MJ2411

SEMINAR ON ENERGY STORAGE

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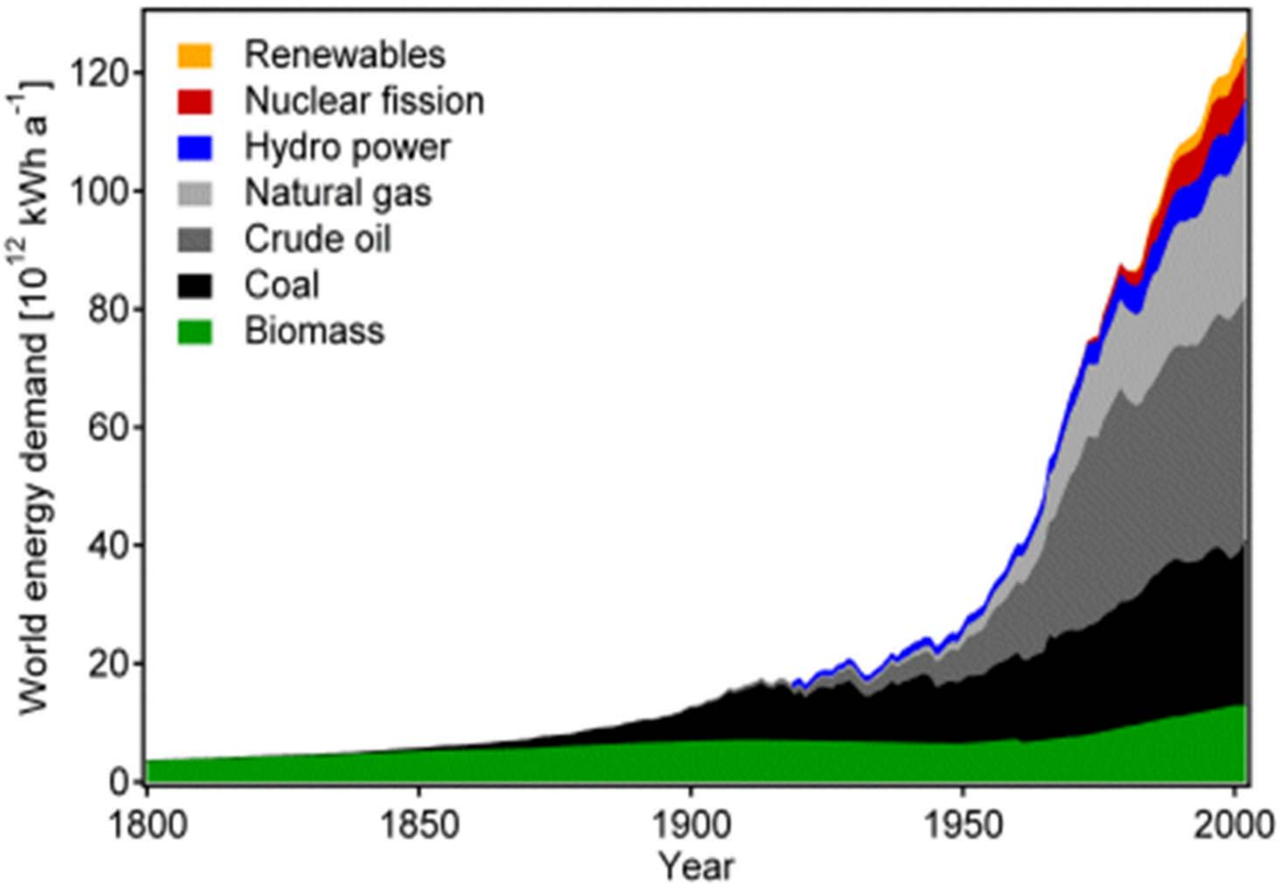
Table of Content

