyecto Fondecyt N°1120490 en nuevos materiales
TES: Development of High Temperature Thermal Energy Storage Material Based on Salt/Copper Foam Composites

Works and Projects TES y CSP

UNIVERSIDAD ADOLFO IBÁÑEZ
FACULTAD DE INGENIERÍA Y CIENCIAS

PUBLICACIONES RECIENTES (años 2012 y 2013)

1) G. Cáceres, N. Anrique, A. Girard, J. Degrève, J. Baeyens et al., ***"Performance of molten salt solar power towers in Chile",*** J. Renewable Sustainable Energy 5, 053142 (2013); doi: 10.1063/1.4826883
2) Zhang, HL., Baeyens, J. Degrève J., Cacères G., **"*Concentrated solar power plants: Review and design methodology"*,** Renewable and Sustainable Energy Reviews, 22, 2013, pags. 466–481.
3) A. Brems, G. Cáceres, R. Dewil, J. Baeyens, F. Pitié, **"*Heat transfer to the riser-wall of a circulating fluidised bed (CFB)"*,** Energy, 50, 2013, pags. 493-500
4) Girard, A., Muneer, T., Caceres, G., **"*Achieving Higher Heat Pump COP through the use of roof-top thermal solar collectors"***, Energy Conversion and Management , 2013 (DOI: 10.1177/1420326X13480057)
5) *N. Corral, N. Anrique, D. Fernandes, C. Parrado, G. Caceres,* ***"Power, placement and LEC evaluation to install CSP plants in northern Chile",*** Renewable and Sustainable Energy Reviews, 16, 2012, pags. 6678–6685.
6) *D. Fernandes, F. Pitié, G. Cáceres and J. Baeyens,* ***"Thermal energy storage: How previous findings determine current research priorities",*** Energy, vol. 39, 2012, pags. 246-257.

Participación como observador experto en el IA ECES de **la Agencia Internacional de la Energía**, (es la primera universidad de Latinoamérica en obtener una plaza).

Una de las universidades lideres en el **SERC-Chile**

Proyecto Fondecyt en nuevos materiales TES: **Development of High Temperature Thermal Energy Storage Material Based on Salt/Copper Foam Composites**

Colaboración con universidades o centros extranjeros como: **WARWICK (UK), NAPIER (UK), 4CMR (U. de Cambridge, UK), LEUVEN (Belgica), Lab. PROMES (Francia), U de Perpignan (Francia).**

UNIVERSIDAD ADOLFO IBÁÑEZ
FACULTAD DE INGENIERÍA Y CIENCIAS

Thanks for your attention!!!

Professor
GUSTAVO CÁCERES

COMITE CHILENO

Sexta Versión Congreso Bienal Internacional Cigré 2013 "Variabilidad del Costo del Suministro Eléctrico"