Lecture # 25

Energy Storage

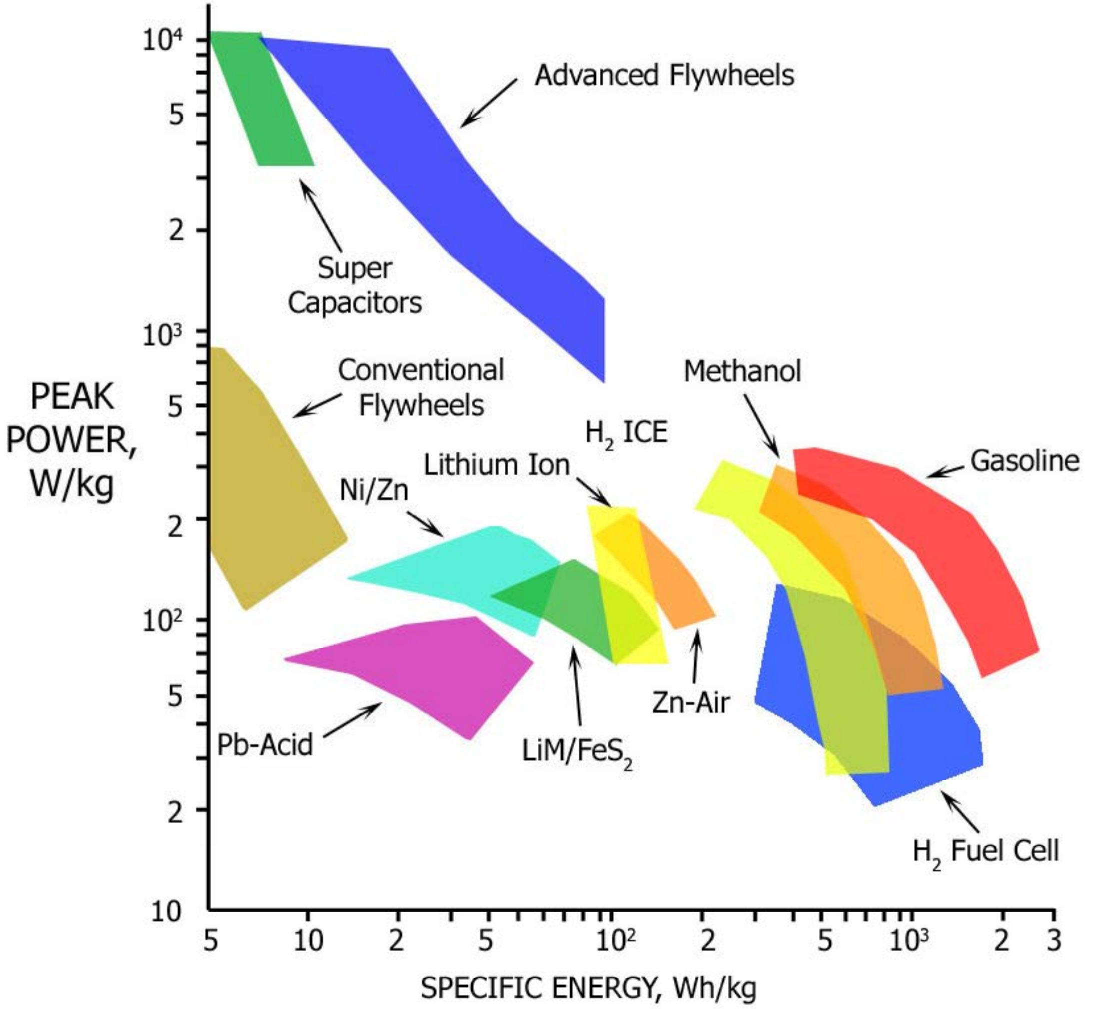
Ahmed F. Ghoniem

May 6, 2020

- Storage technologies, for grid-level!
- Thermal energy storage, and thermochemical options ….

- THE RAGONE DIAGRAM, more applicable mobility.
- Specific energy is key, specific power needed for short burst.
- Renewables-powered mobility can be:
  - Battery electric (BEV)
  - Hydrogen ICE or PEM-FC.

- For stationary applications, criteria for selection are different.
- Scale is important



THE RAGONE DIAGRAM. Figure shows approximate estimates for peak power density and specific energy for a number of storage technology mostly for mobile applications.

Energy Storage: a brief comparison

The table shows technologies for stationary and mobile applications including mechanical and electrochemical. Capacitors are integral parts of mobile storage!

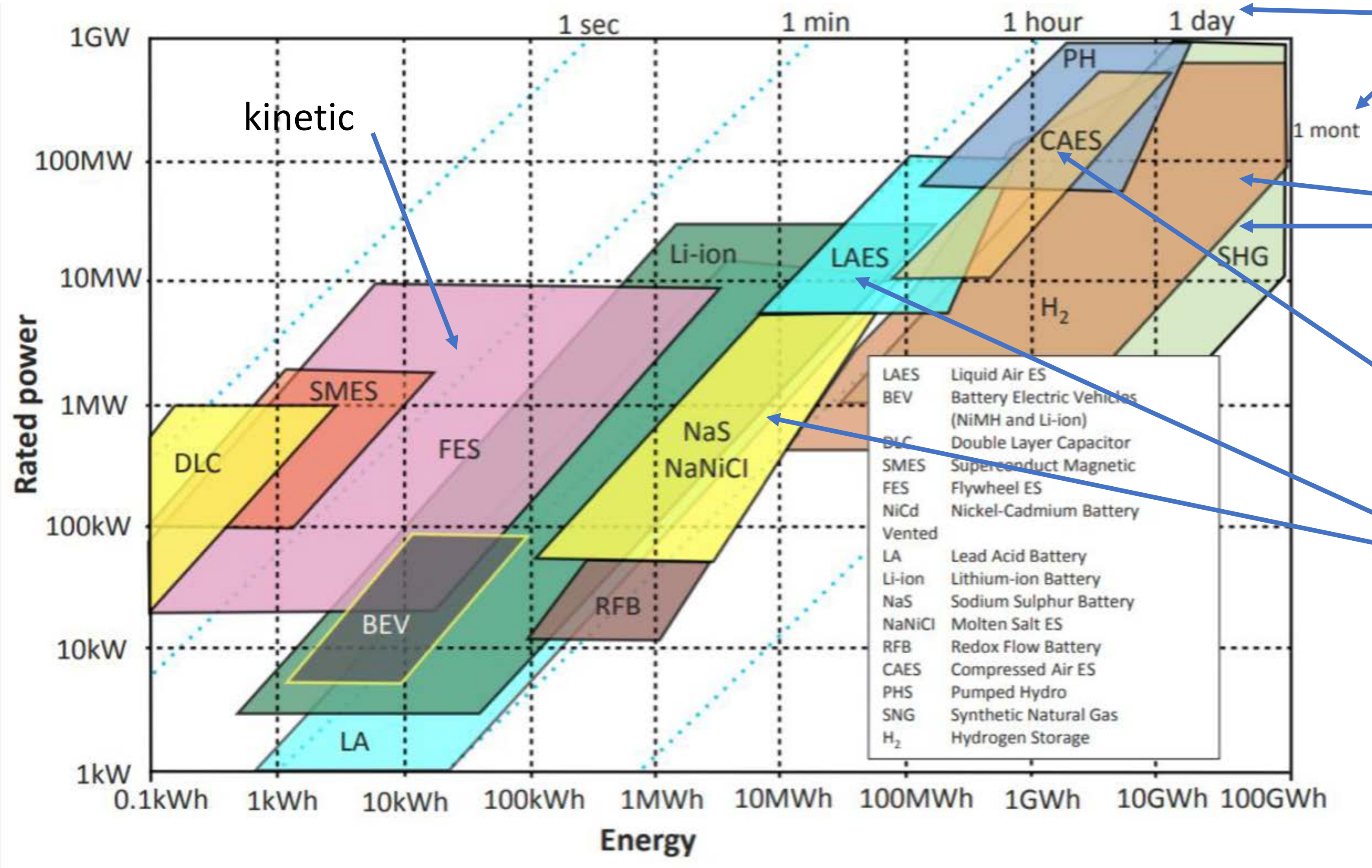
Not inclusive and other options are available and under development.

Does not show thermal (storage) and chemical (hydrogen, fuels and thermochemical) options which are very important.

Prices change constantly but comparison is still reasonable.