1. Introduction to Energy Storage
2. Categories of Energy Storage
3. Hands on Exercises
4. Discussions

1. INTRODUCTION TO ENERGY STORAGE

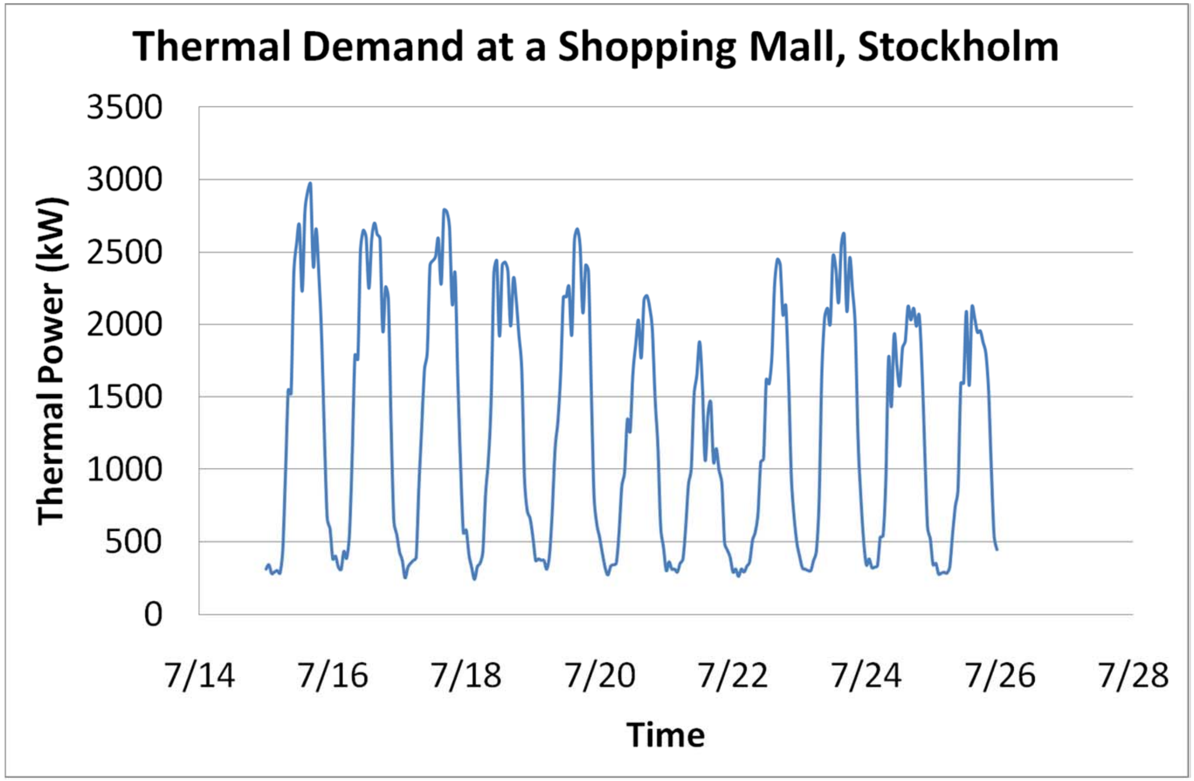
1.1. Increasing Energy Demand



Source: BP Statistical Review of World Energy.

1.2. Mismatch in Time and Space

- Intermittent energy resources
- Fluctuating energy use



Source: Fortum AB.

