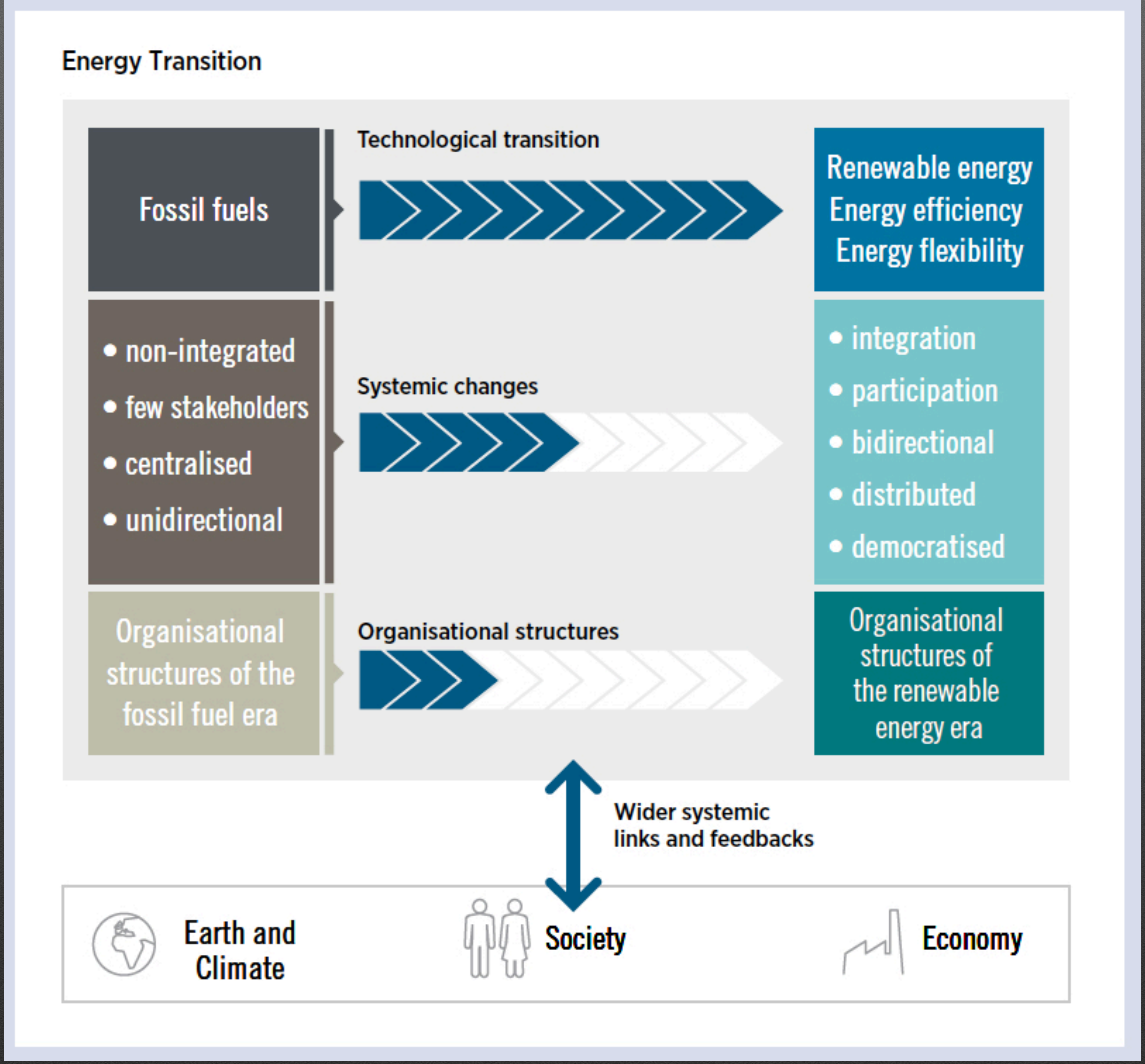
# *Almacenamiento térmico: tecnologías y aplicaciones*

Pedro Curto, Alejandro Medina

Montevideo, septiembre 2024

# The challenge of the energy transition




IRENA, World Energy Transitions Outlook: 1.5° C Pathway (2021)

# Storage is to play a central role in this transition

- Demand shifting
- Variable supply integration
- Sector integration
- Network management

# Electric energy demand in Spain.
# Data from REE, 6/09/24

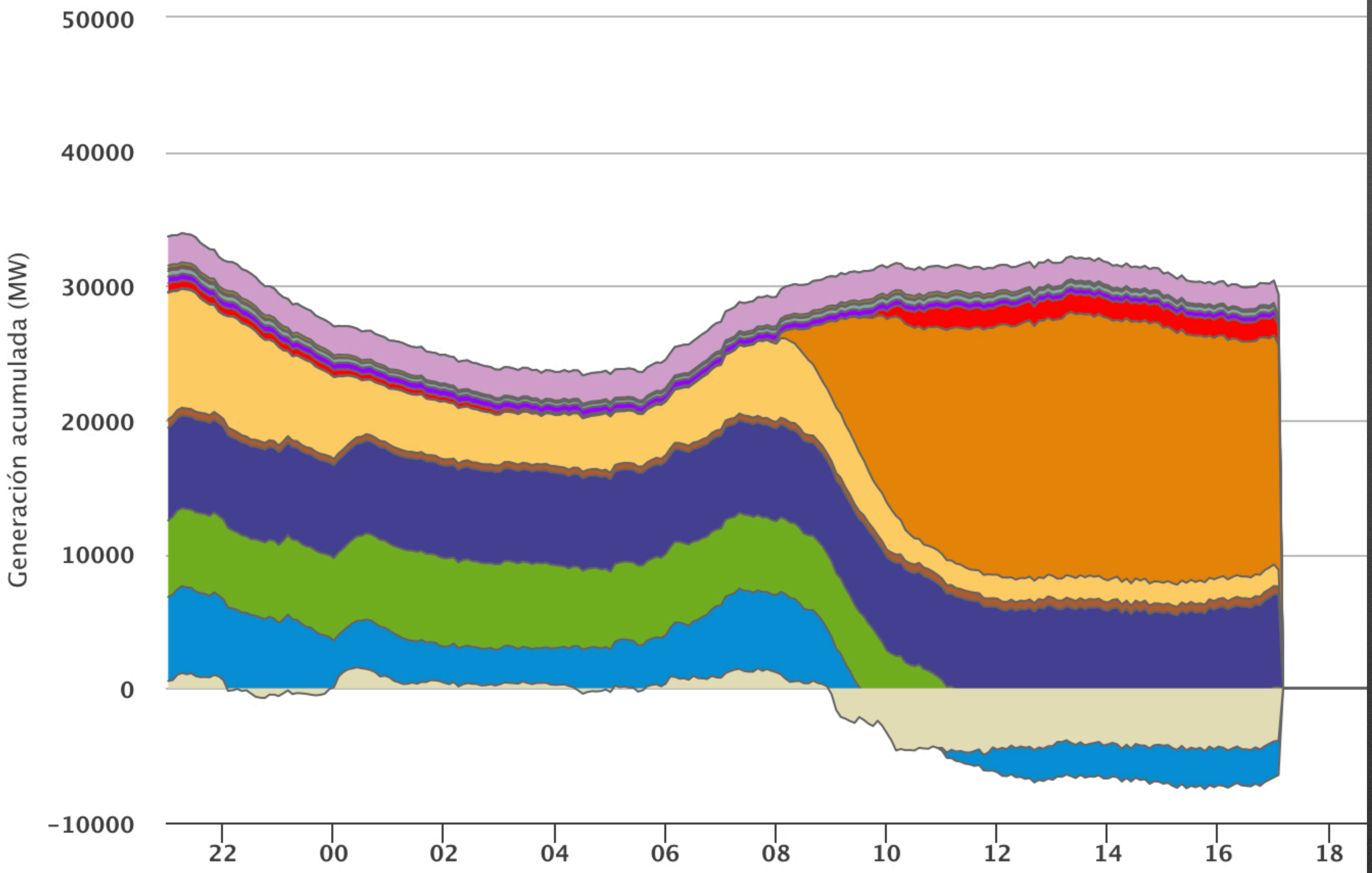
*https://demanda.ree.es*

# Electric energy demand in Spain.
# Data from REE, 6/09/24

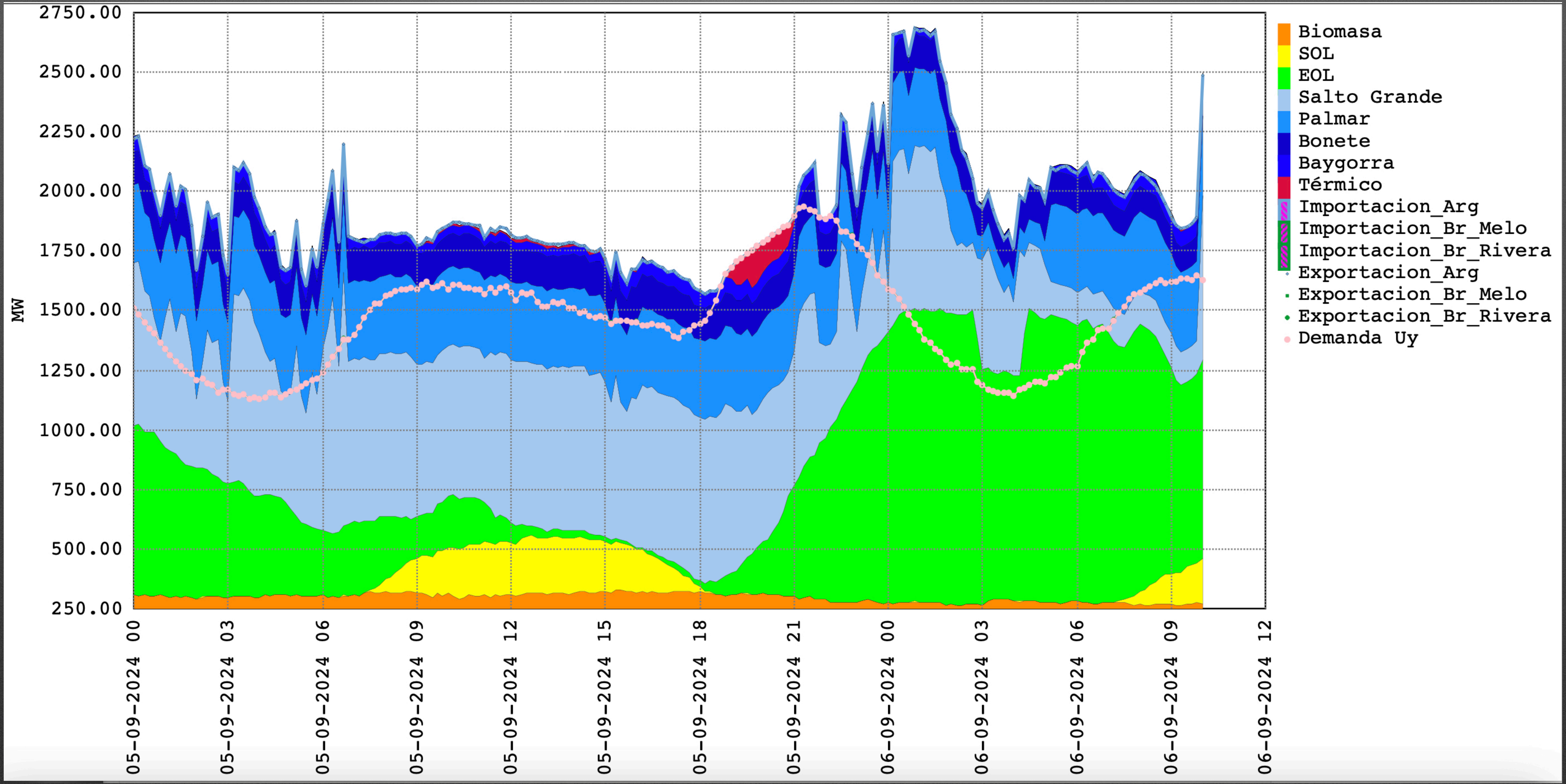
https://demanda.ree.es

Estructura de generación acumulado progresivo (MW) a las 21:00 - 06/09/2024

| | | |
|---|---|---|
| Cogeneración y residuos | 1651 | 4,43(%) |
| Turbina de vapor | 132 | 0,35(%) |
| Turbina de gas | 54 | 0,15(%) |
| Motores diésel | 353 | 0,95(%) |
| Térmica renovable | 443 | 1,19(%) |
| Solar térmica | 1427 | 3,83(%) |
| Solar fotovoltaica | 17593 | 47,25(%) |
| Ciclo combinado | 1620 | 4,35(%) |
| Carbón | 638 | 1,71(%) |
| Nuclear | 6928 | 18,61(%) |
| Eólica | 6392 | 17,17(%) |
| Hidráulica | -2716 | 0(%) |
| Intercambios int | -4591 | 0(%) |