Characteristic	PHS	CAES	Batteries	Flywheel
Energy Range (MJ)	1.8×10^6-36×10^6	180,000-18×10^6	1,800 – 180,000	1 – 18,000
Power Range (MW)	100-1000	100-1000	0.1 – 10	1-10
Overall Cycle Efficiency	64-80%	60-70%	~75%	~90%
Charge/Discharge Time	Hours	Hours	Hours	Minutes
Cycle Life	10,000	10,000	2,000	10,000
Footprint/Unit Size	Large if above ground	Moderate if under ground	Small	Small
Siting Ease	Difficult	Difficult-Moderate	N/A	N/A
Maturity	Mature	Development	Mature except for flow type	Development
Estimated Capital Costs - Power ($/kWe)	600 – 1,000	500-1,000	100-200 (LA)	200 - 500
Estimated Capital Costs - Energy ($/kWh)	10 - 15	10 - 15	150-300	100 - 800

Energy Storage Capacity



Time to discharge available energy at give power

kinetic

chemical

Potential/ pressure

thermal

Chris Mutty and Scott Seo 2019 paper for reference

Storage systems and their utilization

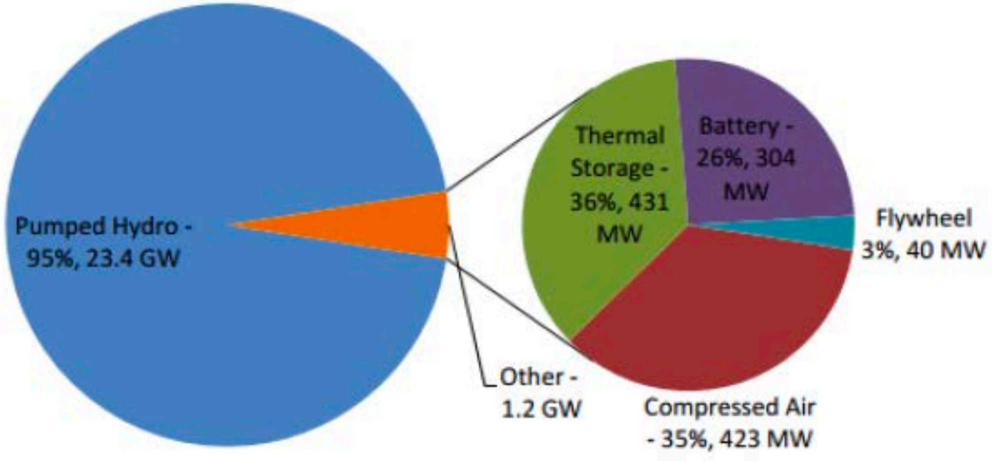


Image courtesy of DOE.

DOE. "Grid Energy Storage":
https://energy.gov/sites/prod/files/2014/09/f18/Grid%20Energy%20Storage%20December%202013.pdf

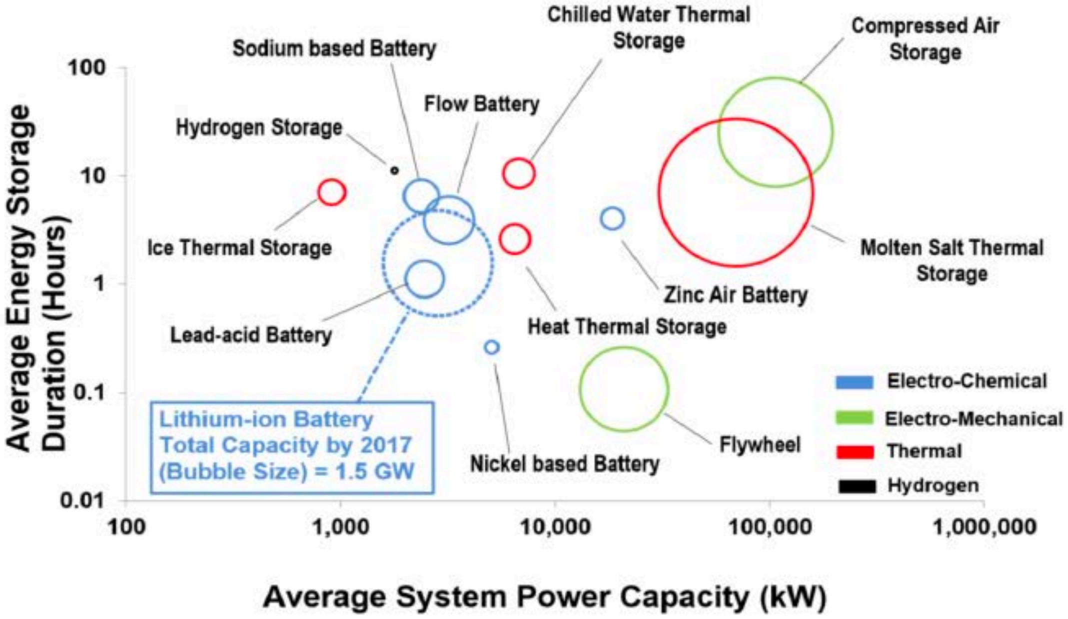


Image courtesy of NREL, DOE.

The power capacity and energy capacity (measured in storage duration) of energy storage plants built between 1958 and 2017. The relative circle size indicates the worldwide installed capacity. Pumped hydro is not shown here due to the large number of plants, but its average size is on the order of 300 MW and 3 GWh (10 hr duration!).

David Feldman, et al. Technical report, National Renewable Energy Lab.(NREL), Golden, CO, US 2016.

Storage systems and their characteristics

An important definition:

The round trip efficiency:

$$\eta_{round} = \frac{\text{energy recovered during discharging}}{\text{energy added during charging}}$$

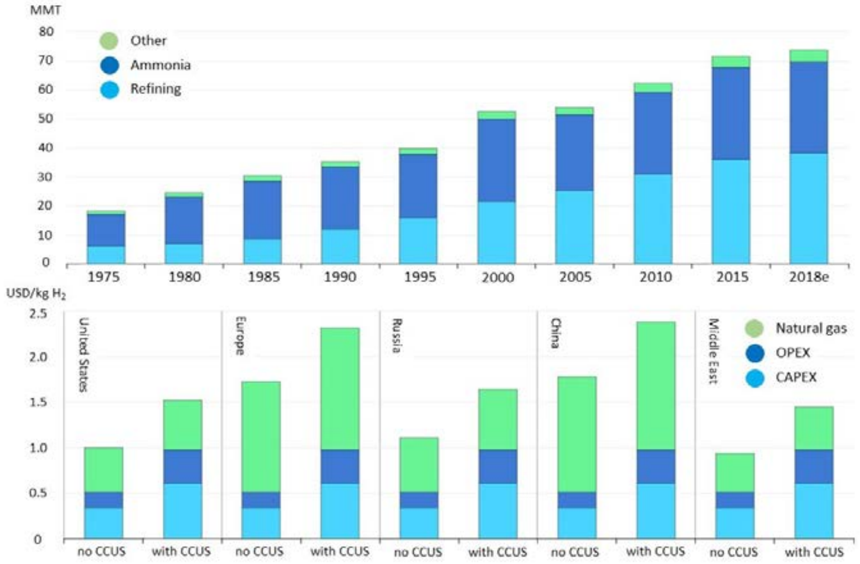
$$= \frac{\text{energy recovered}}{\text{energy stored}} \cdot \frac{\text{energy stored}}{\text{energy added}}$$