1.3. Method: Peak Shaving/ Load Leveling

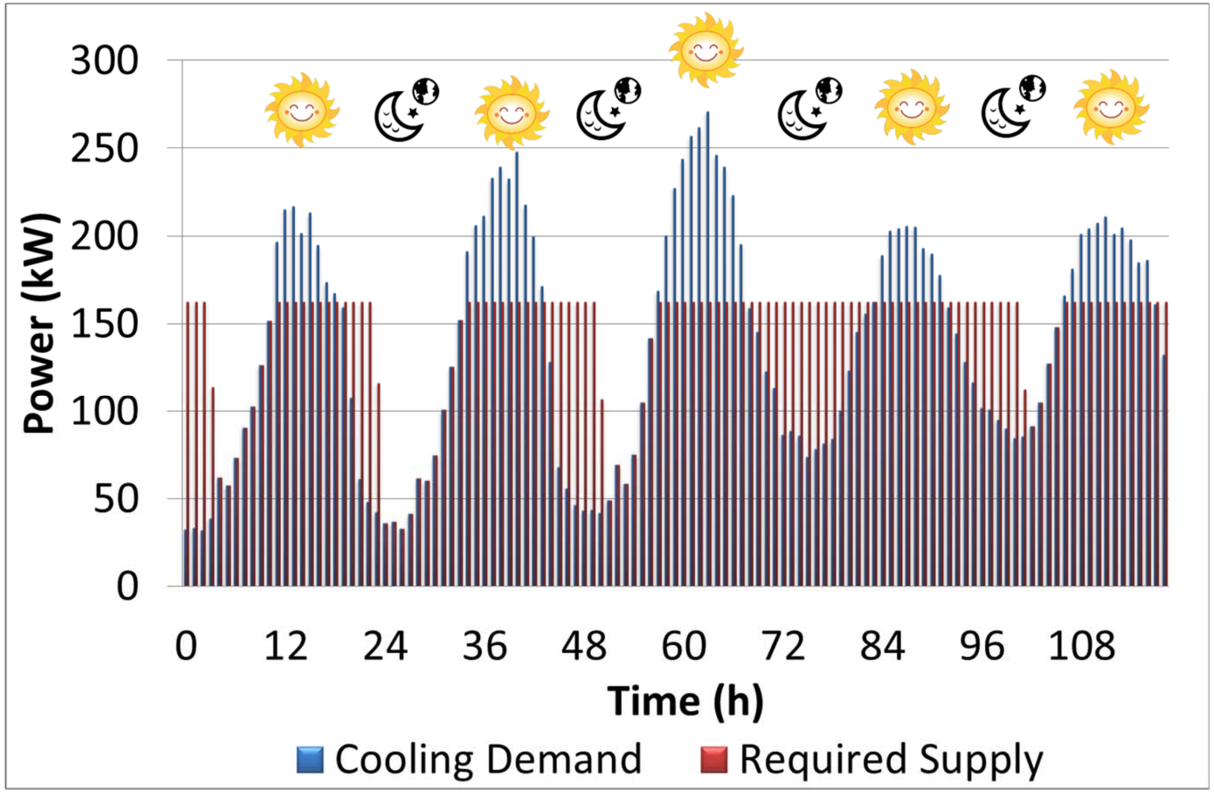
Peak shave → additional power

Load shift → off-peak storage for peak use

Hourly Storage

Daily Storage

Seasonal Storage



1.4. Benefits with Energy Storage

- Energy Arbitrage → Buy and store low-cost energy, sell when price is high
- Generation Capacity Deferral → reduce peak generation, maintain nominal efficiency
- Transmission and Distribution Deferral → alleviate T&D investment
- Ancillary Service → balance supply and demand, reserve capacity
- Reduction of Renewable Curtailment → due to minimum load, ramping, grid limit

2. CATEGORIES OF ENERGY STORAGE

2. Categories of Energy Storage

Mechanical Storage
- Compressed Air
- Fly Wheel
- Pumped Hydro

Electrochemical Storage
- Batteries

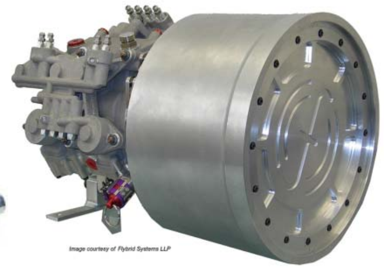
Electromagnetic Storage
- Capacitor
- Magnetic storage