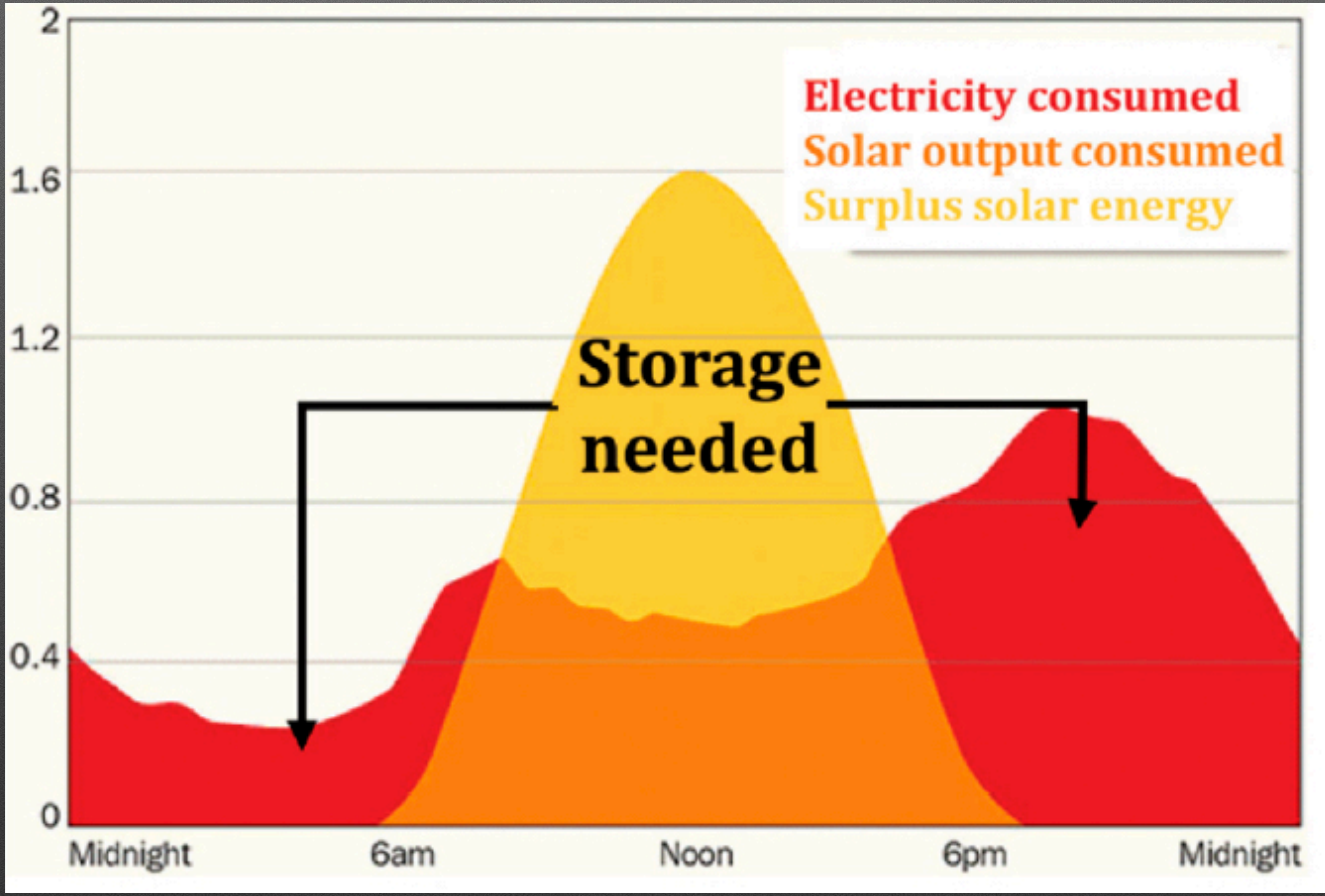


# Curvas de demanda y generación en Uruguay




https://pronos.adme.com.uy

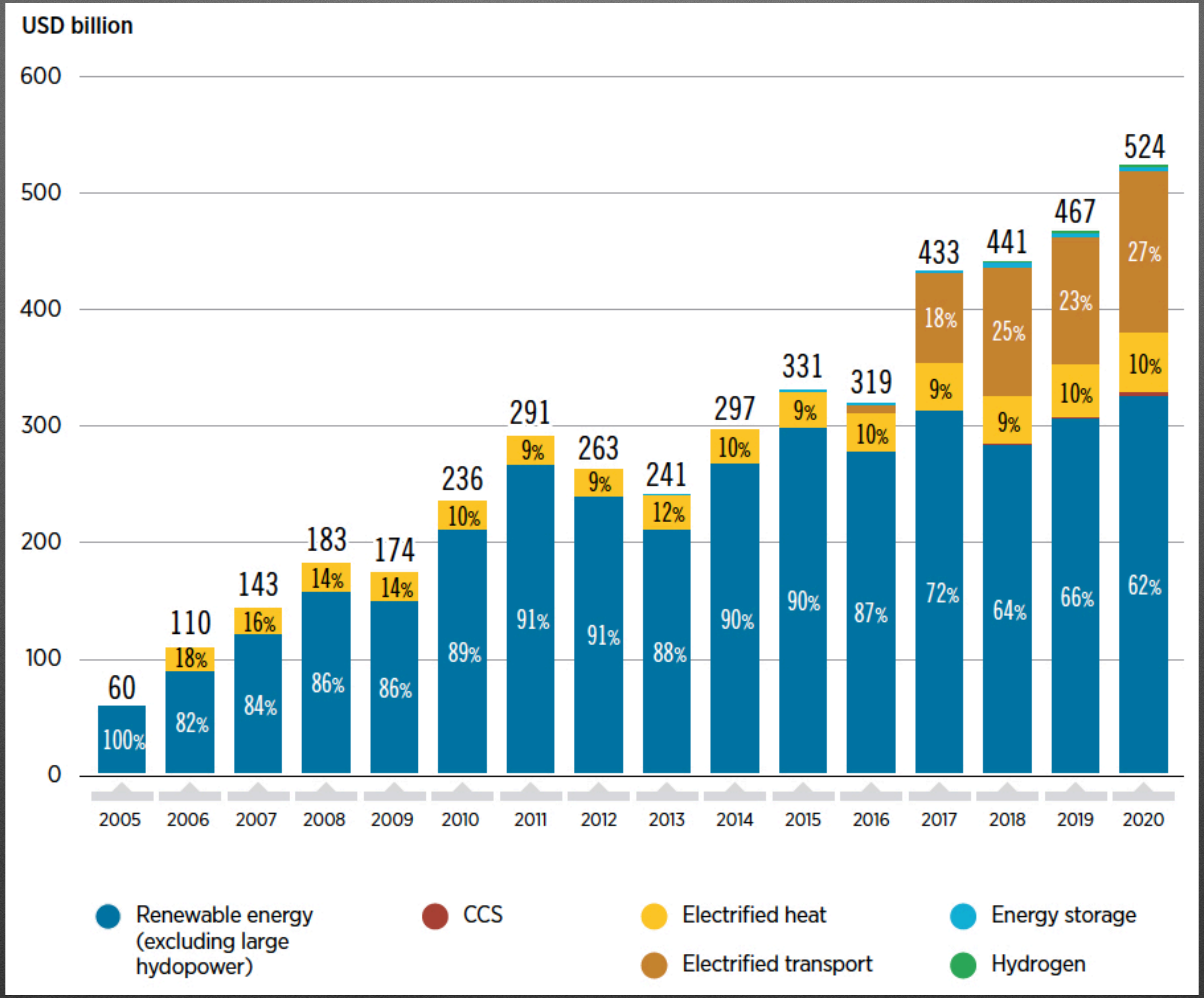
# A particular example




Daily electricity household demand (in kW) and solar production in Melbourne

A.J. Carrillo *et al.*, Chem. Rev. 119, 4777 (2019)

# Worldwide investments in key elements of the Energy Transition




CCS: carbon capture and storage

Although investments on renewable energy are strong and continuous in time, storage is still very far away

## Power

| | | Annual average investments USD billion/yr: Historical 2017-19 | Annual average investments USD billion/yr: 1.5°C Scenario 2021-50 |
|---|---|---|---|
| Power generation capacity | Hydro - all (excl. pumped) | 22 | 85 |
| | Biomass (total) | 13 | 69 |
| | Solar PV (utility and rooftop) | 115 | 237 |
| | CSP | 3 | 84 |
| | Wind onshore | 80 | 212 |
| | Wind offshore | 18 | 177 |
| | Geothermal | 3 | 24 |
| | Marine | 0 | 59 |
| Grids and flexibility | Electricity network | 271 | 600 |
| | Flexibility measures (*e.g.* storage) | 4 | 133 |

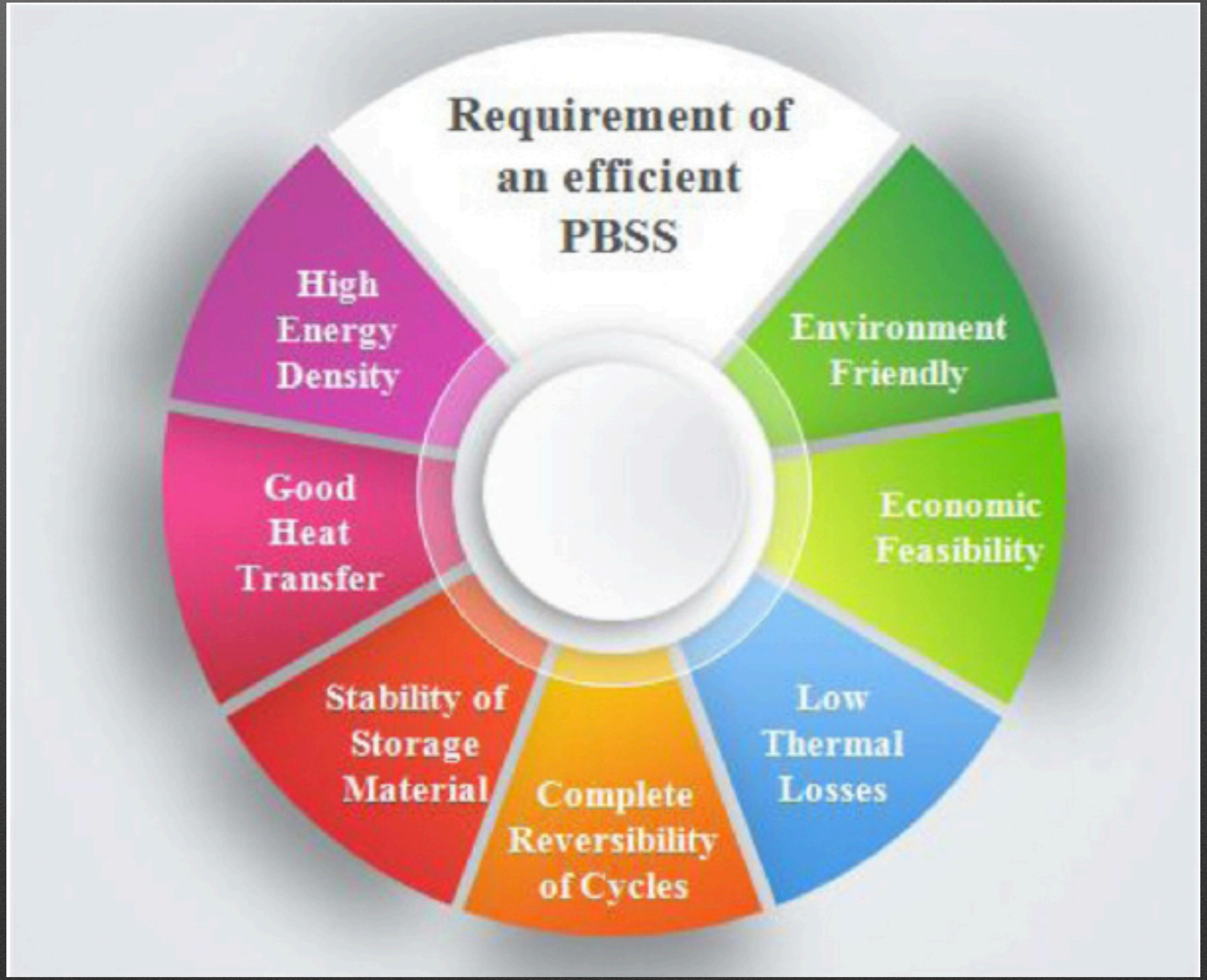
IRENA forecast for required investments in the 1.5°C scenario

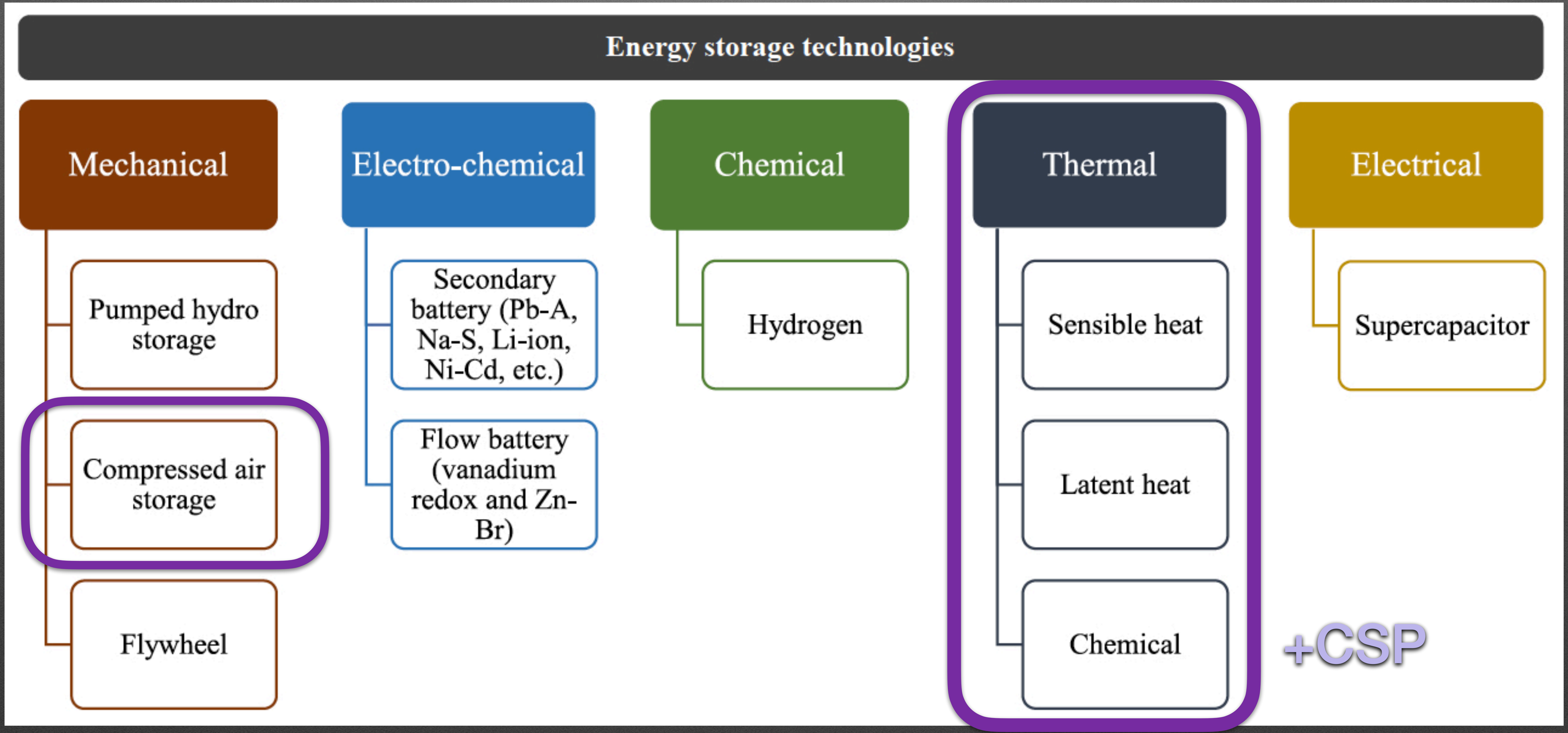
# Technological advances are imperative

- New concepts: research
- Development of already proven technologies

Desirable requirements for storage concepts:

A. Large scale capacity and high energy density
B. Good efficiency
C. Flexible storing periods
D. To avoid the use of critical materials
E. Large number of operation cycles
F. Economically affordable for investors and stakeholders






Thermal Energy Storage (TES) has a privileged position among other technologies because in principle is capable to achieve the mentioned requirements