$$= \eta_{ch\arg e}\eta_{disch\arg e}$$

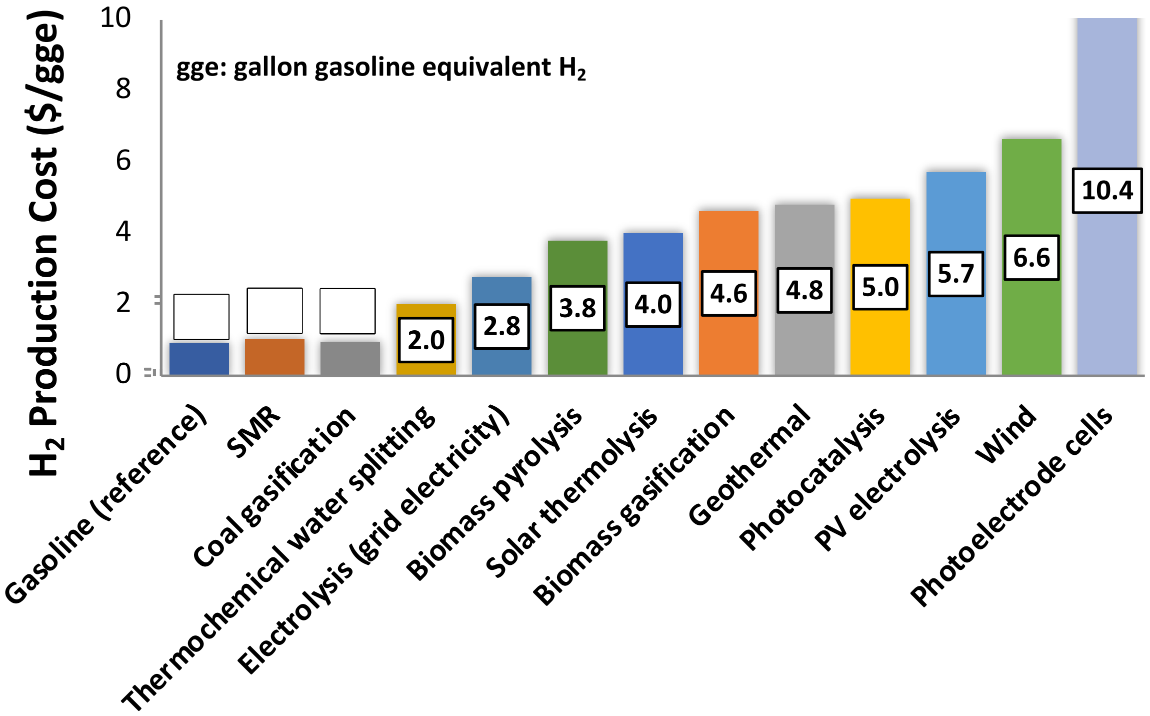
Hydrogen Production

Hydrogen

Worldwide production and cost based on SMR

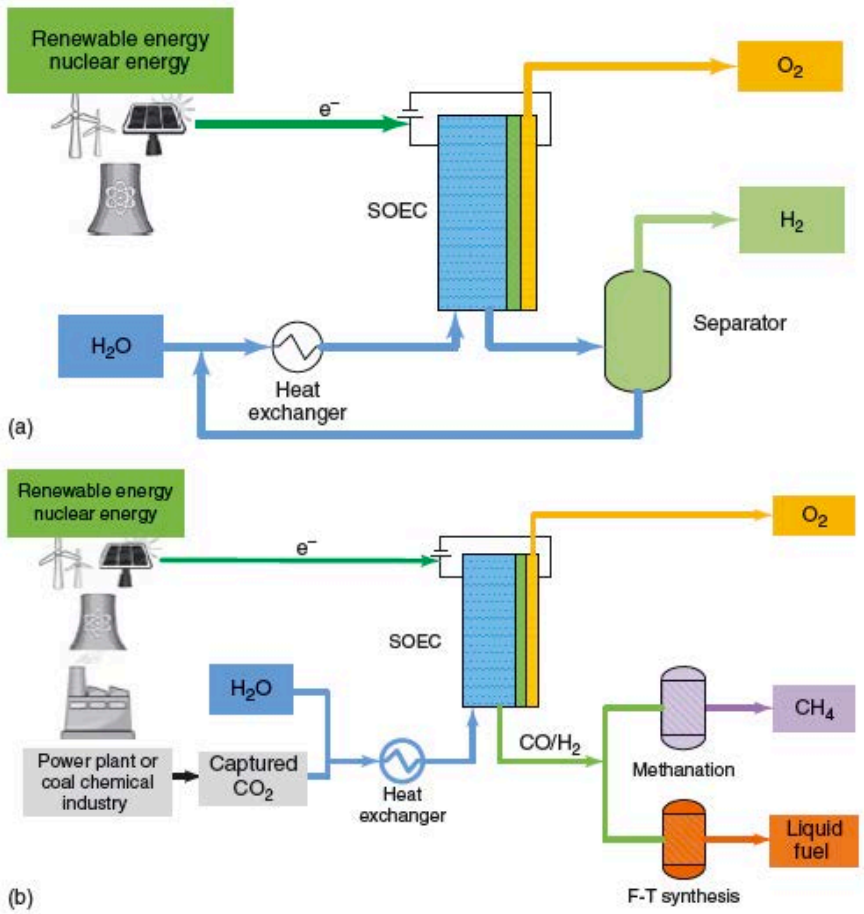


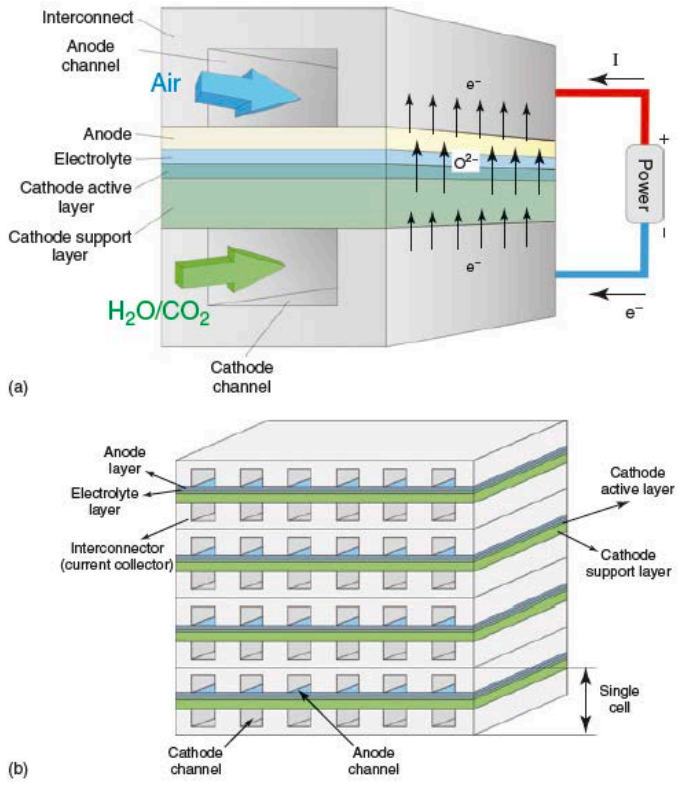
IEA Technology Report, June 2019, https://www.iea.org/reports/the-future-of-hydrogen.



- Steam reforming has reached peak efficiency (70-85%)
- Novel technology needs to be developed to reach the goal
- Alternatives needed for zero CO_2 emissions

Electrolysis for production of H_2 and/or co-production of H_2/CO and synthesis fuels



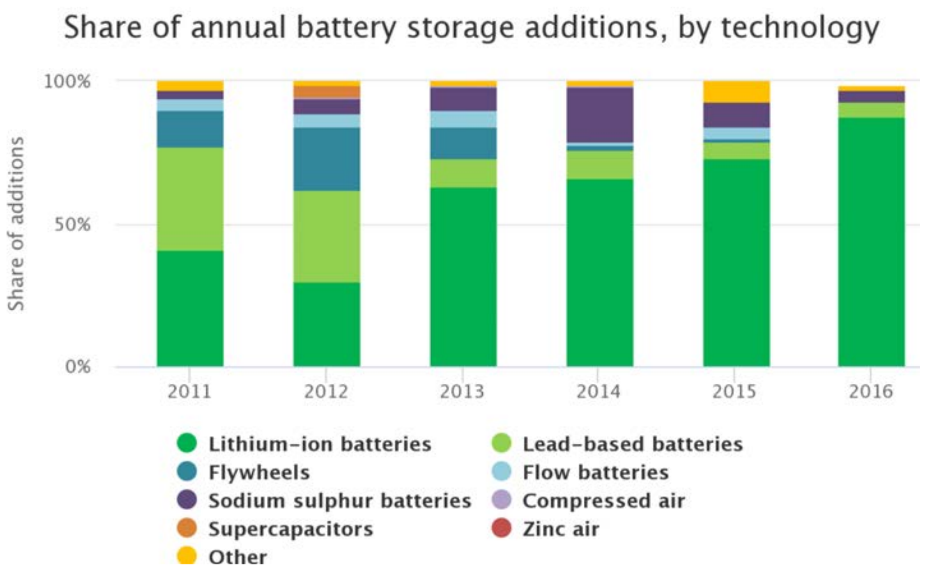


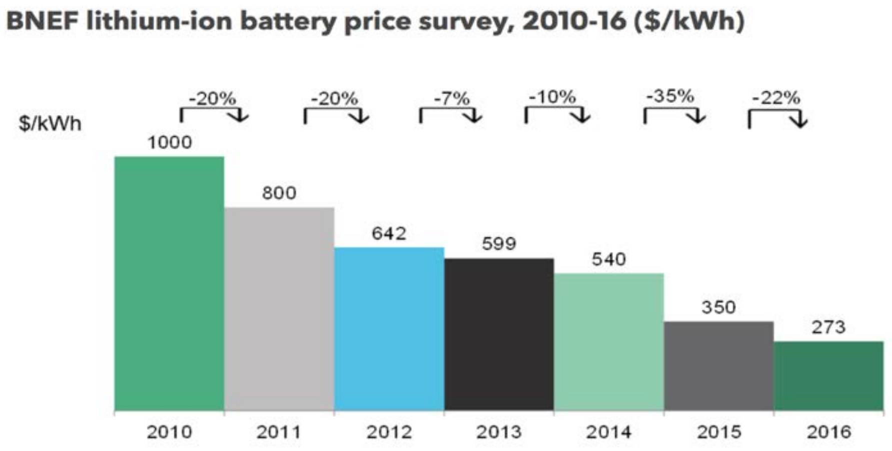
(a) Single element
(b) A stack

Shi et al, Handbook of Clean Energy Systems, 2015, Wiley

Batteries

- Similar to fuel cells in that they convert chemical to electrical energy directly, and the secondary type can reverse the reactions
- But they store their chemicals internally in their electrodes (except for flow batteries)
- Have seen a very wide range of applications, at many scales for centuries!
- Still relatively expensive for large scales storage deployment, although convenient.
- Also heavier than ideal in mobile application.
- Must be carefully managed thermally to avoid thermal run away and fires.


Share of annual battery storage additions, by technology


BNEF lithium-ion battery price survey, 2010-16 ($/kWh)

Gravitational Energy Storage: (1) Pumped Hydro Electric Systems (PHS)