Chemical Storage
- Hydrogen
- Hydrocarbons

Thermal Storage
- Phase change Material

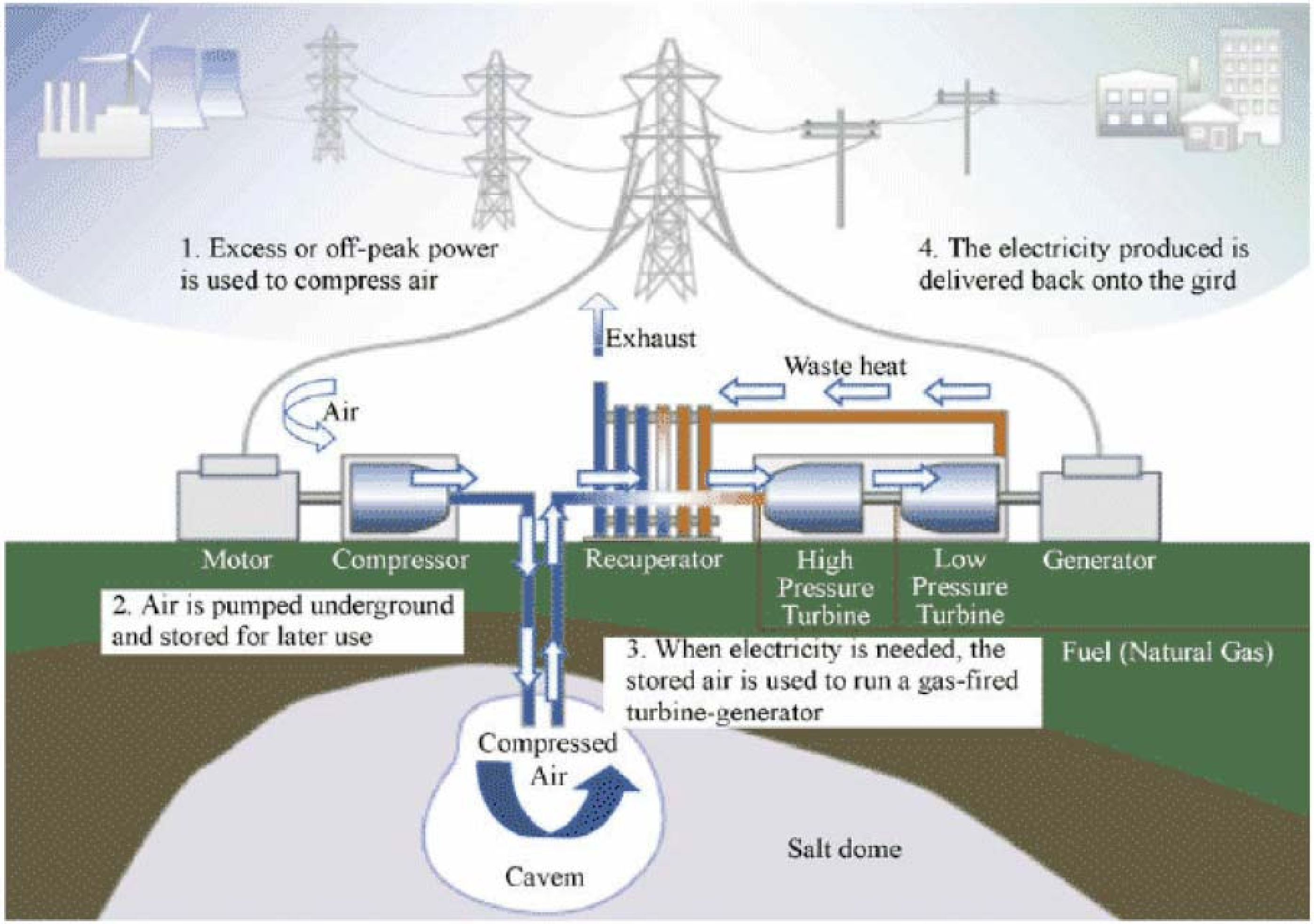
Kinetic Energy

Potential Energy



Source: Vycon, Maxwell, NREL

2.1. Compressed Air Energy Storage



Source: P. Shegner

2.1. Compressed Air Energy Storage

Derive reversible adiabatic (isentropic) compression work required to compress ideal gas.