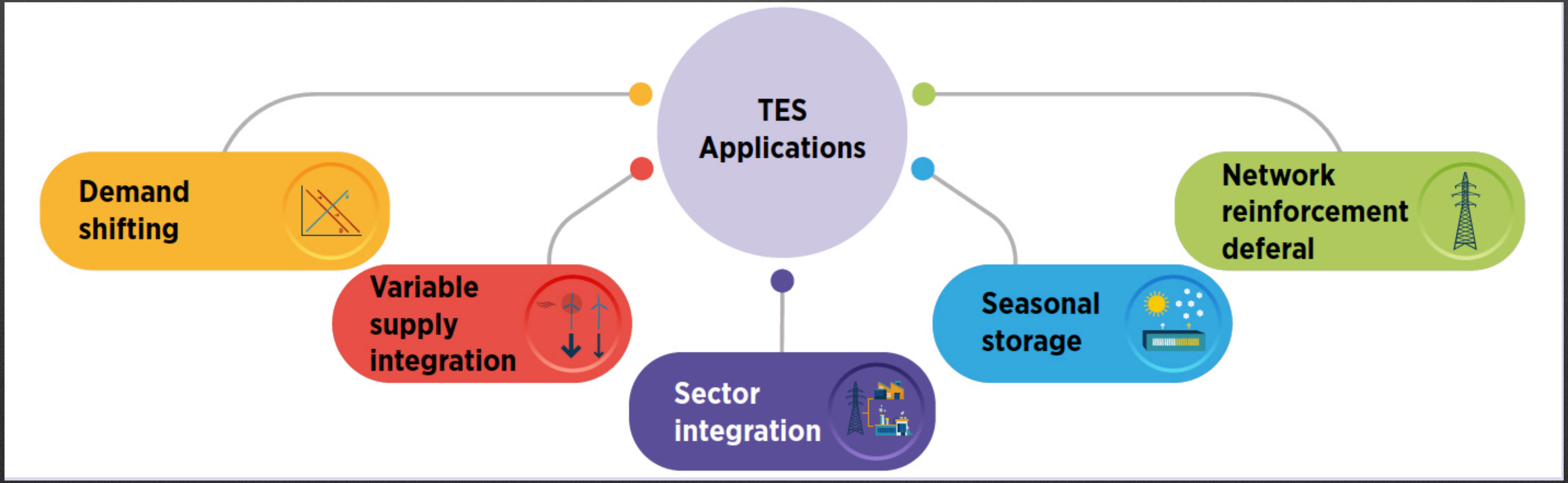
# What is Thermal Energy Storage (TES)?

It is the temporary storage of energy by heating or cooling a storage medium, so that the stored energy can be used at a later time for power generation, heating or cooling applications

*(European Association for Storage of Energy, 2017)*

# Where is it used nowadays?

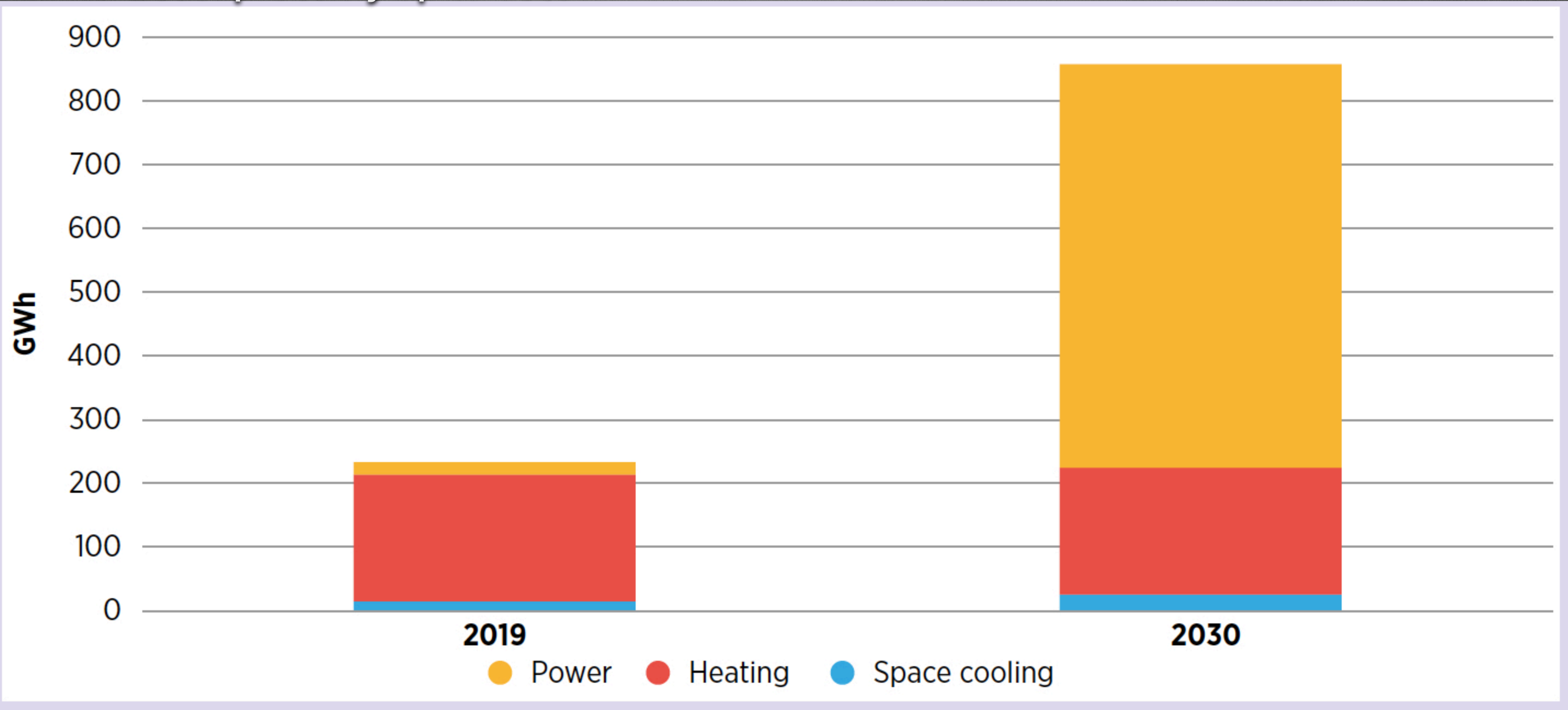
Today TES is tested and deployed in a variety of applications as: power generation, district heating, cold chain logistics



# Irena projections for installed TES capacity

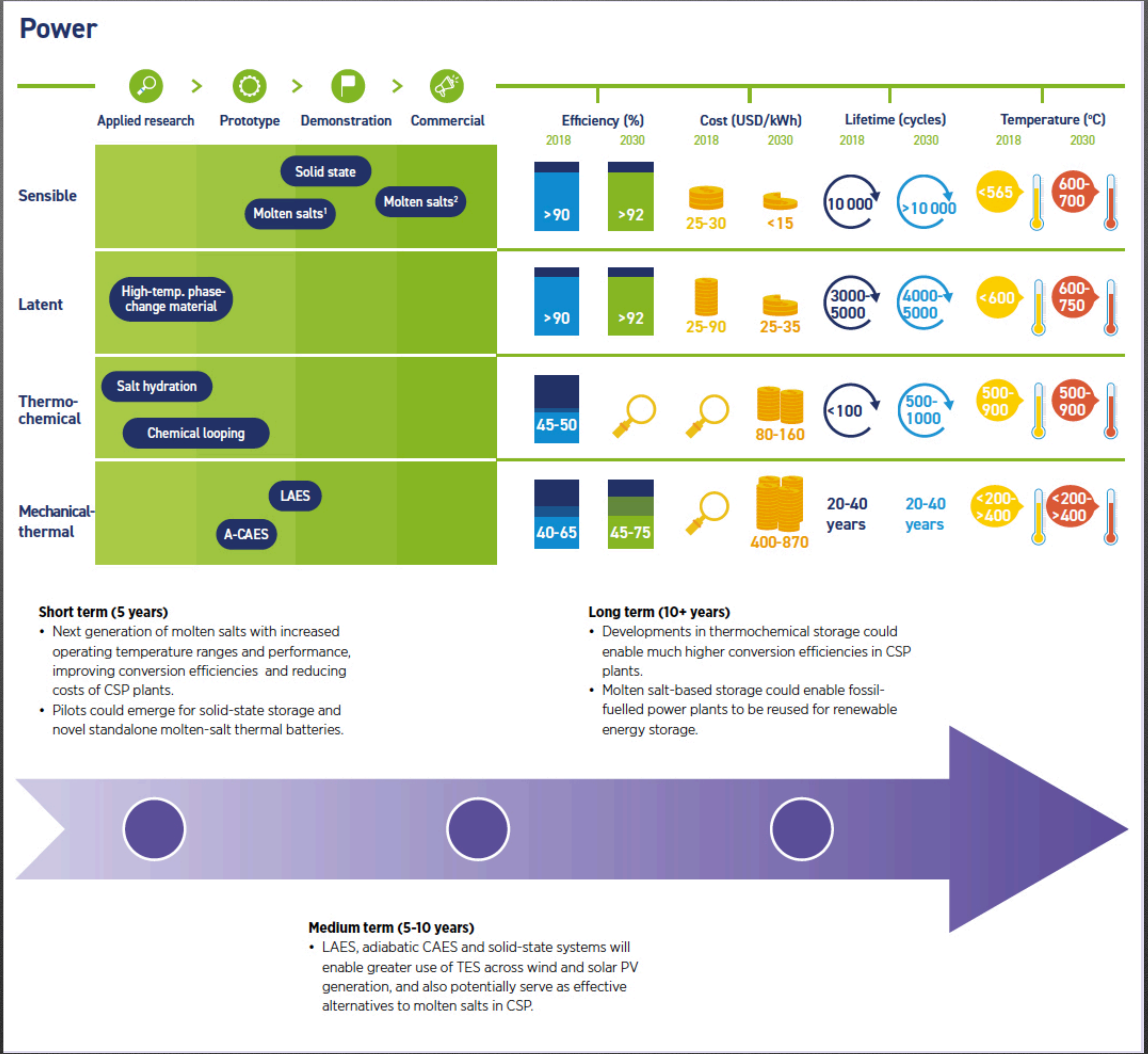
## Renewable energies share evolution:

- 2018: 10% power share worldwide
- 2030: 35%
- 2050: probably up to 50%

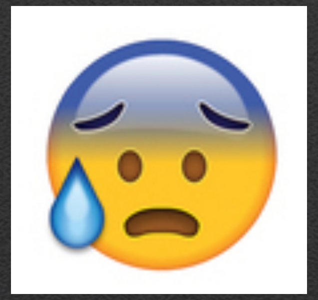



Thermal Energy Storage provides the essential flexibility to integrate high shares of wind and solar PV power

# Some types of TES Technologies (power applications)

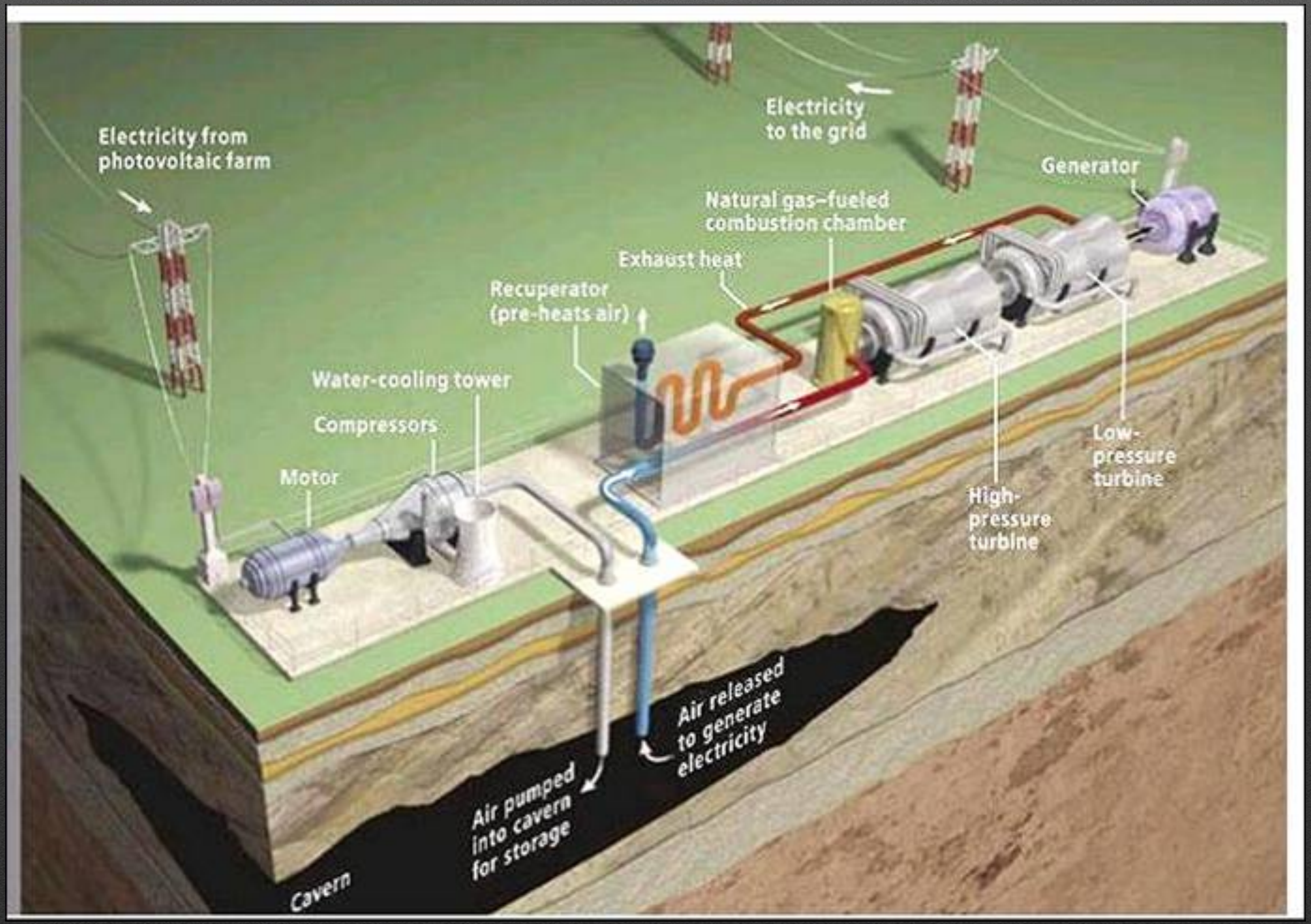



(A jungle of acronyms)



# TES examples:

1. *Concentrated solar power* (CSP)
2. *Compressed air energy storage* (CAES, A-CAES…)
3. *Liquid air energy storage (LAES)*
4. *Pumped heat energy storage* (PTES, PHES…)