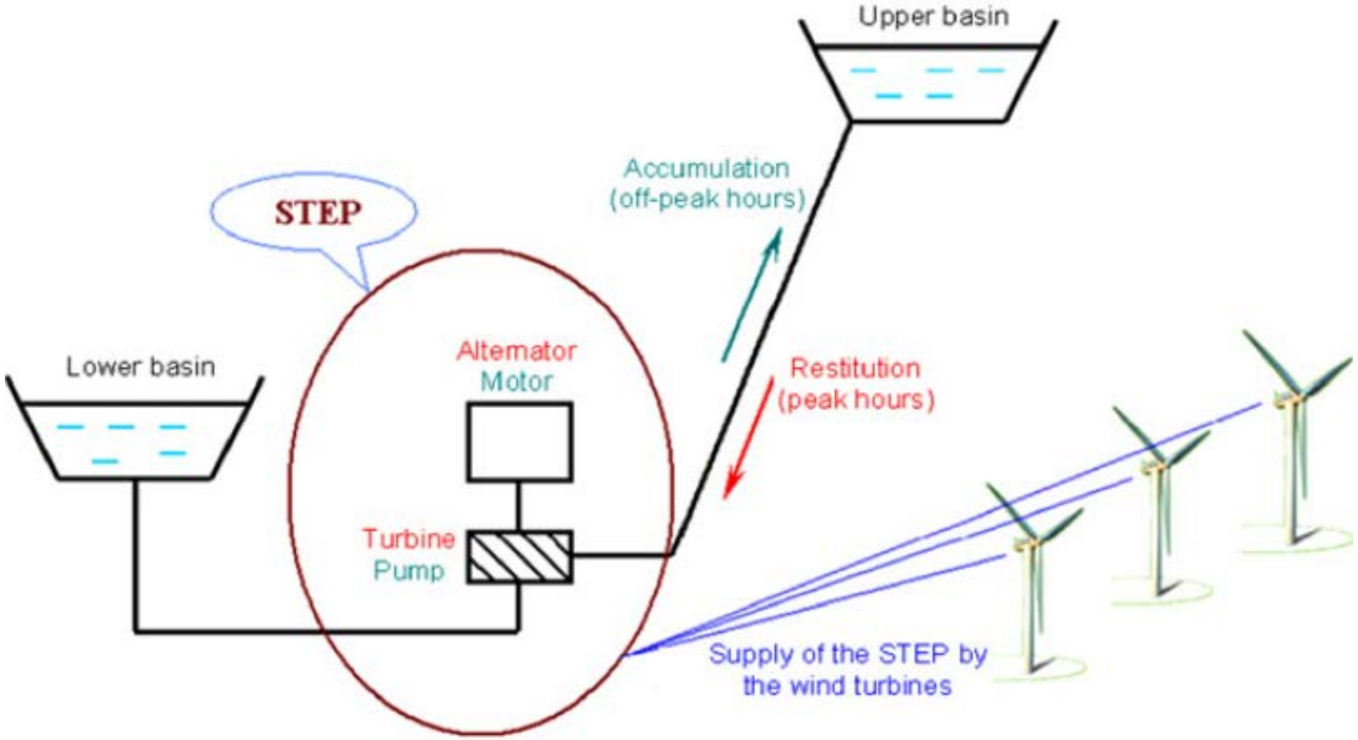
Significant Energy Capacity: $E = MgH = \rho\forall_{water} gH \sim 10^4 \forall H\ \text{J}$

take $H = 10\ \text{m}, E = 0.1\forall_{water}\ \text{MJ}$

take $\forall_{water} = 100 \times 100 \times 10\ \text{m},\ \ E = 10\ \text{GJ}$

Power: $\wp = \dot{m}gH$

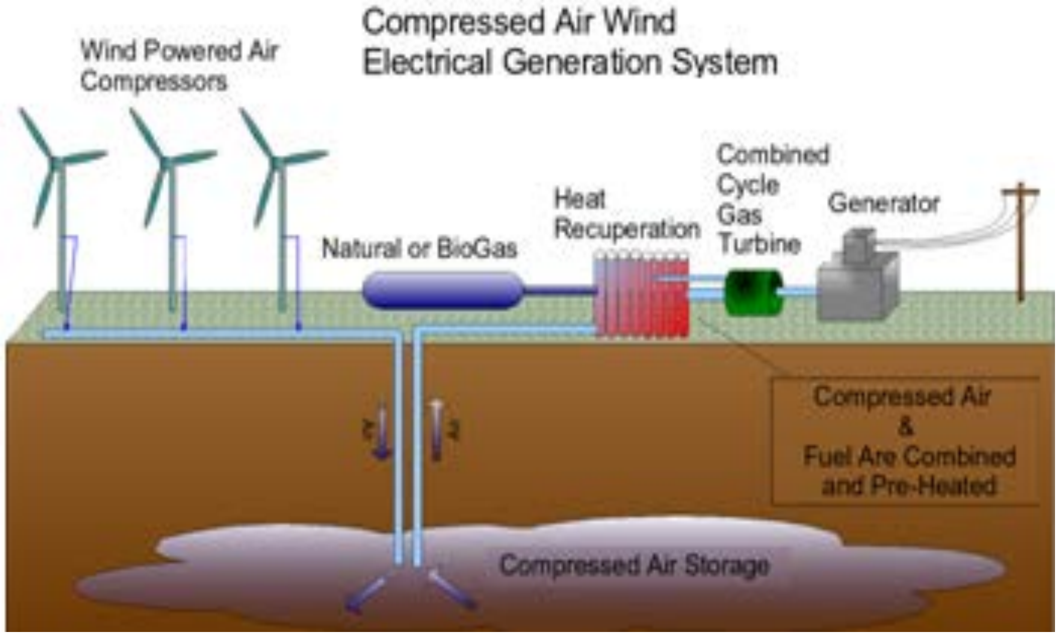
for the same case, $\wp \sim 0.1\dot{m}\ \text{kJ}$

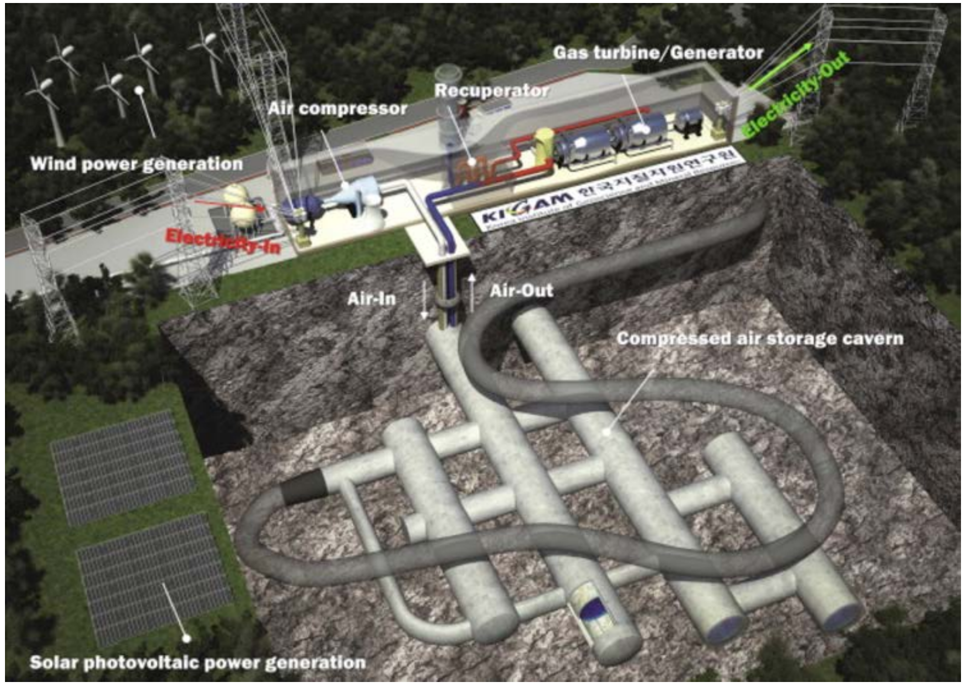


Gravitational Energy Storage: (2) moving solids!

Will be covered by some of you in the projects presentations

Energy Storage: Compressed Air Storage (CAES)

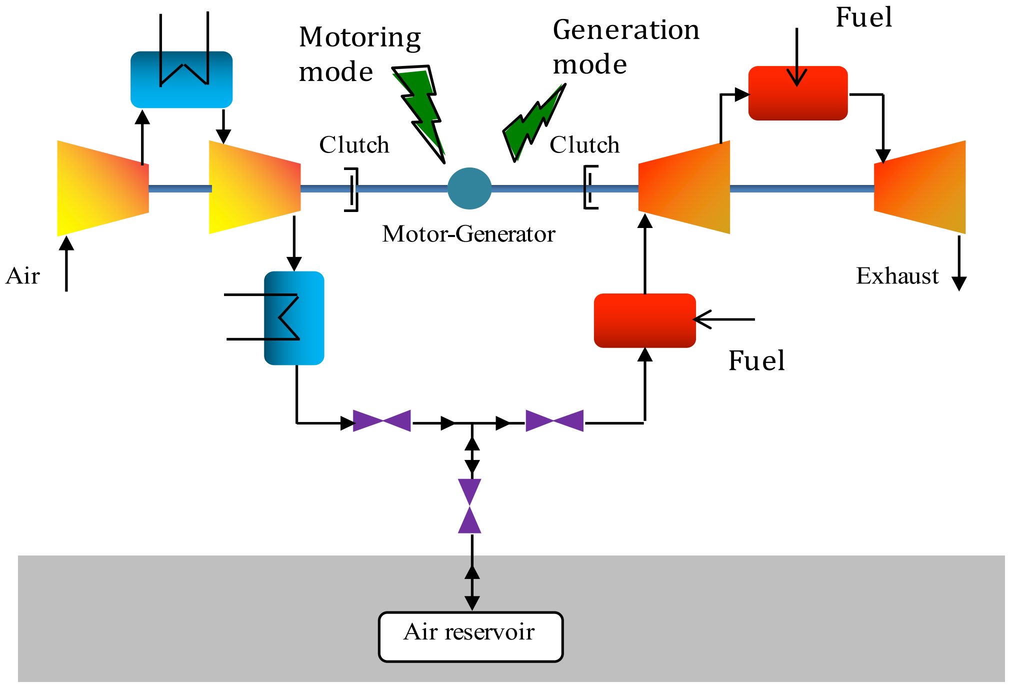




Components of a CAES layout system (from Kim et al, Copyright Applied energy, 2012 – Exploring the concept of compressed energy storage (CAES) in lined rock caverns at shallow depth: A modeling study of air tightness and energy balance, Kim, H-M., Rutqvist, J., Ruy, D-W., Choi, B-H., Sunwoo, C., Song, W-K, Applied energy Vol. 92, pp. 653-667, 2012).