PV^n = constant

W= $-\int_1^2 P.dV = -\int_1^2 cte.\frac{dV}{V^n} = -\frac{cte.V_2^{1-n} - cte.V_1^{1-n}}{1-n}$

$= \frac{P_2.V_2^{\ n}.V_2^{\ 1-n} - P_1.V_1^{\ n}.V_1^{\ 1-n}}{n-1} = \frac{P_2.V_2 - P_1.V_1}{n-1}$ or $\frac{P_1.V_1}{n-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$

or

$= \frac{m.r.T_2 - m.r.T_1}{n-1}$

with $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} = \left(\frac{V_2}{V_1}\right)^{1-n}$

2.2. Flywheel

Stored energy:

$$KE = \frac{1}{2} I \omega^2 = \frac{1}{2} kmR^2 \omega^2$$

ω = rotational velocity

I = moment of inertia (ability of an object to resist changes in its rotational velocity)

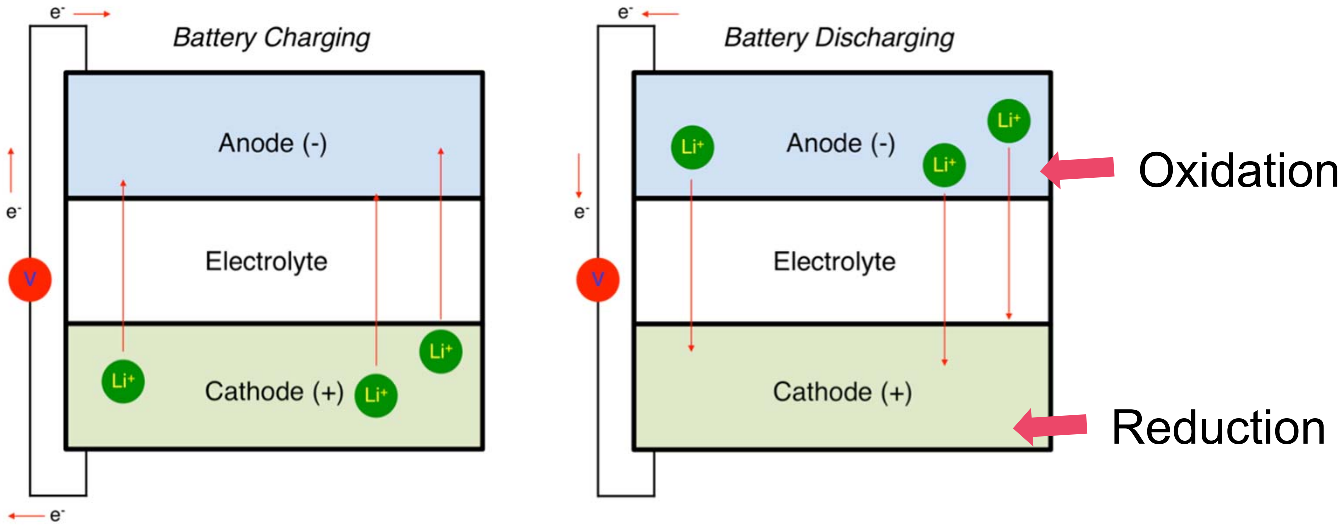
= kmR^2

k: inertial constant depends on shape; m: mass; R: radius

Wheel loaded at rim (bike tire); k = 1: solid disk of uniform thickness; k = 1/2 solid sphere; k = 2/5; spherical shell; k = 2/3; thin rectangular rod; k = 1/2

Source: A. Krothapalli

2.3. Batteries



Storage Density

- 30- 250 Wh/kg
- 100- 650 Wh/L

Cathode (+): $LiCoO_2 \underset{discharge}{\overset{charge}{\rightleftarrows}} Li_{1-x}CoO_2 + xLi^+ + xe^-$

Anode (-): $C_n + xLi^+ + xe^- \underset{discharge}{\overset{charge}{\rightleftarrows}} C_nLi_x$

Overall: $LiCoO_2 + C_n \underset{discharge}{\overset{charge}{\rightleftarrows}} C_nLi_x + Li_{1-x}CoO_2$