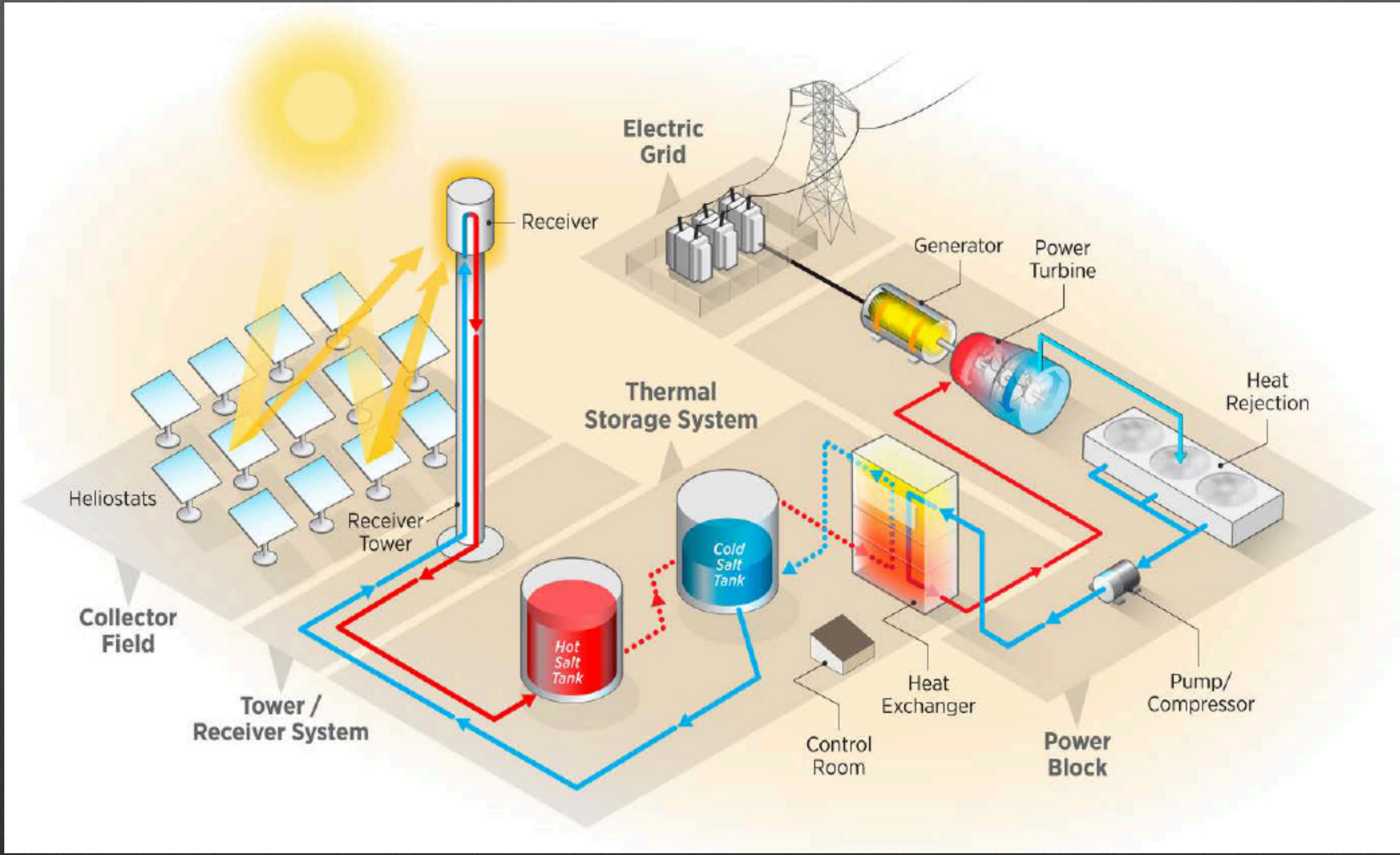


# TES technologies

| EES | Mechanical | Thermo-mechanical | | |
|---|---|---|---|---|
| | Pumped-hydro | PTES | CAES | LAES |
| Power rating (MW) | 30-5000 | 10-150 | 0.5-1000 | 1-300 |
| Energy capacity (MWh) | 100-20000 | Up to GWh | 0.1-2860 | Up to GWh |
| Energy density (Wh/l) | 0.5-2 | 10-100 | 0.5-20 | 50-200 |
| Energy efficiency (%) | 65-87 | 48-75 | 40-90 | 45-70 |
| thermal storage | | | | |
| Response time | Mins. | s-Mins. | Mins. | Mins. |
| Discharge time | 1-24 h | 1-12 h | 1-24 h | 1-12 h |
| Storage duration | Hrs.-months | Hrs.-days | Hrs.-months | Hrs.-days |
| Site constraints | Yes | No | Yes[(a)] | No |
| TRL Level | 9 | 2-5 | 5 -9 | 7-8 |
| Maturity | Mature | In-develop. | (b) | In-develop. |
| Installed capacity | 168 GW | - | 431 MW | ~5 MW |

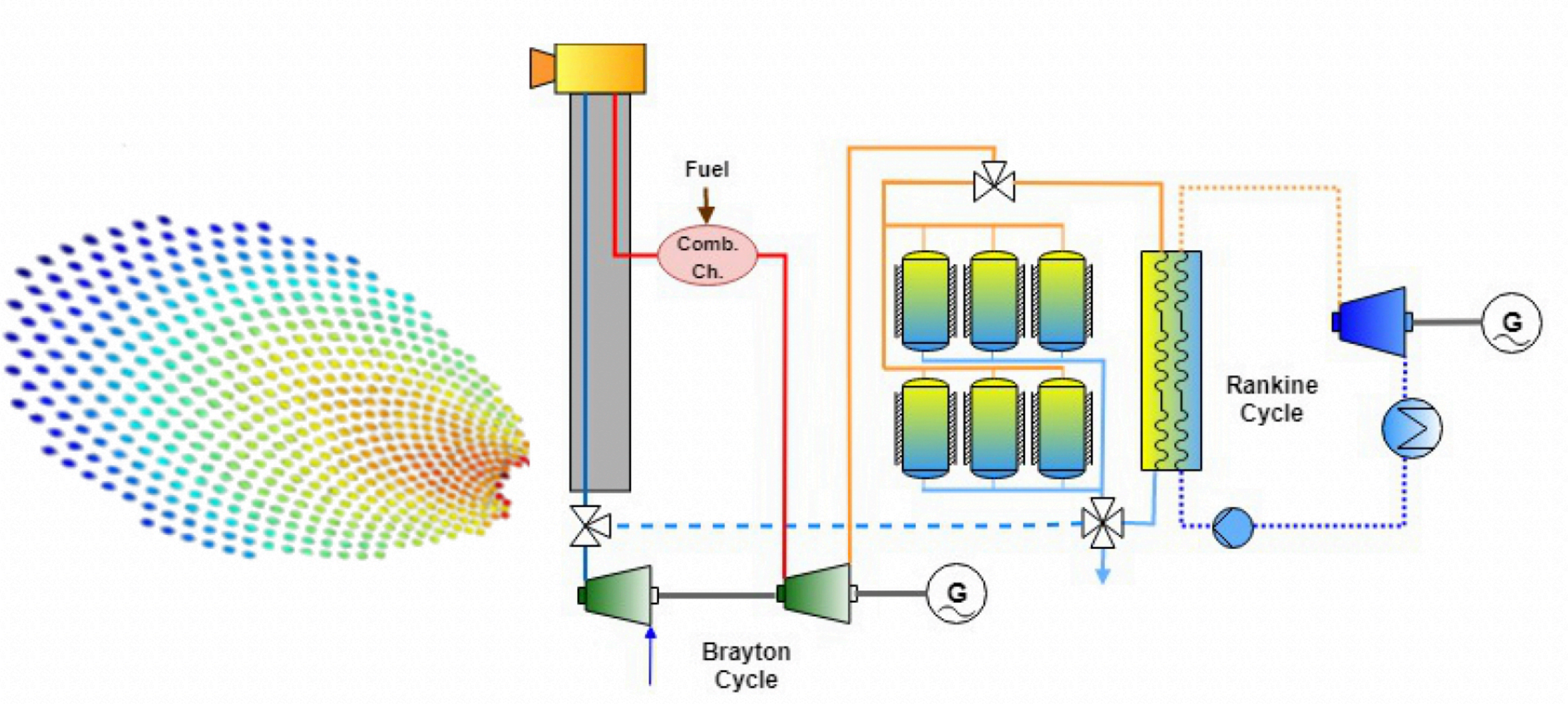
# 1.- *Concentrated solar power (CSP)*

*Rankine cycles with molten salt storage*



# 1.- *Concentrated solar power (CSP)*

## High temperature Brayton cycles with solid storage



# 1.- *Concentrated solar power (CSP)*

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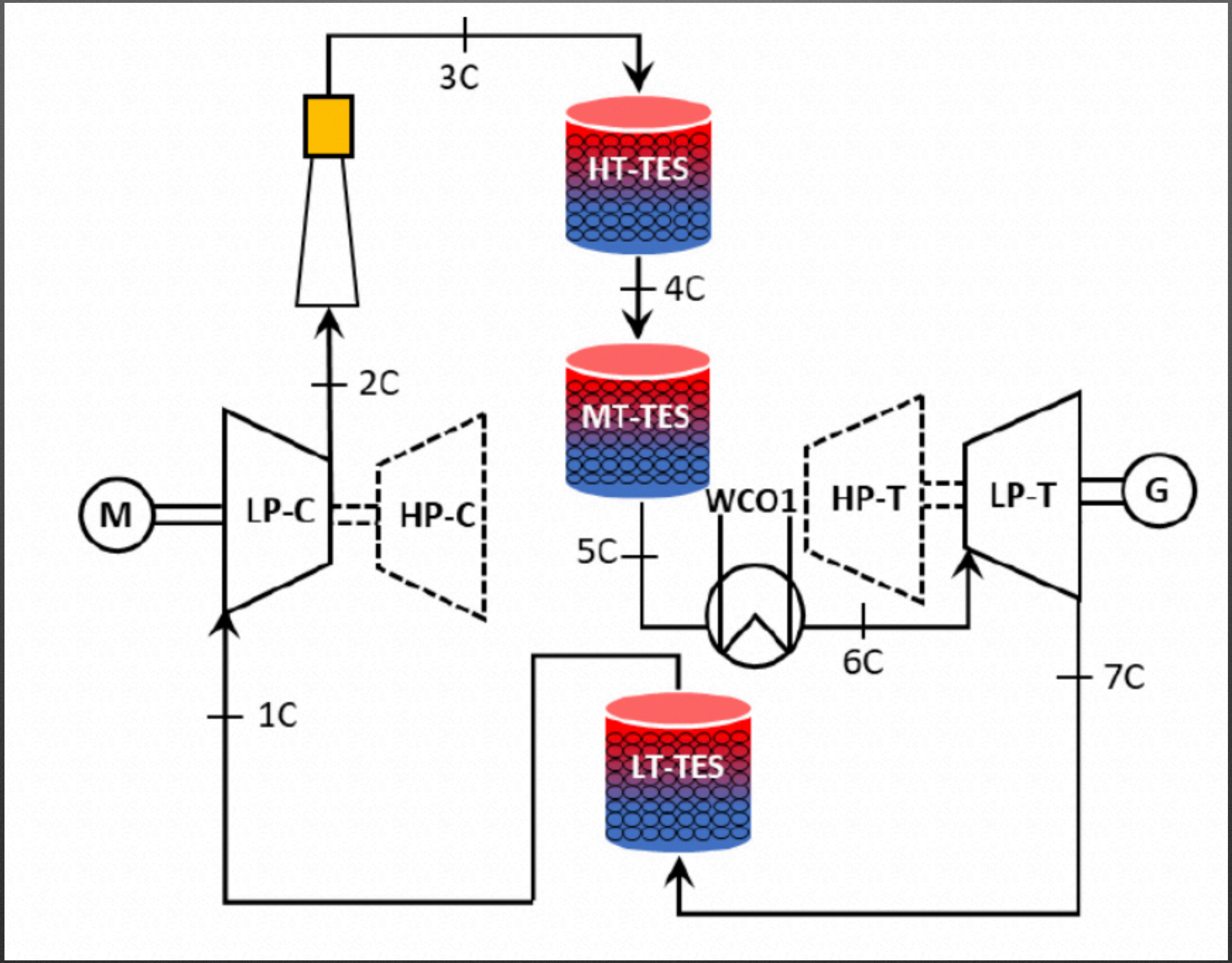
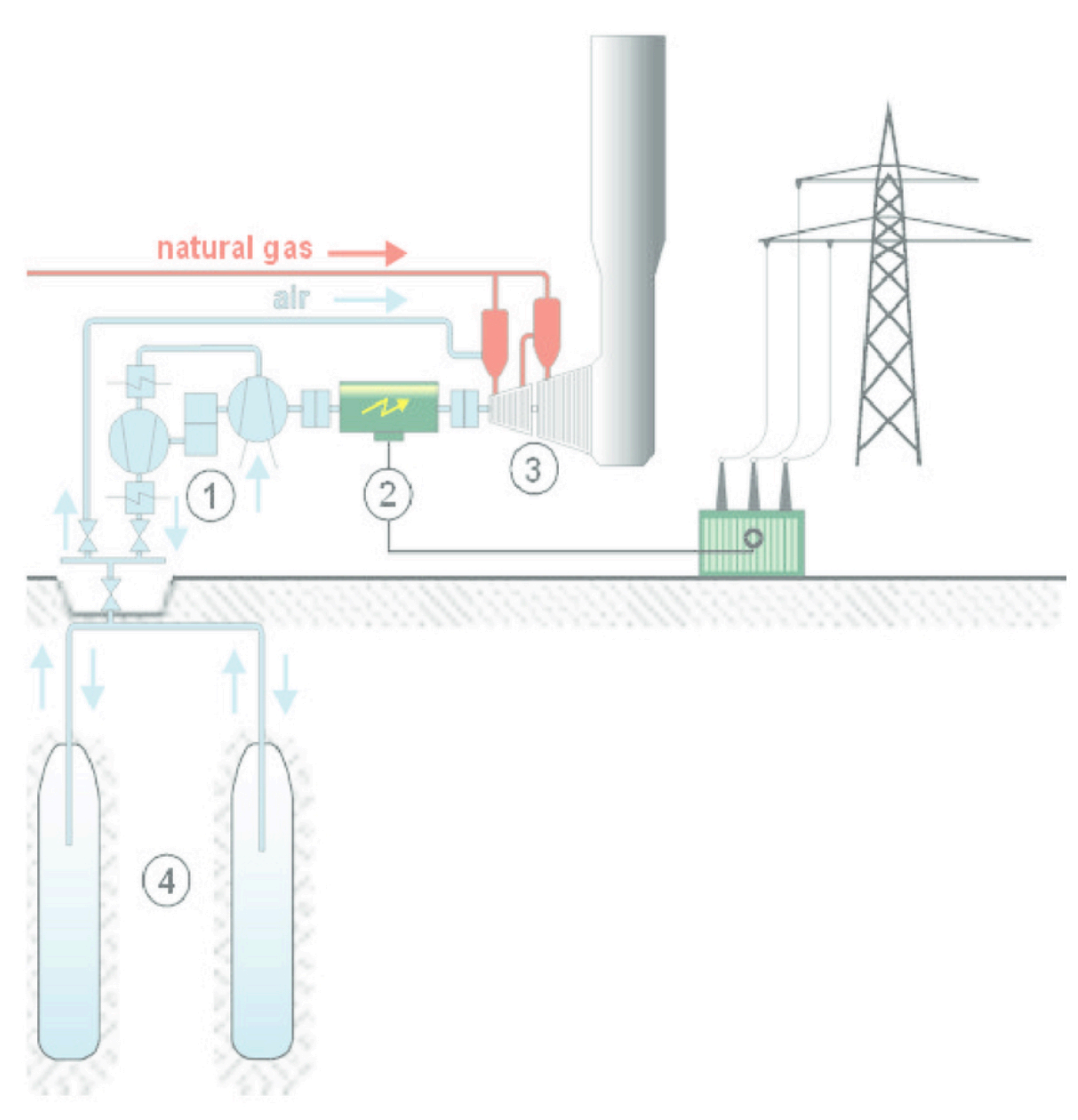