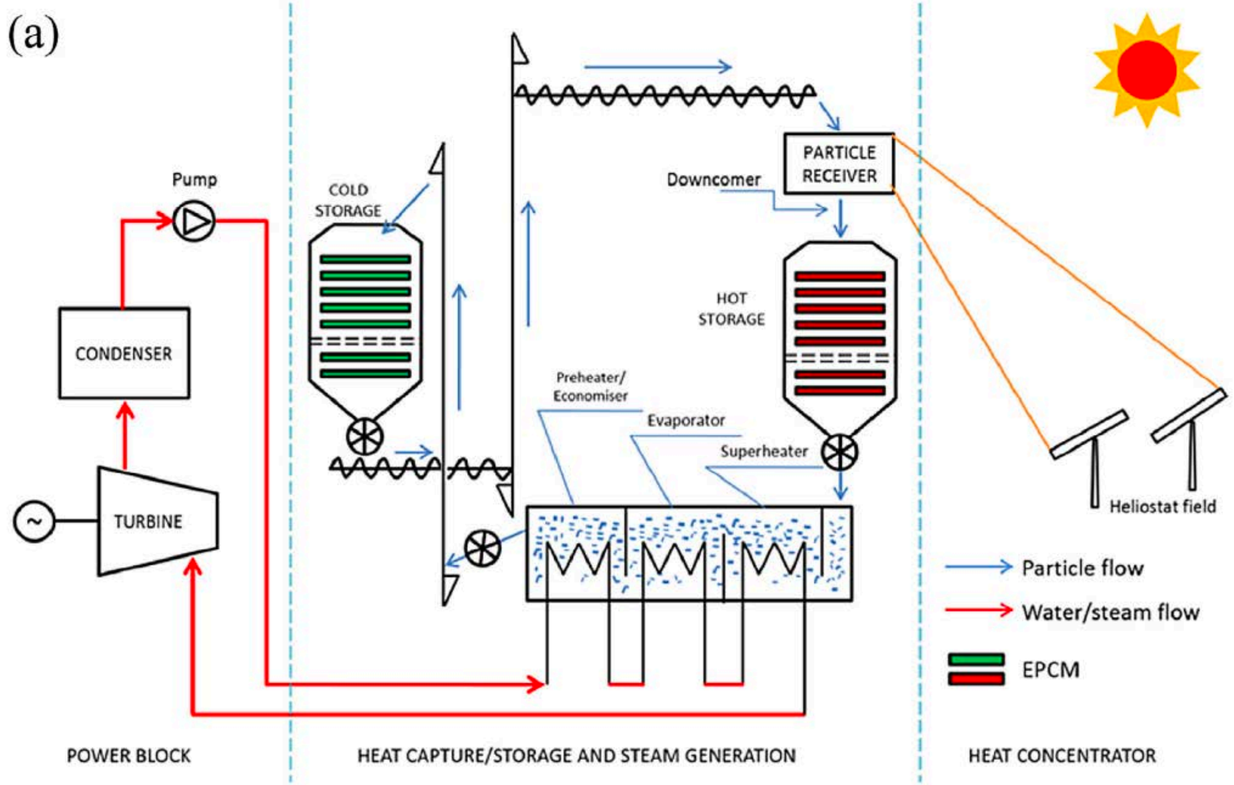
Table Typical performance data of compressed air energy storage (CAES) systems.

	Huntorf, Germany	McIntosh, Alabama	Sunagawa, Japan
Capacity, MW	290	110	35
Generation, hours	2	26	6
Compression, hours	4	1.6	1.2
Volume, 10^3 m^3	311	538	30
Cavern temperature,	35	35	50
Expander train:			
High pressure			
Inlet pressure, bars	46	45	40
Inlet temp, °C	540	540	800
Low pressure			
Inlet pressure, bars	11	15	15
Inlet temp, °C	670	670	1250
Expander mass flow, kg/s	415	154	47
Recuperator	No	Yes	Yes



Thermal energy storage and recovery

- Should store heat at the highest economically and practically possible temperature to save space and improve the power cycle efficiency (while avoiding corrosion, thermal stresses, chemical transformation, etc.)
- Need a medium to transport the heat, it should have high heat capacity and should be easy to transport, either a fluid or a fluid like medium
- Need a storage medium/tank for the high temperature heat, and another for the low temperature medium.
- The storage medium should have high gravimetric ($\rho\, c_p$) or volumetric heat capacity. May or may not be the same as the heat transport medium.

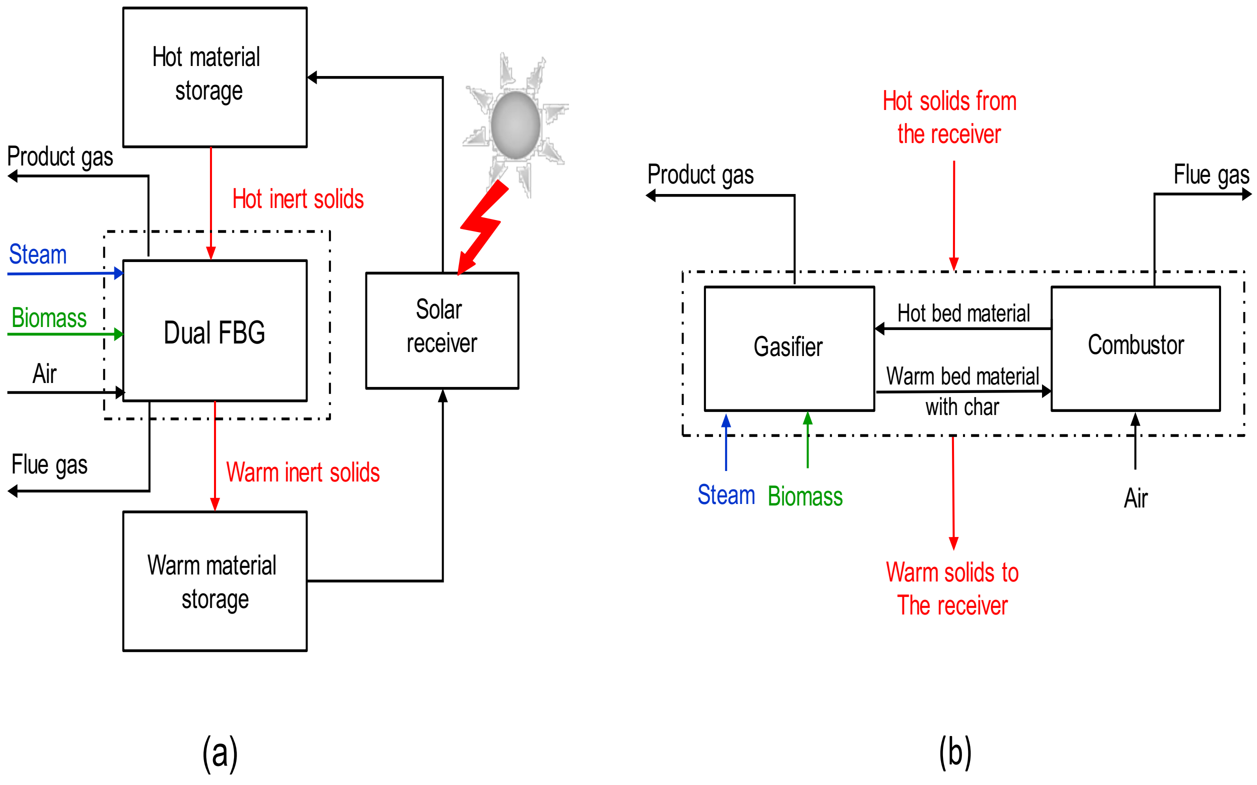


Powder or particulates (50-100 microns) are heated up in the solar receiver and transported/conveyed mechanically and by gravity to a high T storage tank, a heat exchanger to raise steam for the power cycle, then to a low T storage tank before going back to the receiver.

Zhang et a., PECS 53 (2016) 1

Thermal energy storage in the form of chemical*

- Steam gasification of biomass (or coal or natural gas) is an endothermic process. The produced syngas can be stored for later use.
- Typically the heat added is equivalent to ~ 25% of the heating value of the original fuel.
- In case of solar energy, it is difficult (expensive) to get solar heat above 700 C, the temperature required for gasification.
- In this case some of the biomass can be burned to provide heat to supplement the solar heat.
- Using a dual bed gasifier makes it possible to separate the combustion (of char) from the gasification (of the volatiles and some char), and hence producing pure syngas (without nitrogen) while using air for combustion.
- Therefore, separate gasifier and combustor are used with "bed" material (sand) circulating in between the two and the solar receiver.