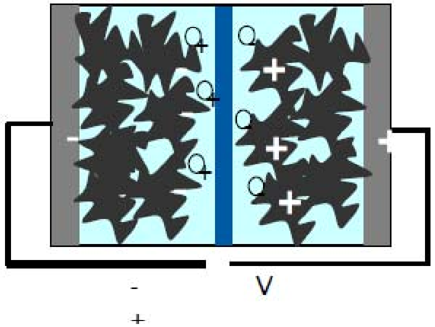
SOURCE: HTTPS://AREWEANYCLOSER.WORDPRESS.COM/2013/05/20/LITHIUM-ION-BATTERY-PRIMER; C. CARTY

2.4. Capacitors

Function double layer capacitor (supercap)

- electrostatic mechanism
- no chemical conversion involved

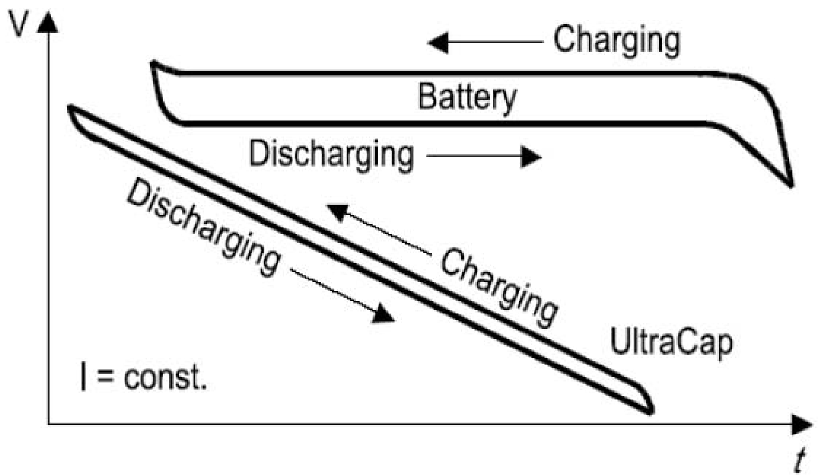
→ Fast and highly reversible processes



→ high cycle life

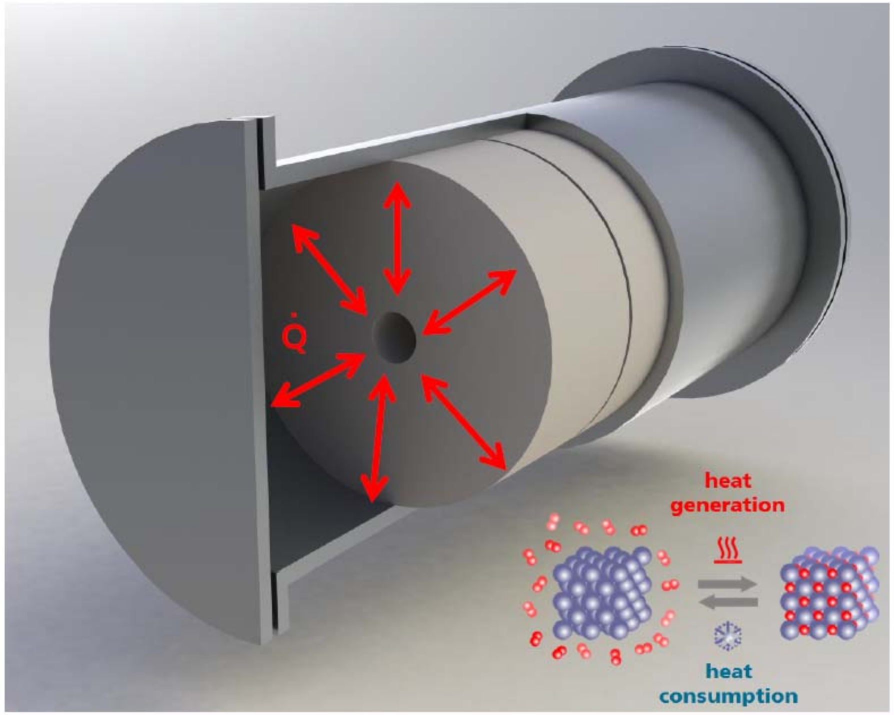
→ high power density

→ linear potential increase during charging



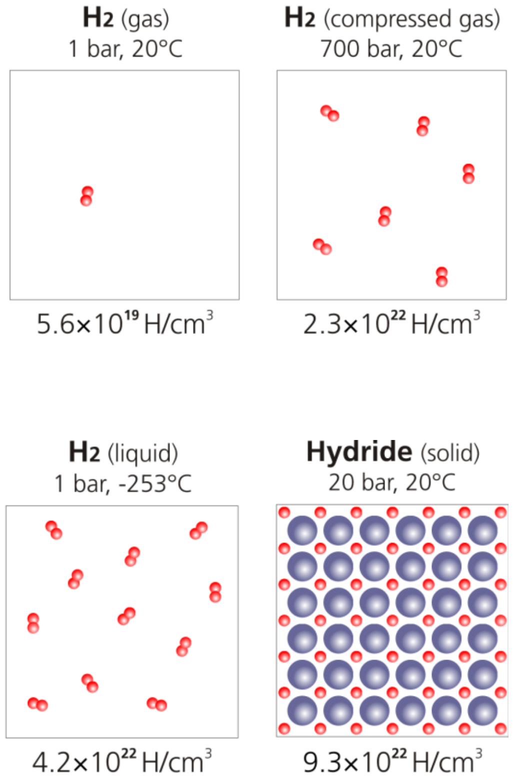
2.5. Hydrogen Storage

Metal Hydride Storage Systems