# 2.- *Compressed air energy storage (CAES)*

## Diabatic CAES

**Huntorf plant, Germany. In operation from 1978, efficiency about 42%. 290 MW**

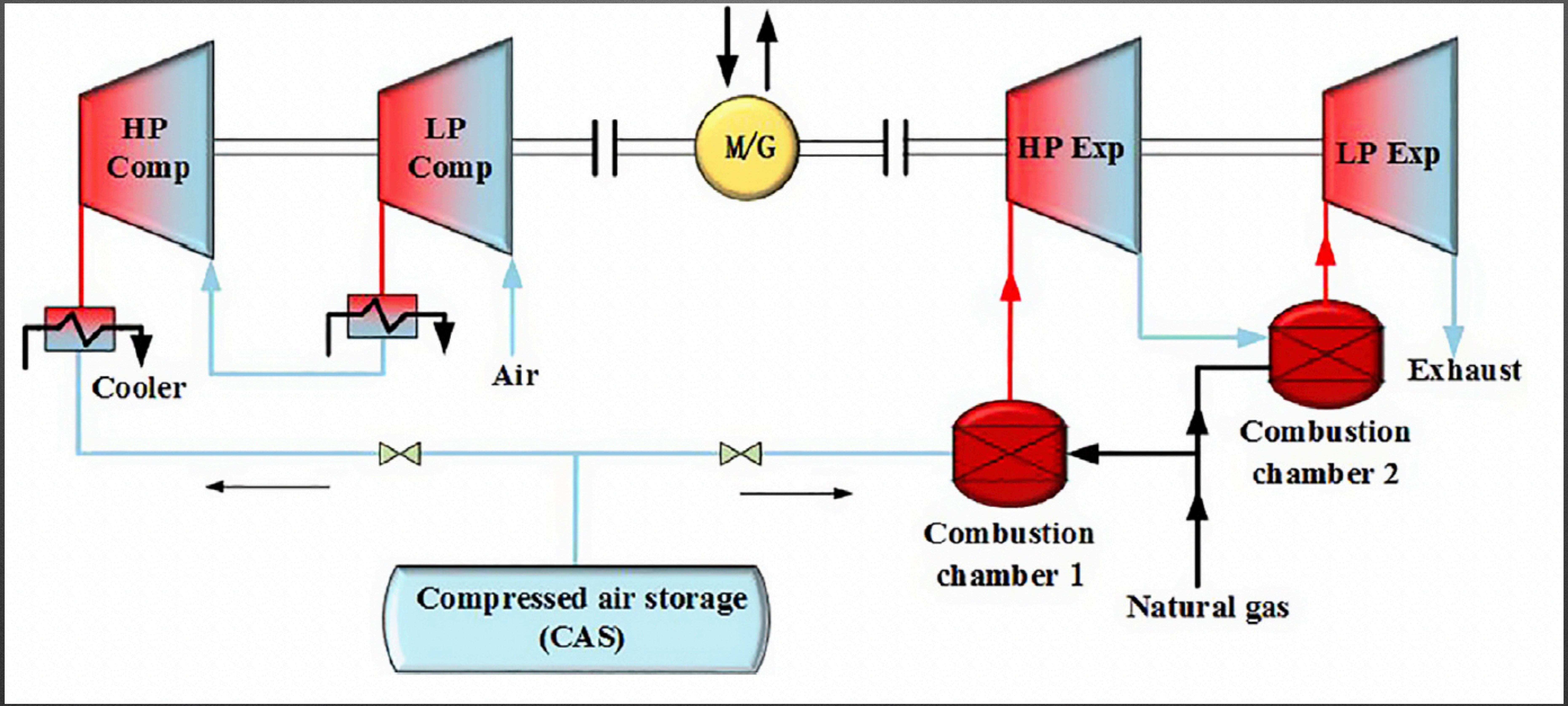




Huntorf CAES scheme (1 □ compressor, 2 □ generator, 3 □ gas turbine, 4 □ salt caverns) [7]