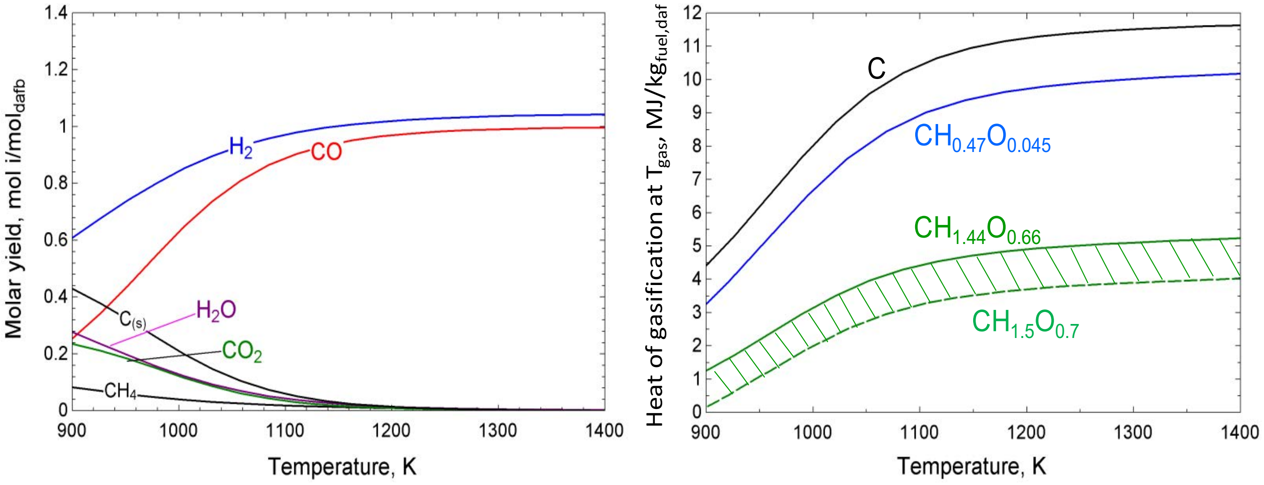
Layout of a solar-biomass gasification system: (a) Biomass gasifier in a solar loop with a solid particles receiver; (b) Steam gasification in a dual fluidized bed gasifier (SDFBG)

*Gomez-Barea, Suarez-Almeida and Ghoniem

The thermochemistry (mass and energy balance) of biomass steam gasification

$$CH_{1.44}O_{0.66} + \lambda_{H_2O}\, H_2O \rightarrow n_{H_2} H_2 + n_{CO} CO + n_{CO_2} CO_2 + n_{CH_4} CH_4 + n_{C_2H_4} C_2H_4 + n_{C_{(S)}} C_{(s)} + n_{H_2O} H_2O + n_{C_{10}H_8} C_{10}H_8$$

- The heat required for gasification increases with temperature, until the fuel is converted in CO and H_2.
- At ~ 1000-1200 K, and for biomass with LHV of ~18-18.5 MJ/kg_{bio} the heat of gasification is 3.5-5.5 MJ/kg_{bio}.
- Thus, gasification stores more energy in the fuel, ~ 20-35% more than the original.
- Heat. Required for biomass (marked in green) is well below that for char (blue) and pure carbon (C in black).
- Clearly, the higher the carbon-to-hydrogen ratio the larger the heat of gasification and the more water is needed.



(a) (b)

The effect of temperature on: (a) the molar gas yields of the main species for steam gasification of biomass according to R1 (Tars and other light hydrocarbons are not depicted since their concentrations are very low compared to the rest of species included in the figure). (b) specific heat of steam gasification according to R1 (per kg of daf fuel) for different fuels: carbon, char and biomass (the hatched region in the figure corresponds to a typical biomass). Simulation corresponds to equilibrium predictions with ER_{H2O} =1.

System operation during the day and night

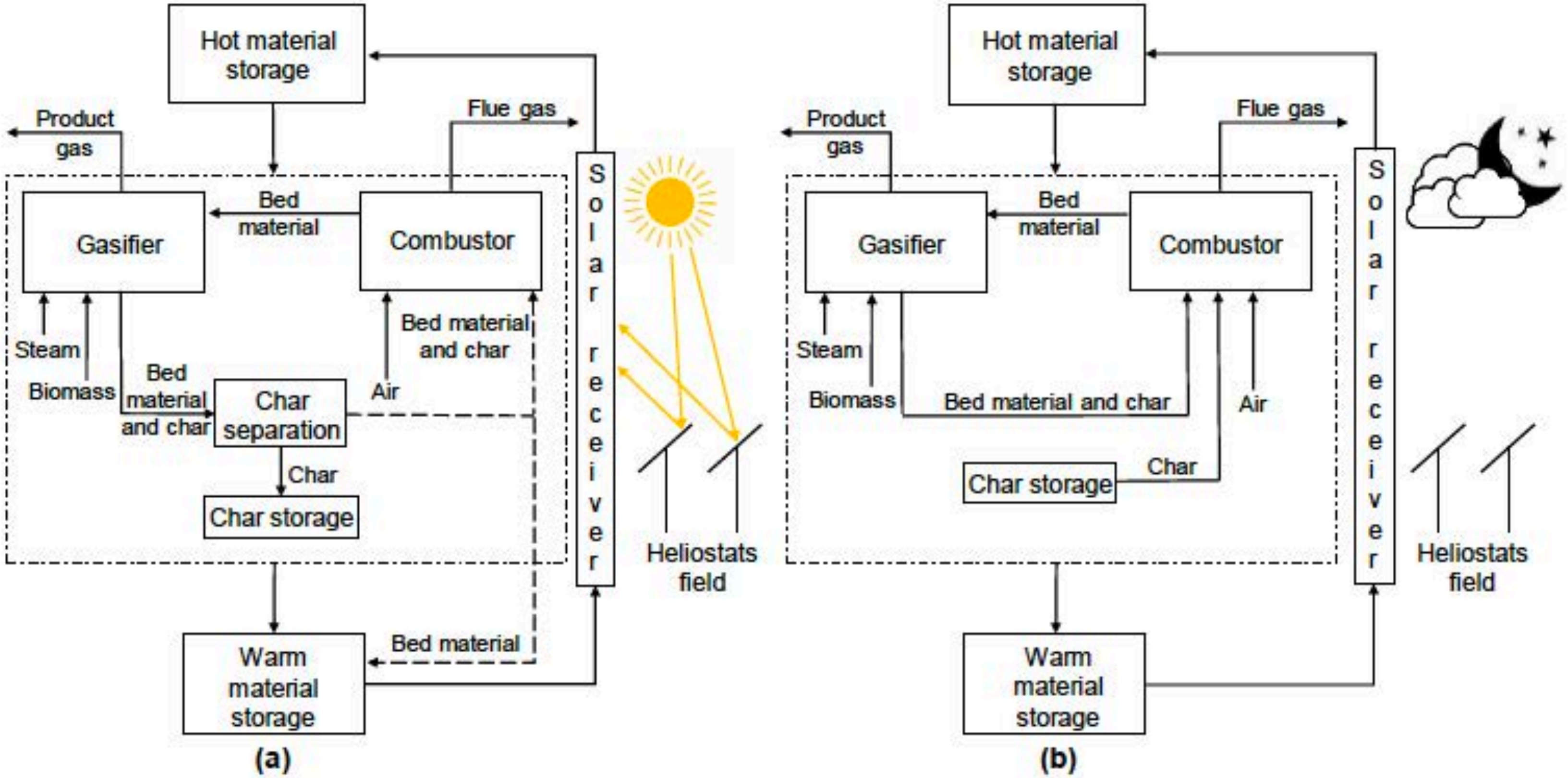


Fig. 2. Operation of the system with char separation and storage: (a) char separation and storage when solar energy is available; (b) discharge of the char storage in absence of solar energy

(Very) High-temperature energy storage
Firebrick resistance heated energy storage “FIRES”
D. Stack (2.62-2016)*

- Firebrick can go up to > 1600 C
- Thermal capacity ~ 1MWh/m^3 or 3.6 GJ/m^3 (DT~1000 C and mc$_p$~ 3.6 MJ/m^3 K)
- [note that for water has high mc$_p$~ 4.2 MJ/m^3 K but it is DT that makes firebrick superior]
- Can be heated electrically (resistance of inductive heating which is more efficient) to achieve the desired temperature.
- Discharged by blowing cooler air through the honeycomb structure
- Hot air can power a closed Brayton cycle or a ScCO$_2$ cycle for higher efficiency
- Operating these cycles at higher max temperature improves the storage round-trip efficiency defines as: (electricity out/electricity in).

Figure 8: Firebrick regenerator for a glass furnace[19]

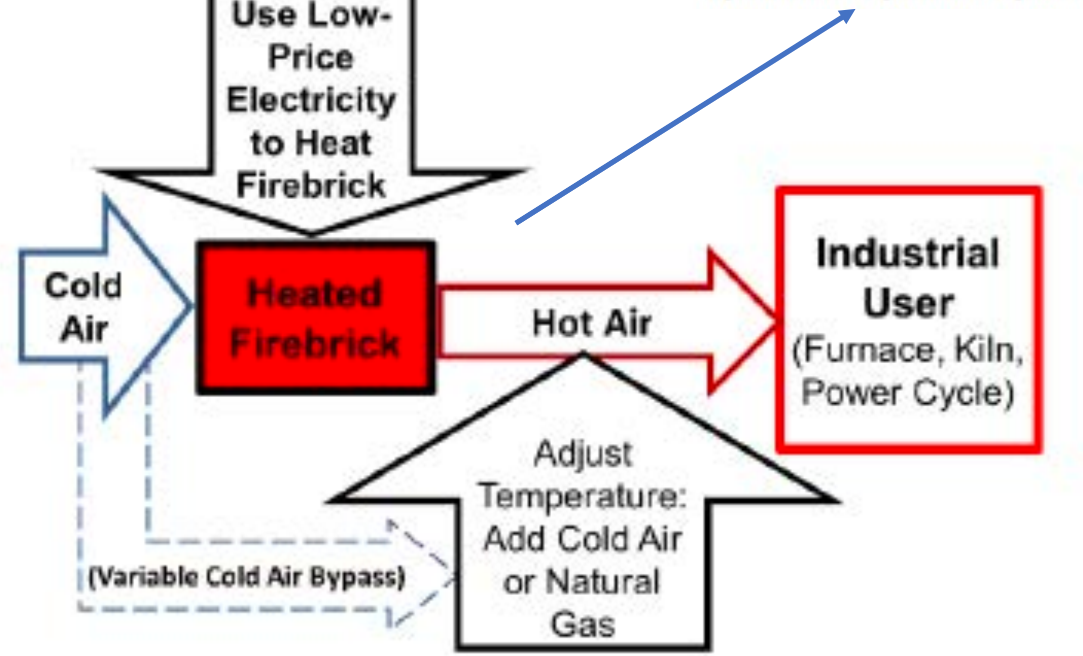


Figure 10: General Schematic of FIRES Implementation

---

* Also D. Stack M.Sc. Thesis at MIT, same year)

- Same concept proposed for nuclear power plant.
- Air for the Brayton cycle is preheated using molten salt (used to cool the nuclear reactor).
- Next, the warm air is heated by the hot firebricks, before going to the gas turbine.
- When excess electricity is generated (overnight!), it is stored in the form of high T heat in the firebricks.
- For "peak power" or when the firebricks are cold, some natural gas can be used.
- This flexibility can reduce cost.
- Using heat from the firebrick, and hybridizing with natural gas, makes it possible to operated a high efficiency combined cycle (>60%).
- Depending on the thermodynamic cycle used for heat-to-power, the round trip efficiency of firebrick storage is 40-60%.