- mechanical integrity
- gas permeability
- thermal conductivity

λ ~ 10 to 20 W/(mK)
→ sufficient heat transfer



2.6. Power to Gas

Electrolysis of Water

$$2\ H_2O(l) \rightarrow 2\ H_2(g) + O_2(g)$$

Reverse Water Gas Shift Reaction

$$CO + H_2O \leftarrow CO_2 + H_2$$

Fischer Tropsch Process

$$(2n + 1)\ H_2 + n\ CO \rightarrow C_nH_{(2n+2)} + n\ H_2O$$

2.7. Thermal Energy Storage

❑Sensible Heat Storage

- Wide range of materials

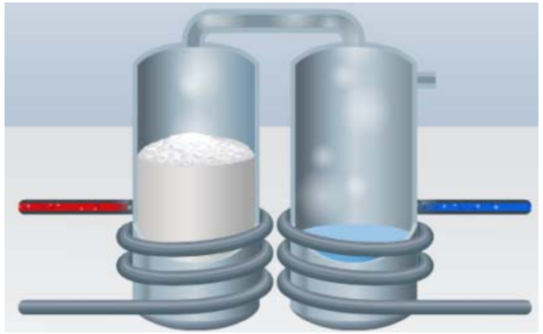
❑Latent Heat Storage- **P**hase **C**hange **M**aterial