## 2.- *Compressed air energy storage (CAES)*

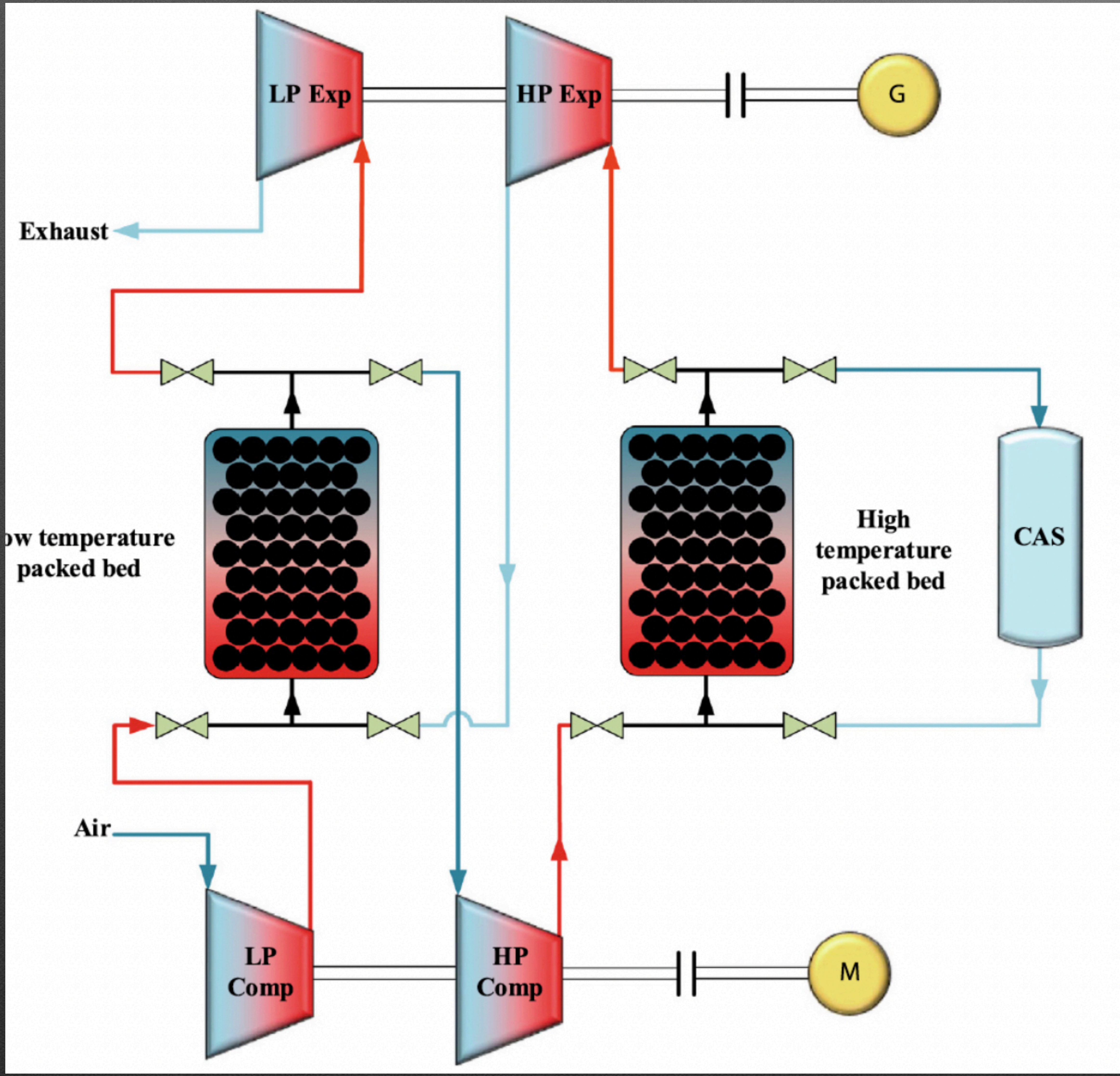
### Diabatic CAES

### Huntorf plant scheme

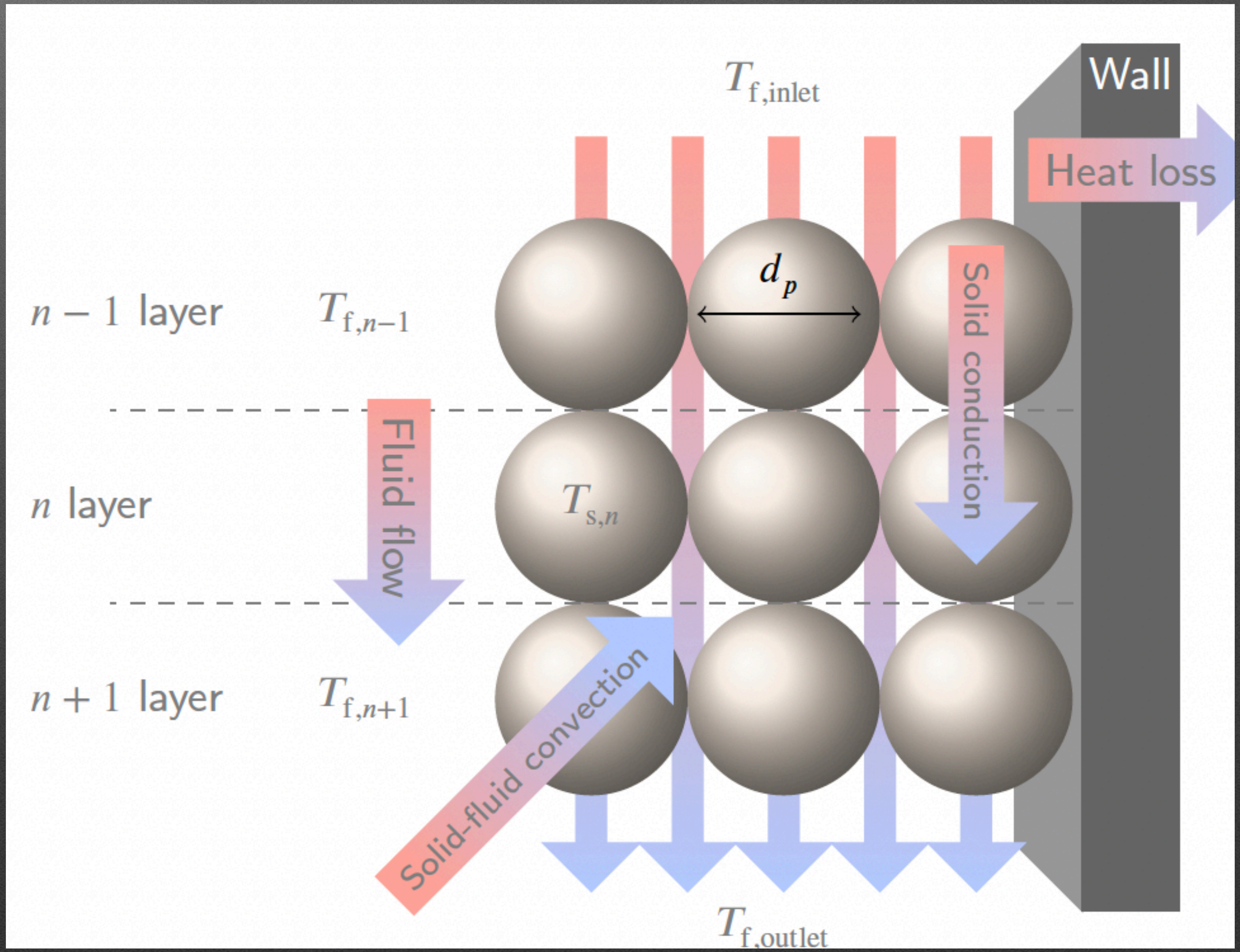


# 2.- *Compressed air energy storage (CAES)*

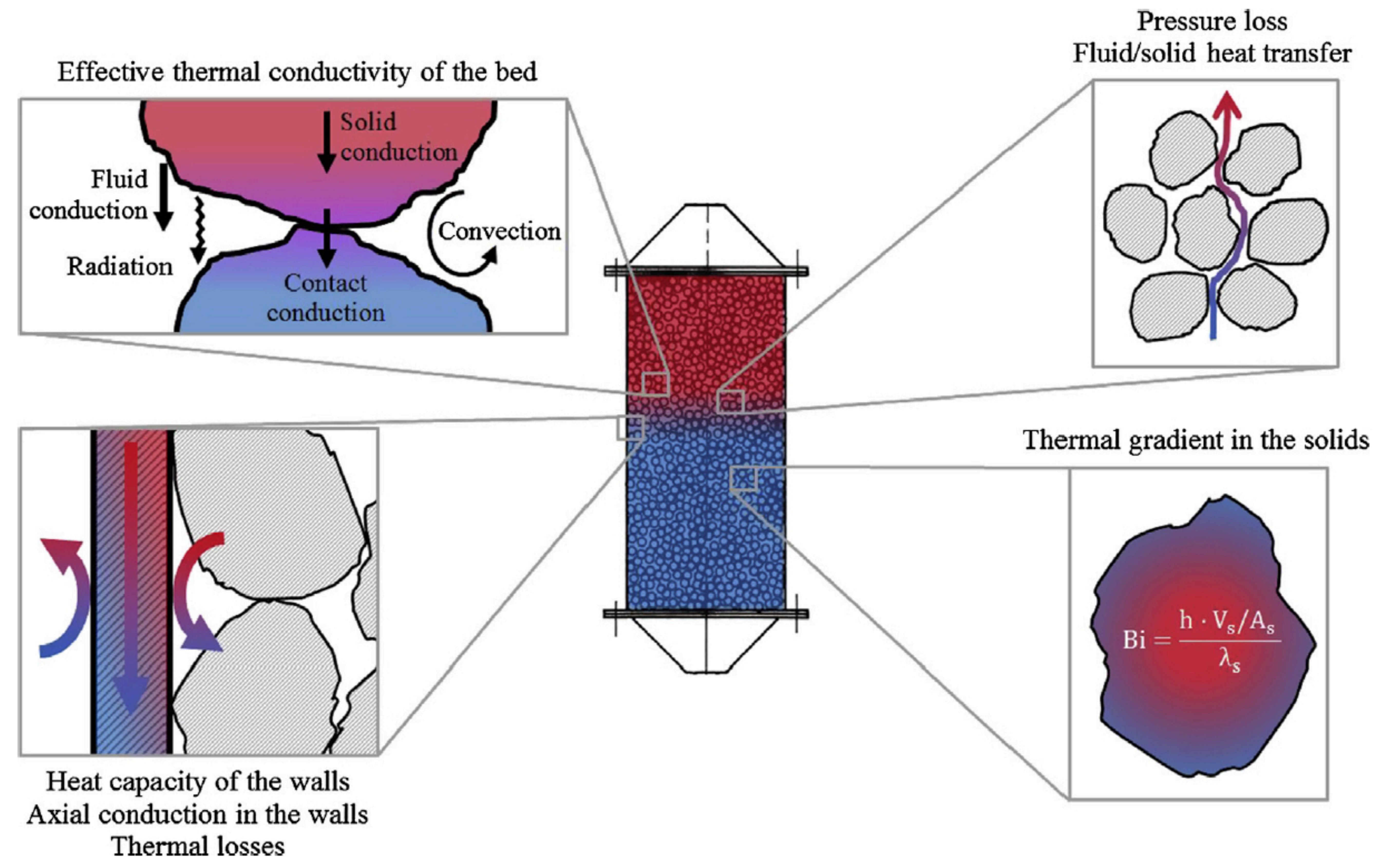
## Adiabatic CAES (A_CAES)

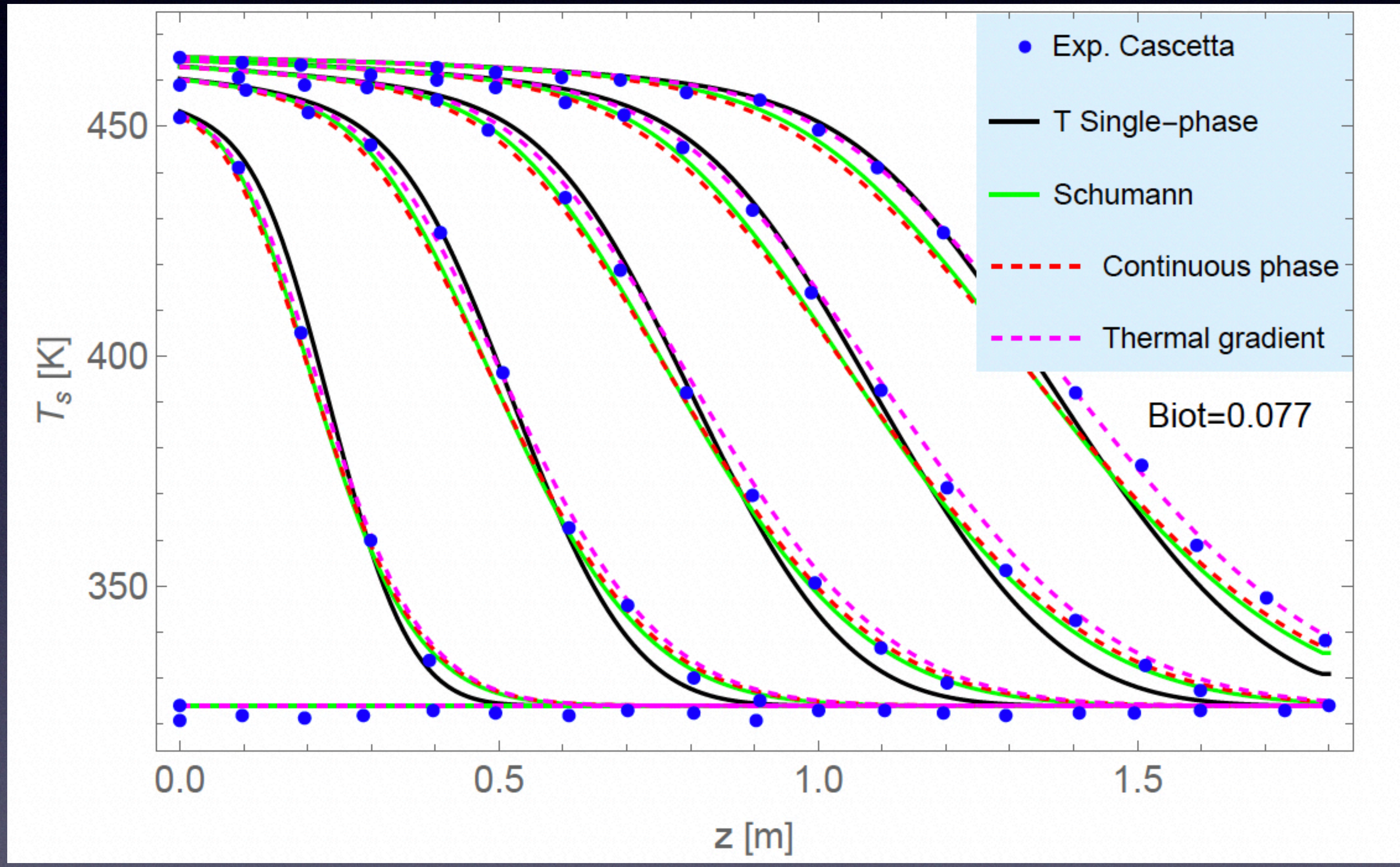



## Packed bed solid storage



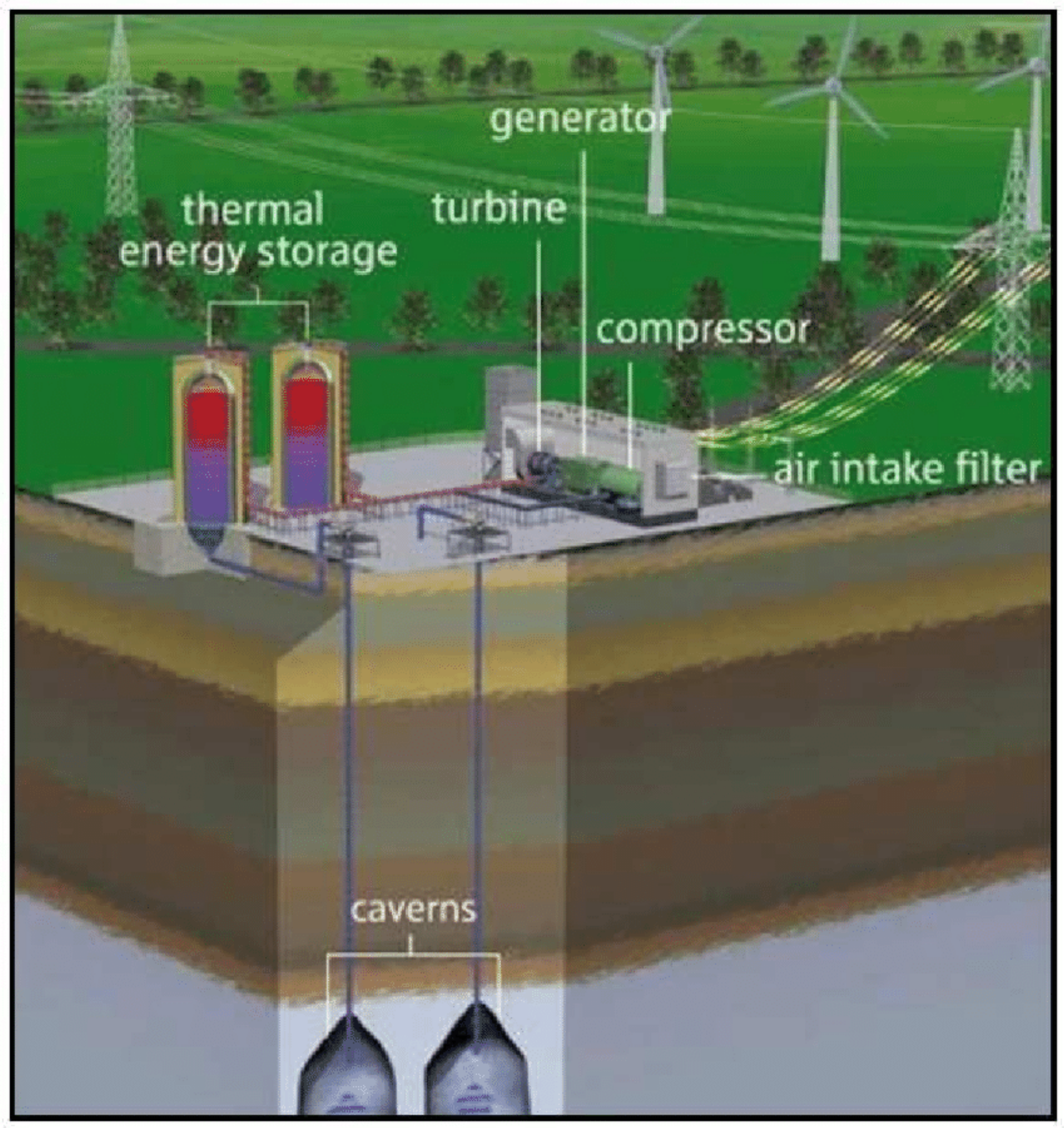
# High temperature storage (over 800°C)
# *Packed bed* media