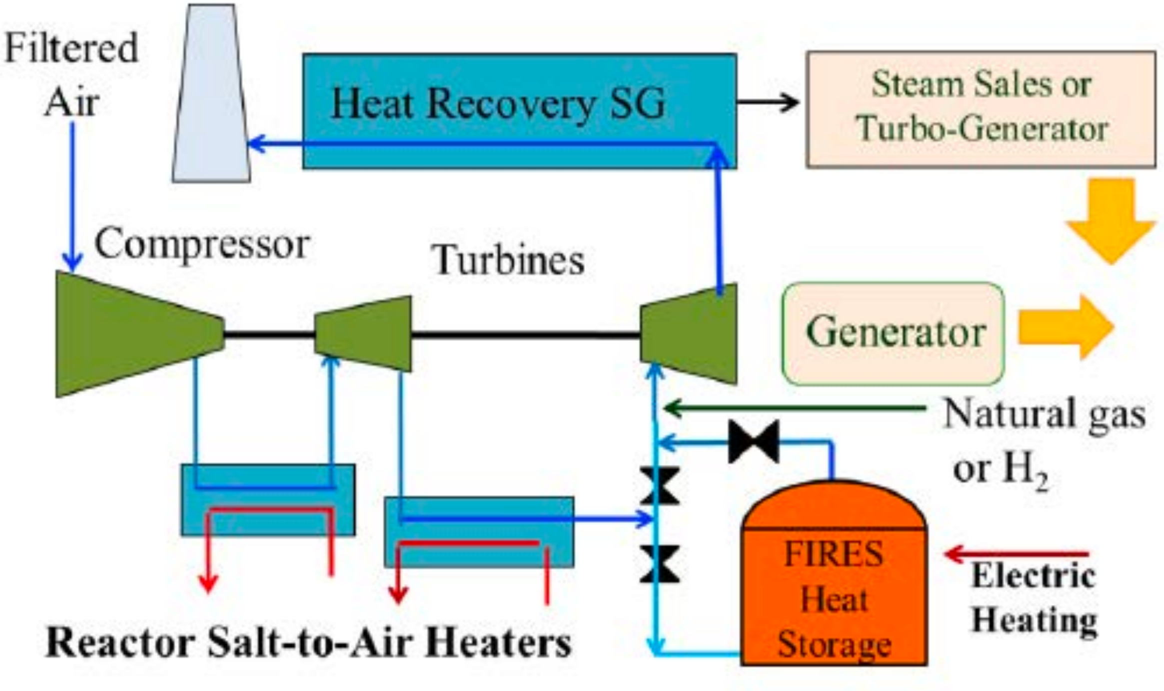
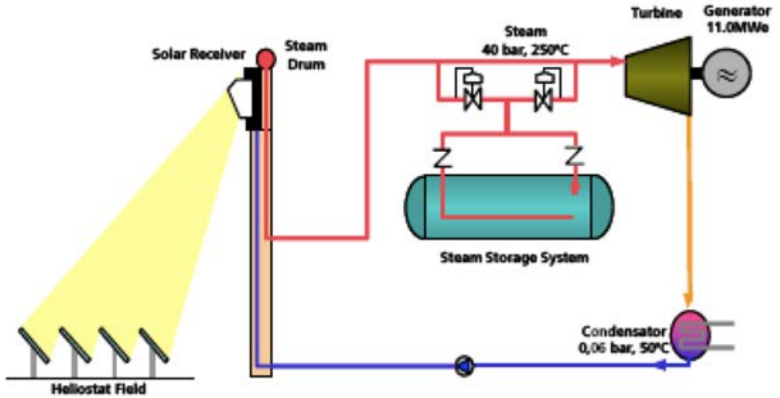


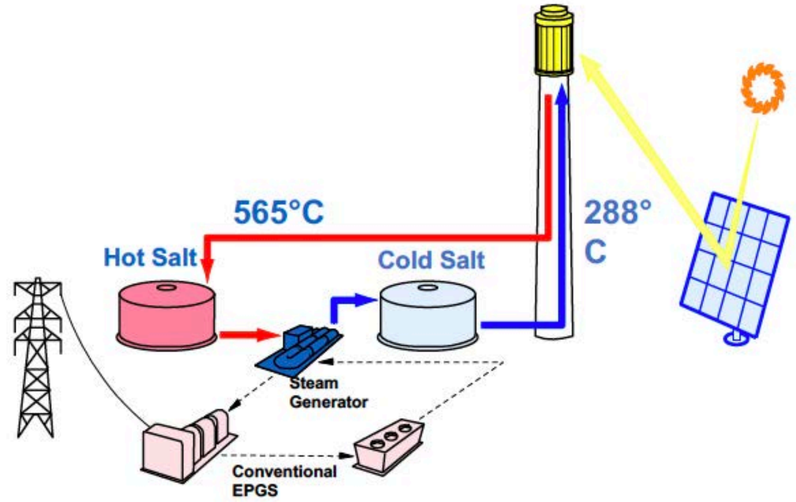
Figure 11: Schematic of FIRES implemented with the FHR NACC[21]

THERMAL ENERGY STORAGE

- A lot cheaper than storing electricity
- Can be deployed at large scale
- Different media can be used at different hot temperature
- Thermal energy can be stored as sensible or latent energy
- Depending on the design, wither the hot working fluid or the hot heat transfer fluid.
- Thermal energy is recovered by either media
- The storage media can be fluid or solid, adding or recovering heat from the storage medium vary.
- In the case of liquid, two tanks, hot and cold, are used, or a single tank with a thermocline.
- Thermal energy storage is compatible with power cycles (mostly steam Rankine cycle, but supercritical CO2 have also been considered)
- It is also possible to store electricity in the form of high temperature thermal energy, and convert that back to electricity at a reasonable round trip efficiency.



Dispatchable Power Requires Storage



THERMAL ENERGY STORAGE

Characteristics of sensible heat storage solids and liquids

Storage medium	Temperature range Cold C	 Hot (C)	density kg/m3	heat conductivity W/mK	heat capacity kJ/kg K
Sand-rock-mineral oil	200	300	1700	1	1.36
Reinforced concrete	200	400	2200	1.5	0.85
NaCl (solid)	200	500	2160	7	0.85
Magnesia fire bricks	**200**	**1200**	**3000**	**1**	**1.15**
Synthetic oil	250	350	900	0.11	2.3
Silicon oil	300	400	900	0.1	2.1
Nitrate salts (liquid)	**265**	**565**	**1870**	**0.52**	**1.6**
Carbonate salts (liquid)	450	850	2100	2	1.8
Liquid sodium	270	530	850	71	1.3
Silicon carbide	**200**	**1400**	**3210**	**3.6**	**1.06**
SiO2 (crystobalite)	200	1200	2350	0.92	1.13

Zhang et a., PECS 53 (2016) 1

Phase Change Material (PCM)

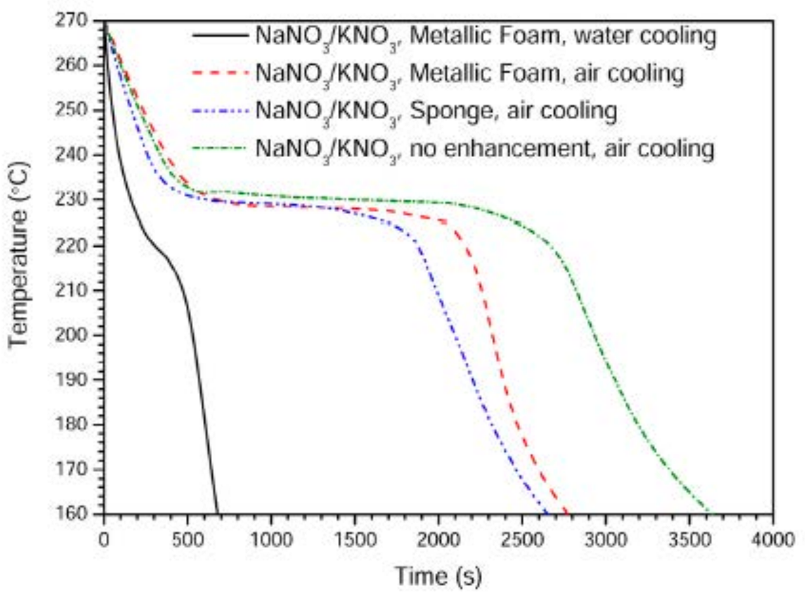


Fig. 11. Temperature vs. time cooling of the E-PCM (nitrates) [27]. Air-cooling of liquid PCM (1) no inserts; (2) metallic sponge; (3) metallic foam. Air-cooling of solid PCM (4) no inserts; (5) metallic sponge; (6) metallic foam; water-cooling of (7) liquid PCM + foam; and (8) solid PCM + foam.