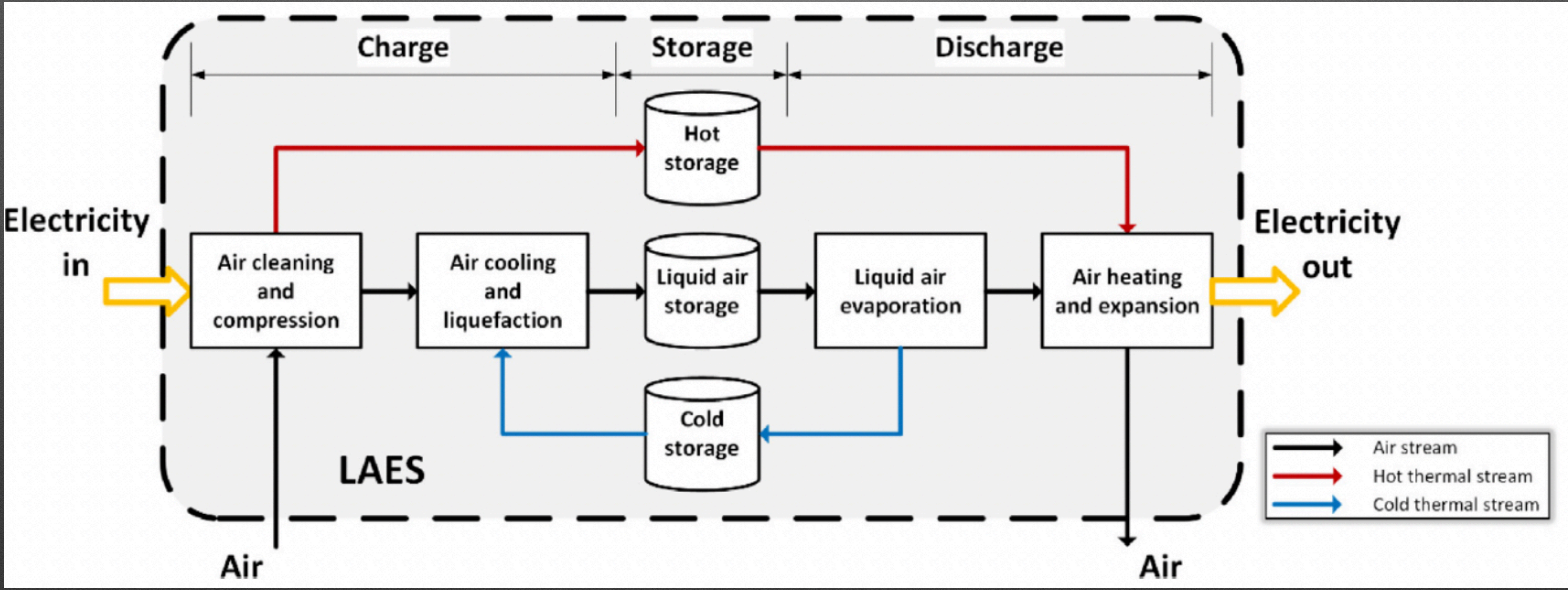

A. Gautam *et al*., J. Ener. Storage 27 (2020) 101046

# ADELE A-CAES project, Germany (2017)

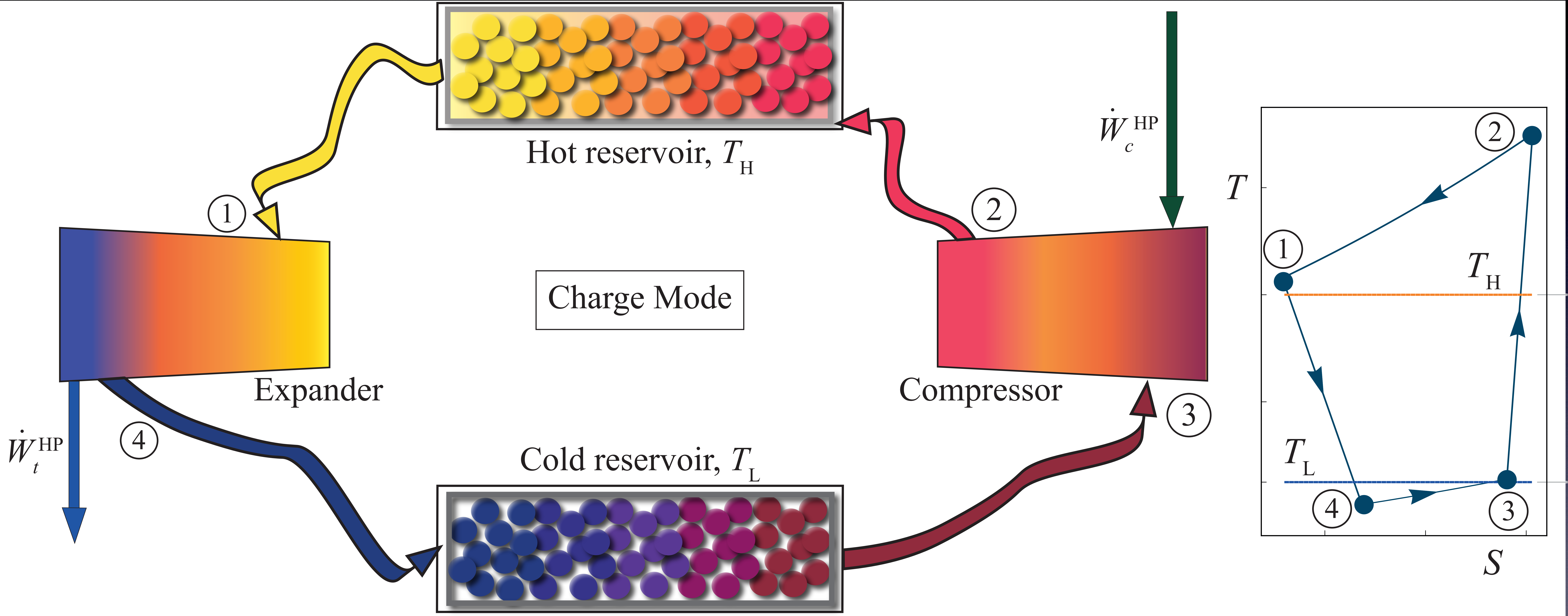



200 MW
Maximum T: 600ºC
Maximum pressure: 100 bar
Efficiencies: 60-70%

# 3.- *Liquid Air Energy Storage (LAES)*



# 4.- *Pumped Heat Energy Storage* (PHES, PTES…)
(storage in solids)




**Pump and engine coupled Brayton cycles**

Round-trip efficiency

$$\phi = \frac{W_{out}}{W_{in}} = \frac{P_{out}}{P_{in}}$$

D. Pérez-Gallego *et al.*, Entropy. 23 (2021) 1564

# Still R&D&i required: only pre-commercial scale prototypes

Energy & environment

## Newcastle University connects first grid-scale pumped heat energy storage system

News | 2 min read

World-first in grid-scale pumped heat energy storage places UK at forefront of energy storage R&D, team claims

Newcastle University, 2019

Packed bed (sand, gravel)
Working fluid, Ar
Inlet pressure, 12 bar
$T_{max}$: 750 K
*Round-trip efficiency*: 75~80%

# Material properties are essential

**Thermophysical requirements**

a. High specific heat

b. High density

c. High thermal conductivity

d. Wide thermal stability

e. Chemical stability

f. Low thermal expansions

**Practical issues**

I. Non-toxic

II. Non-flammable

III. Eco-friendly

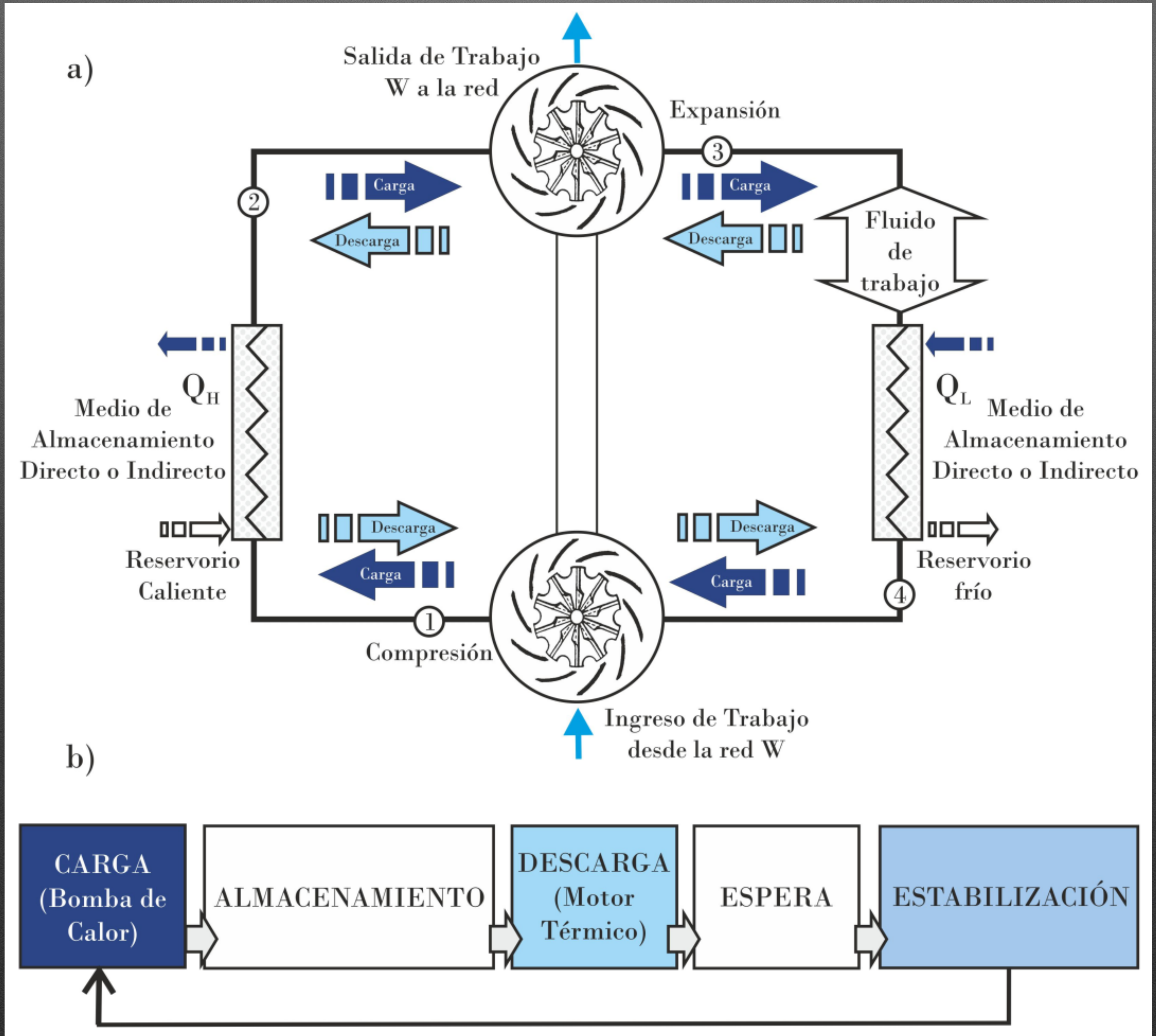
IV. Low cost and availability

# Thermophysical properties of several TES materials

| Storage medium | Temperature | | Average density (kg/m$^3$) | Average heat conductivity (W/mK) | Average heat capacity (kJ/kg K) |
|---|---|---|---|---|---|
| | Cold (°C) | Hot (°C) | | | |
| Sand-rock-mineral oil | 200 | 300 | 1700 | 1 | 1.3 |
| Reinforced concrete | 200 | 400 | 2200 | 1.5 | 0.85 |
| NaCl (solid) | 200 | 500 | 2160 | 7 | 0.85 |
| Cast iron | 200 | 400 | 7200 | 37 | 0.56 |
| Silica fire bricks | 200 | 700 | 1820 | 1.5 | 1 |
| Magnesia fire bricks | 200 | 1200 | 3000 | 1 | 1.15 |
| HITEC solar salt | 120 | 133 | 1990 | 0.60 | – |
| Mineral oil | 200 | 300 | 770 | 0.12 | 2.6 |
| Synthetic oil | 250 | 350 | 900 | 0.11 | 2.3 |
| Silicon oil | 300 | 400 | 900 | 0.1 | 2.1 |
| Nitrite salts | 250 | 450 | 1825 | 0.57 | 1.5 |
| Nitrate salts | 265 | 565 | 1870 | 0.52 | 1.6 |
| Carbonate salts | 450 | 850 | 2100 | 2 | 1.8 |
| Liquid sodium | 270 | 53 | 850 | 71 | 1.3 |
| Silicon carbide | 200 | 1400 | 3210 | 3.6 | 1.06 |
| $SiO_2$ (crystobalite) | 200 | 1200 | 2350 | 0.92 | 1.13 |

# 4.- *PHES with liquid storage*

*Rankine or Brayton cycles*



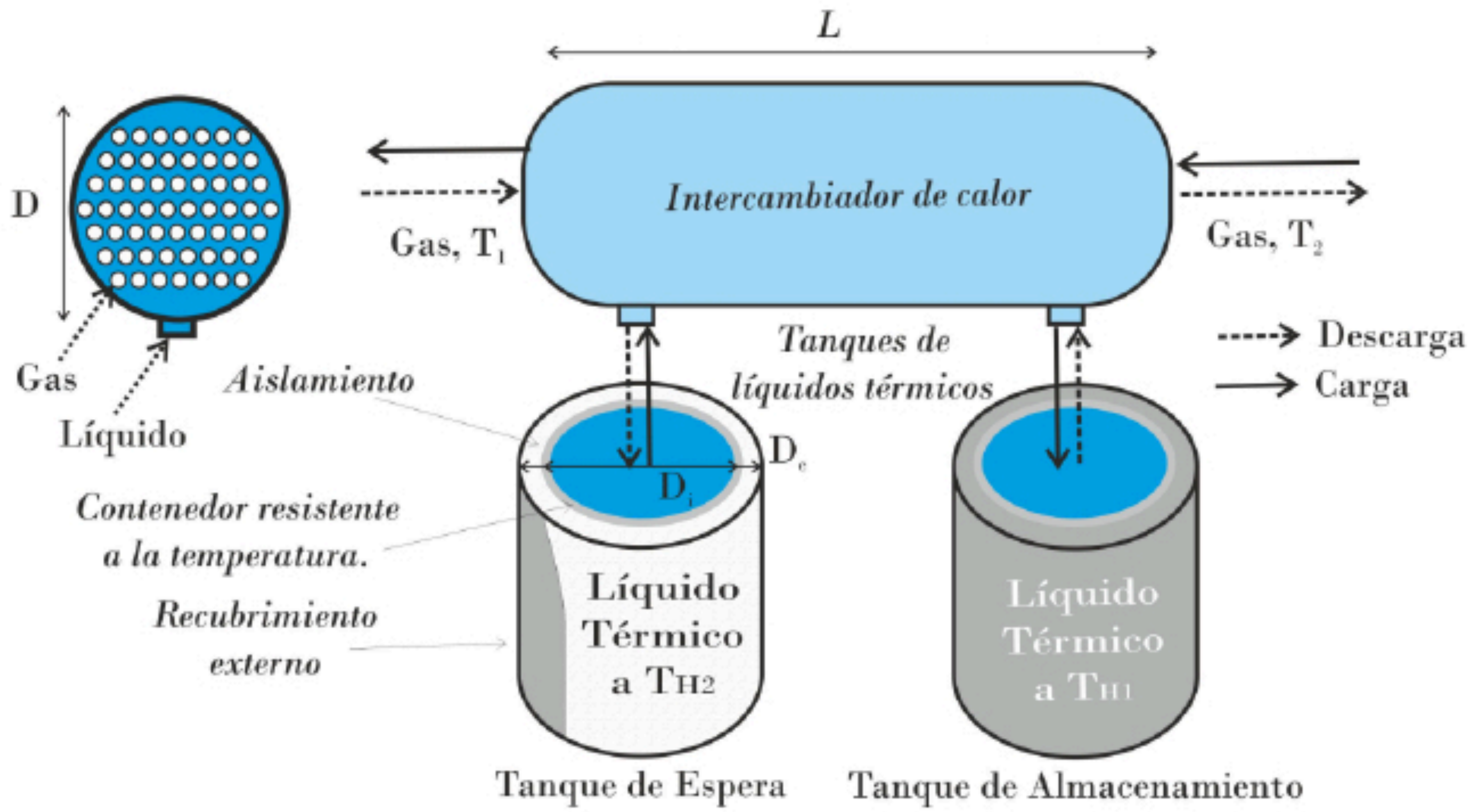

Brayton-like cycles
for both modes:
pump and heat engine

# 2.- *PHES with liquid storage*

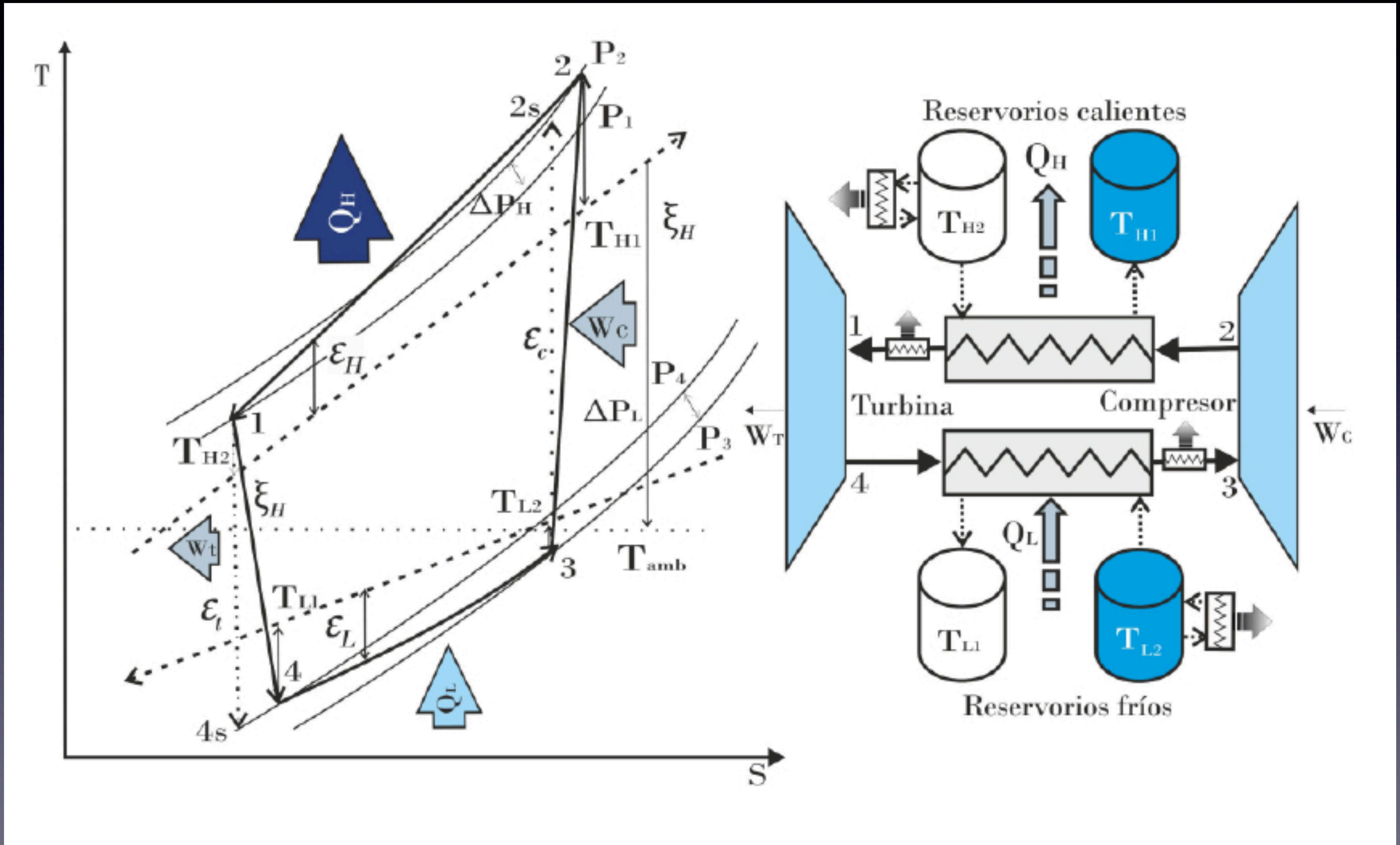
*Rankine or Brayton cycles*

## Almacenamiento de Energía con ciclo Brayton

La diferencia en sistemas de almacenamiento líquido, es que el calor se almacena en tanques que no están en contacto con el fluido de trabajo. Esto permite operar con tanques a menores presiones (más baratos) y controlar las pérdidas (mayor o menor aislante).