Melting point °C	Heat of fusion kJ/kg	Density kg/m^3	Specific heat kJ/kg K	Thermal conductivity W/m.K
142	84	1990	1.34	0.6
307/308	74	2260/2257	NA	0.5
318	290	2000	1.85	1.0
333/336	266	2110	NA	0.5
350	215	2250	0.96	0.95
380	150	2044	NA	0.5
380	400	1800	0.96	NA
767	790	2100/2670	1.97/1.84	1.7/5.9

Zhang et a., PECS 53 (2016) 1

Hitec: KNO3—NaNO2—NaNO3
NaNO3
65.2%NaOH—20%NaCl—14.8%Na2CO3
KNO3
22.9% KCl—60.6% MnCl2—16.5% NaCl
KOH
MgCl2/KCl/NaCl
80.5% LiF—19.5% CaF2 eutetic

Thermochemical Energy Storage

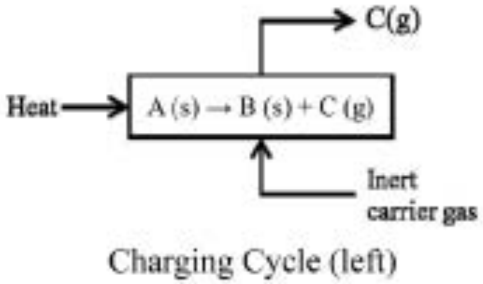
Zhang et a., PECS 53 (2016) 1

The equilibrium T_{eq} for the reaction is T when the driving force for moving the reaction is either direction is zero, corresponding to the equilibrium constant = 1.

$$\Delta G_R(T_{eq},p)=0, \text{ and } T_{eq}=\frac{\Delta H_R\left(T_{eq},p\right)}{\Delta G_R\left(T_{eq},p\right)}$$

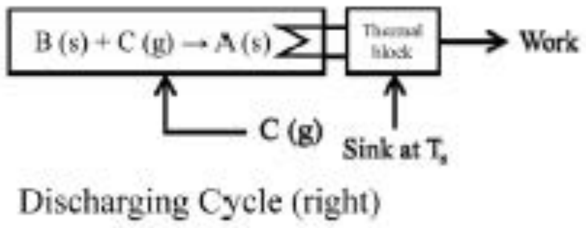
at $T < T_{eq}$, reaction releases heat and moves towards reactants

at $T > T_{eq}$, reaction gains heat and moves towards products



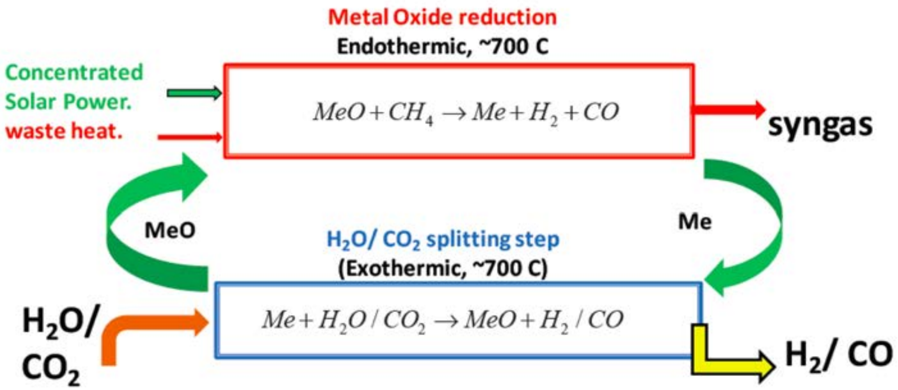
Charging Cycle (left)

Adding heat at high T



Discharging Cycle (right)

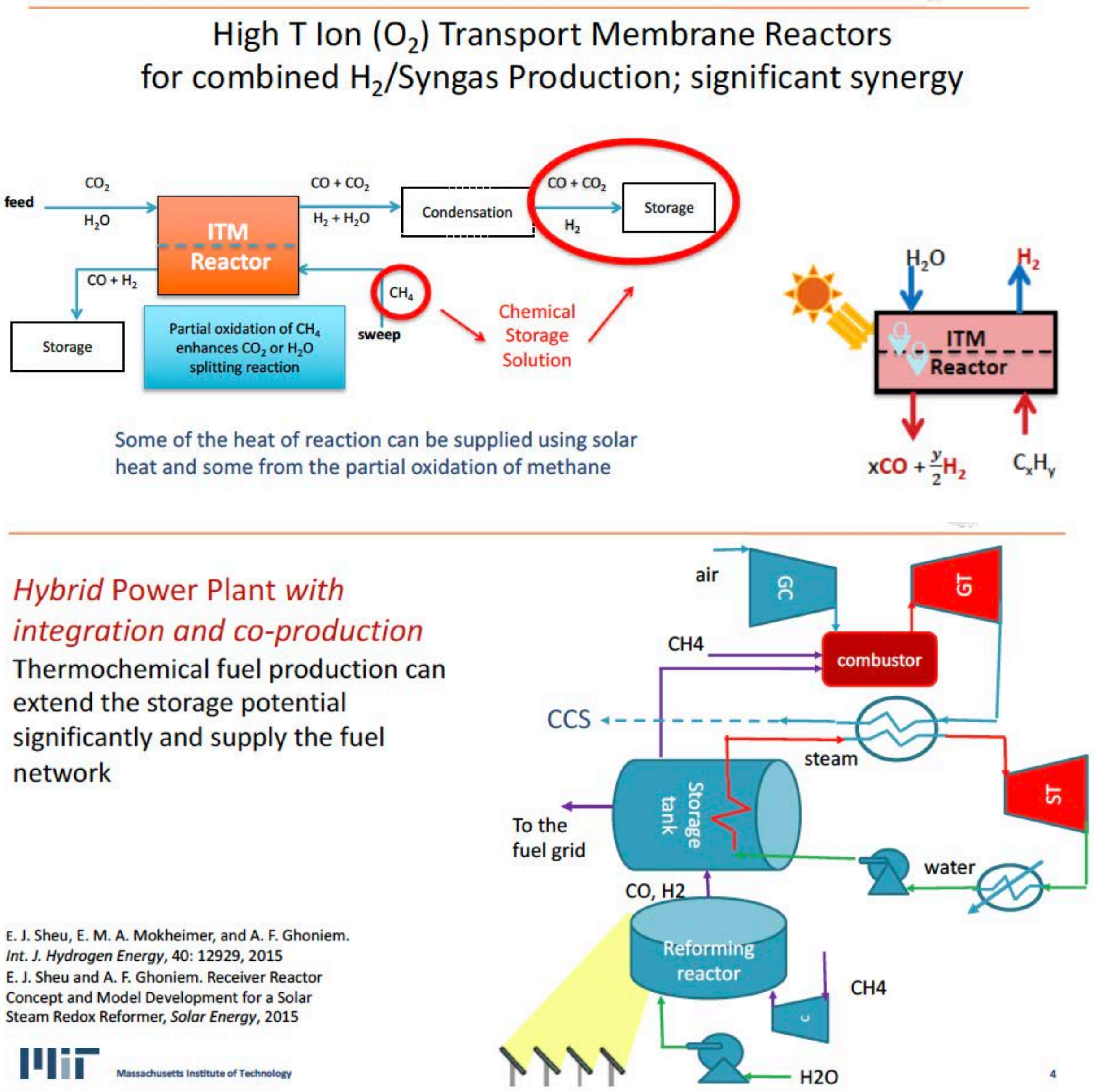
Taking heat out at lower T to do work (power cycle)



Possible reaction pairs.

Reaction	T_{eq} °C (p=1 atm)	ΔH_R (kJ/kg) at T_{eq}
$Mg(OH)_2$ $MgO + H_2O$	259	1396
$MgCO_3$ $MgO + CO_2$	303	1126
Ca(OH)2 $CaO + H_2O$	479	1288
$CaMg(CO_3)_2$ $MgO + CaO + 2CO_2$	490	868
$CaCO_3 + H_2O$ $Ca(OH)_2 + CO_2$	573	137
$CaCO_3$ $CaO + CO_2$	839	1703
$2Co_3O_4$ $6CoO + O_2$	870	844
$5Mn_2O_3$ $5Mn_3O_4 + O_2$	90 6	185
Mn_2O_3 $2MnO + 1/2\ O_2$	1586	1237

Ripe area for research and development



High T Ion (O_2) Transport Membrane Reactors for combined H_2/Syngas Production; significant synergy

Some of the heat of reaction can be supplied using solar heat and some from the partial oxidation of methane

Hybrid Power Plant with integration and co-production

Thermochemical fuel production can extend the storage potential significantly and supply the fuel network

E. J. Sheu, E. M. A. Mokheimer, and A. F. Ghoniem. *Int. J. Hydrogen Energy*, 40: 12929, 2015
E. J. Sheu and A. F. Ghoniem. Receiver Reactor Concept and Model Development for a Solar Steam Redox Reformer, *Solar Energy*, 2015

Courtesy Elsevier, Inc., http://www.sciencedirect.com. Used with permission.

2.60J Fundamentals of Advanced Energy Conversion
Spring 2020