# Charge (heat pump) mode



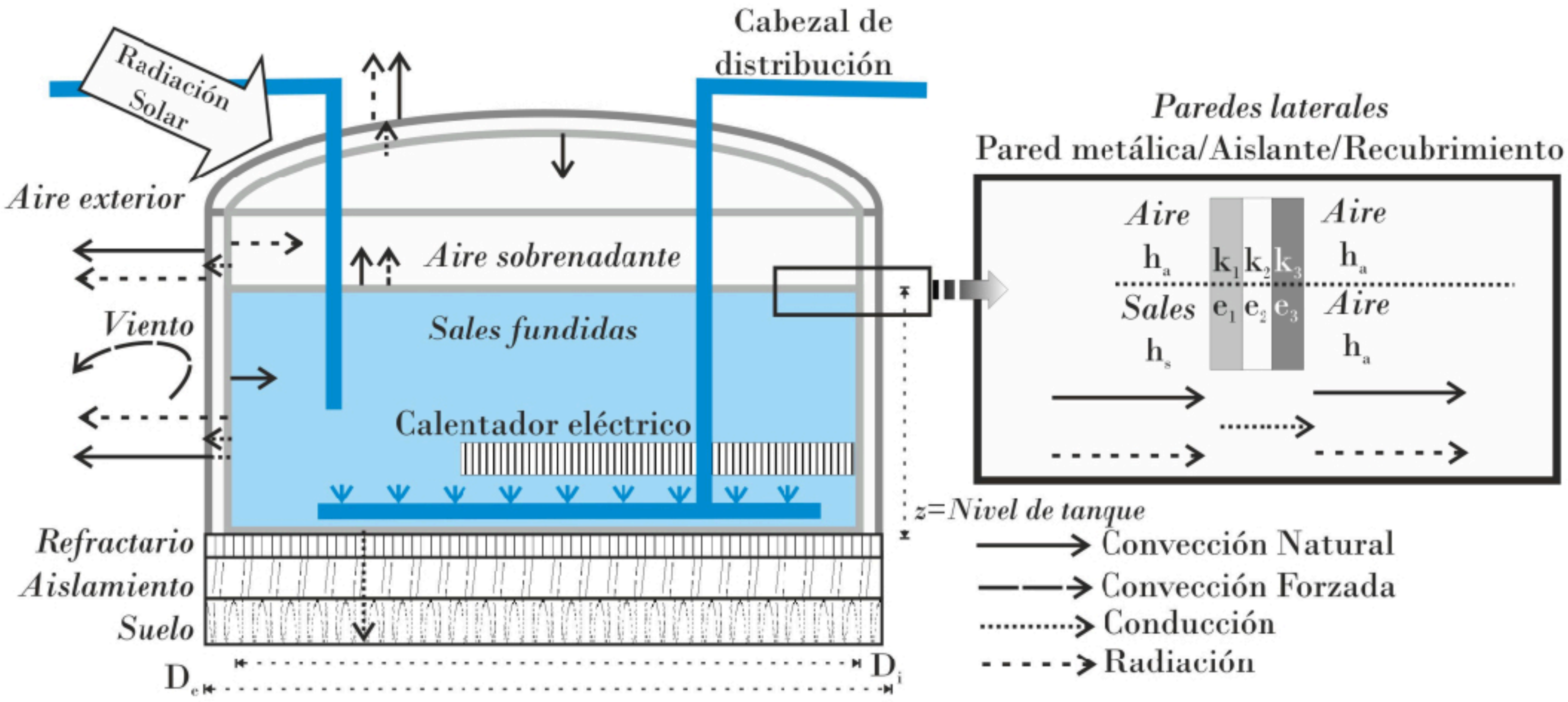
El ciclo Brayton opera entre dos niveles de presión, alcanza una temperatura $T_H$ y $T_L$. A diferencia del ciclo de la turbina de gas, las fuentes de temperatura intercambian con el fluido de trabajo. Se almacena sal caliente a $T_{H1}$ y un líquido frío a $T_{L2}$.

## Irreversibilidades

- Eficiencias en los procesos de compresión y expansión ($\varepsilon_c$ y $\varepsilon_t$)
- Eficiencias en los procesos de intercambio de calor ($\varepsilon_H$ y $\varepsilon_L$)
- Pérdidas de carga en los intercambiadores ($\Delta P_H$ y $\Delta P_L$).

También hay que considerar Heat Leak, pero como no son procesos estacionarios. El Heat Leak es más importante durante el período de almacenamiento.

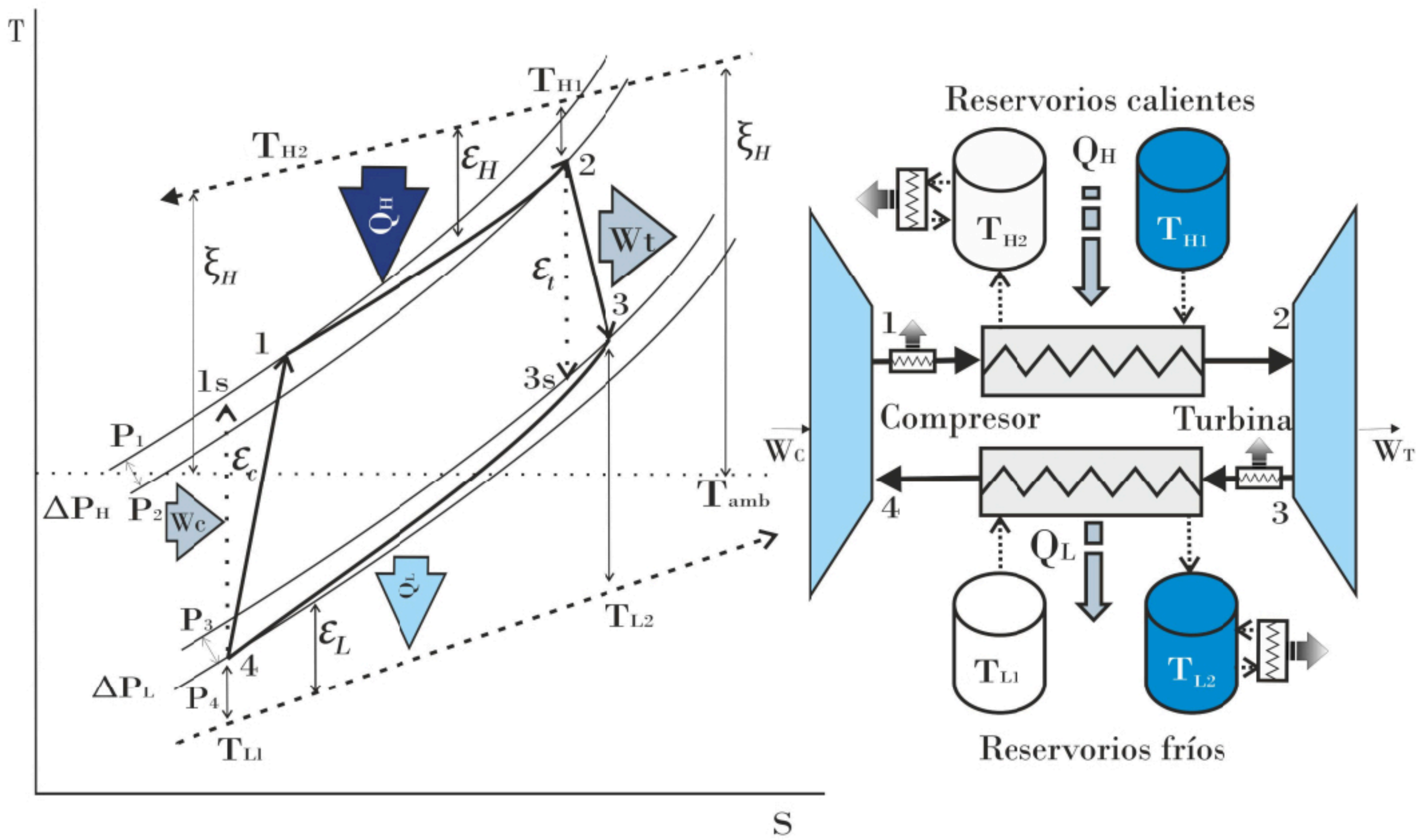
# Pérdidas de calor (Heat Leak)



## Procesos de transferencia de calor en los tanques.

- Conducción a través de la capa de aislamiento térmico y las protecciones externas (Techo, fondo, pared).
- Convección entre el aire sobrenadante y la sal.
- Convección entre la sal y las paredes (laterales y suelos).
- Convección entre el aire sobrenadante y las paredes (laterales y techos).
- Convección entre el aire exterior y la pared exterior (Forzada o natural en techos y paredes).
- Radiación desde la pared metálica al interior del tanque (techos y paredes).
- Radiación de las paredes laterales y techos al exterior.
- Radiación solar incidente (Techos y paredes laterales).

En el proceso de descarga se invierte el sentido del ciclo y la máquina témica funciona en un ciclo de Brayton, tomando un calor $Q_H$ del fluido de alta temperatura y cediendo un calor $Q_L$ al fluido de baja temperatura.



# Comportamiento dinámico variando la relación de velocidades en carga y descarga.

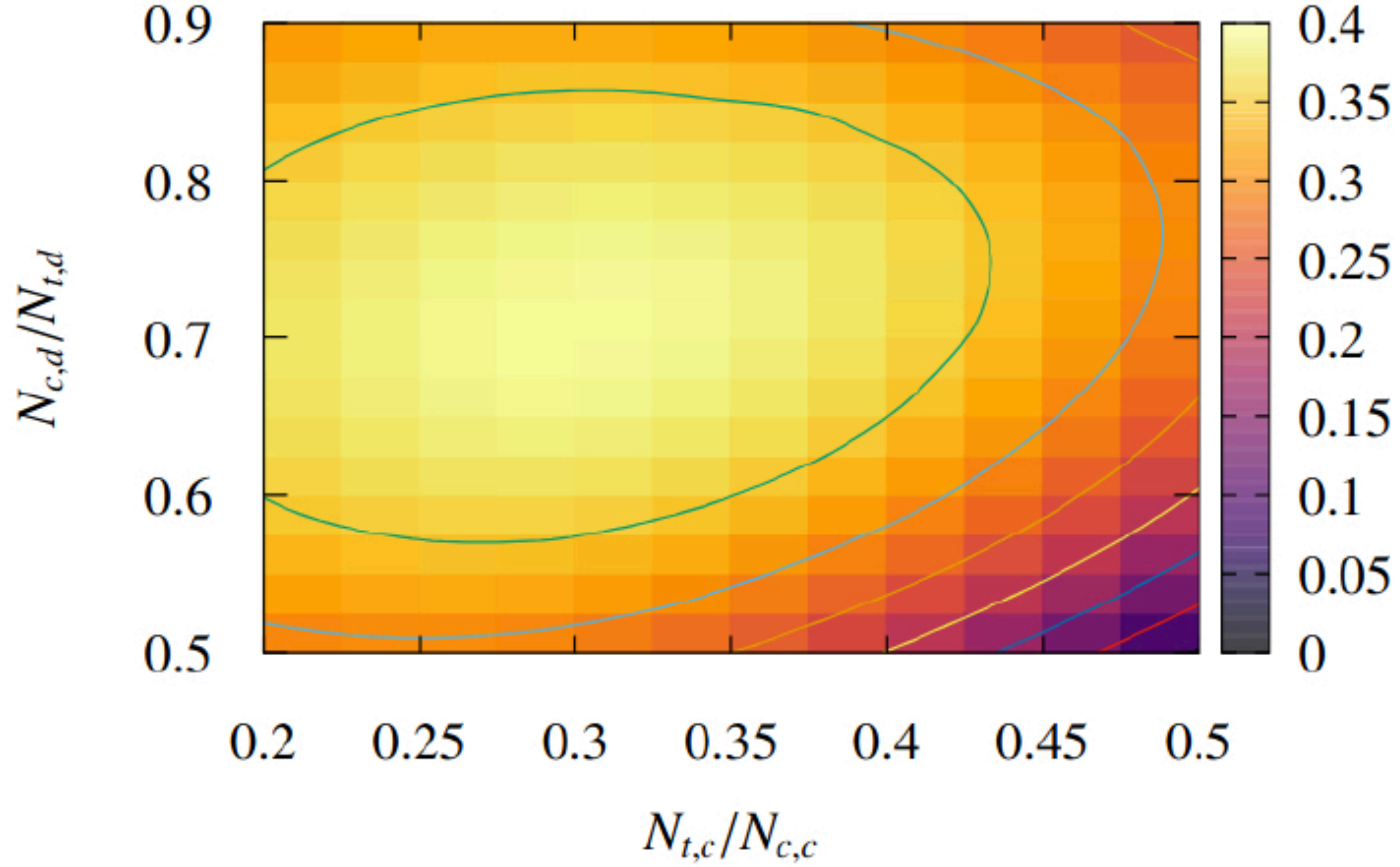



Figure: RTE para descargas con $N_{t,d} = 400$rpm variando $N_{c,d}/N_{t,d}$ y para cargas con $N_{c,c} = 550$rpm variando $N_{t,c}/N_{c,c}$

De esta forma se puede utilizar la diferencia de velocidades entre compresor y turbina para generar el salto de presión. Y hay una relación que maximiza el RTE.