- High storage density
- Small temperature swing

❑Thermo-Chemical Storage

- Long term storage





Source: P. Widmer, A. Castell, Climatewell

2.7. Thermal Energy Storage

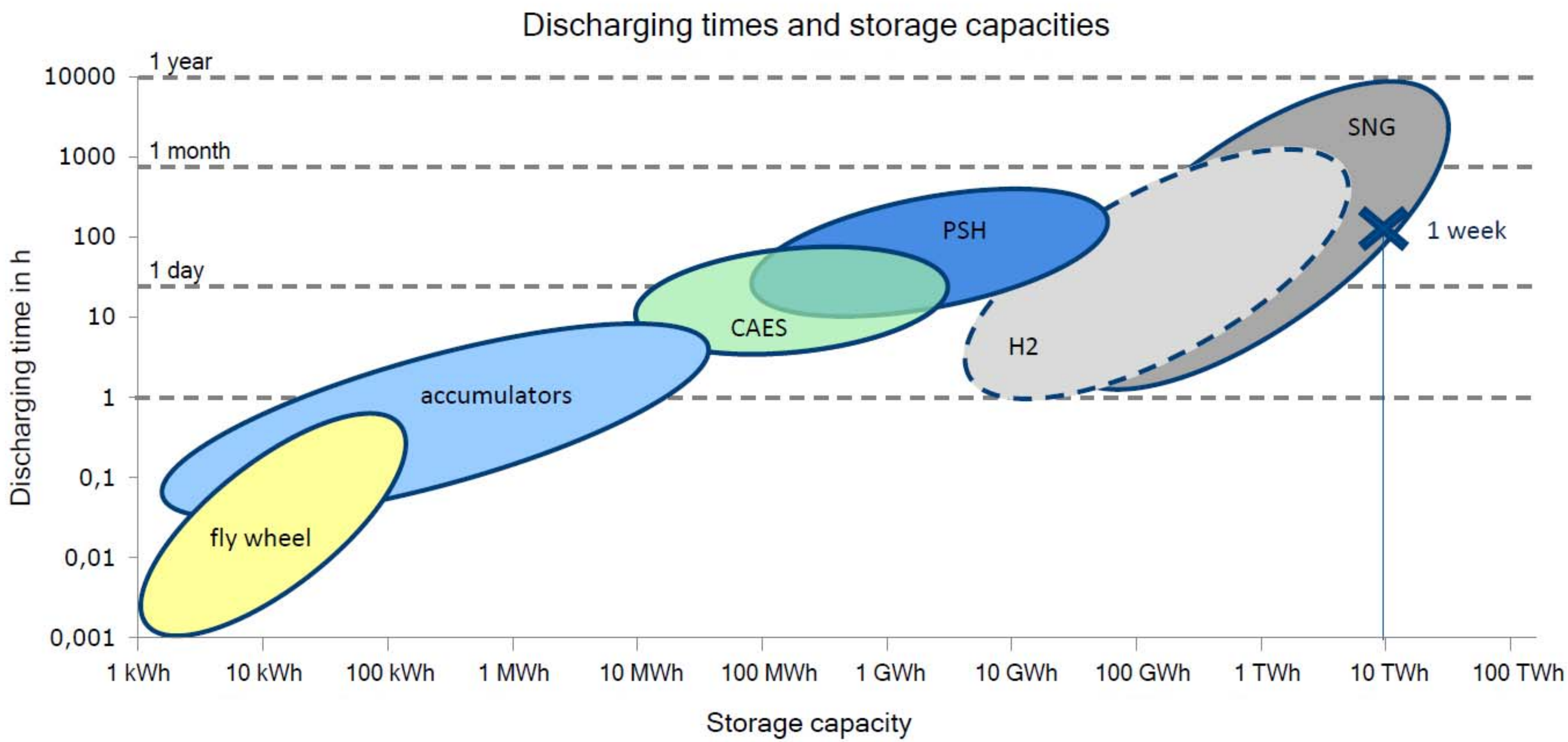
Amount of energy stored (Q) over temperature range $[T_1;T_2]$ with λ specific latent heat, h specific enthalpy, m mass, and c_p specific heat capacity:

$$Q_{pcm} = \int_{T_1}^{T_{PC}} m \cdot c_{p\,sol}(T) \cdot dT + m \cdot \lambda + \int_{T_{PC}}^{T_2} m \cdot c_{p\,liq}(T) \cdot dT$$

In most cases, phase transition is accompanied with temperature change, hence:

$$Q_{pcm} = \int_{T_1}^{T_2} m \cdot dh_{pcm}(T) = \int_{T_1}^{T_2} m \cdot c_{p\,pcm}(T) \cdot dT$$

2.8. Comparison of Storage Technologies



Source: Dr. P. Shegner

3. EXERCISES

Exercise 1.

Tini = 50°C; Tfin = 70°C. What is the storage density for water? What is the storage density for S58 PCM? With packing factor (PF) of 0.8 for latent heat storage. What is the volume uptake ratio between the two storages?

Water: c_p= 4.18 kJ/kg-K and ρ=1 kg/L

S58 PCM: c_p= 2.55 kJ/kg-K, λ=145 kJ/kg and ρ=1.5 kg/L

- For water: q_{water} = 4.18* (70-50)= 83.6 kJ/kg or 83.6 kJ/L

- For PCM S58: q_{PCM} = 2.55*20+145 =196 kJ/kg or 294 kJ/L

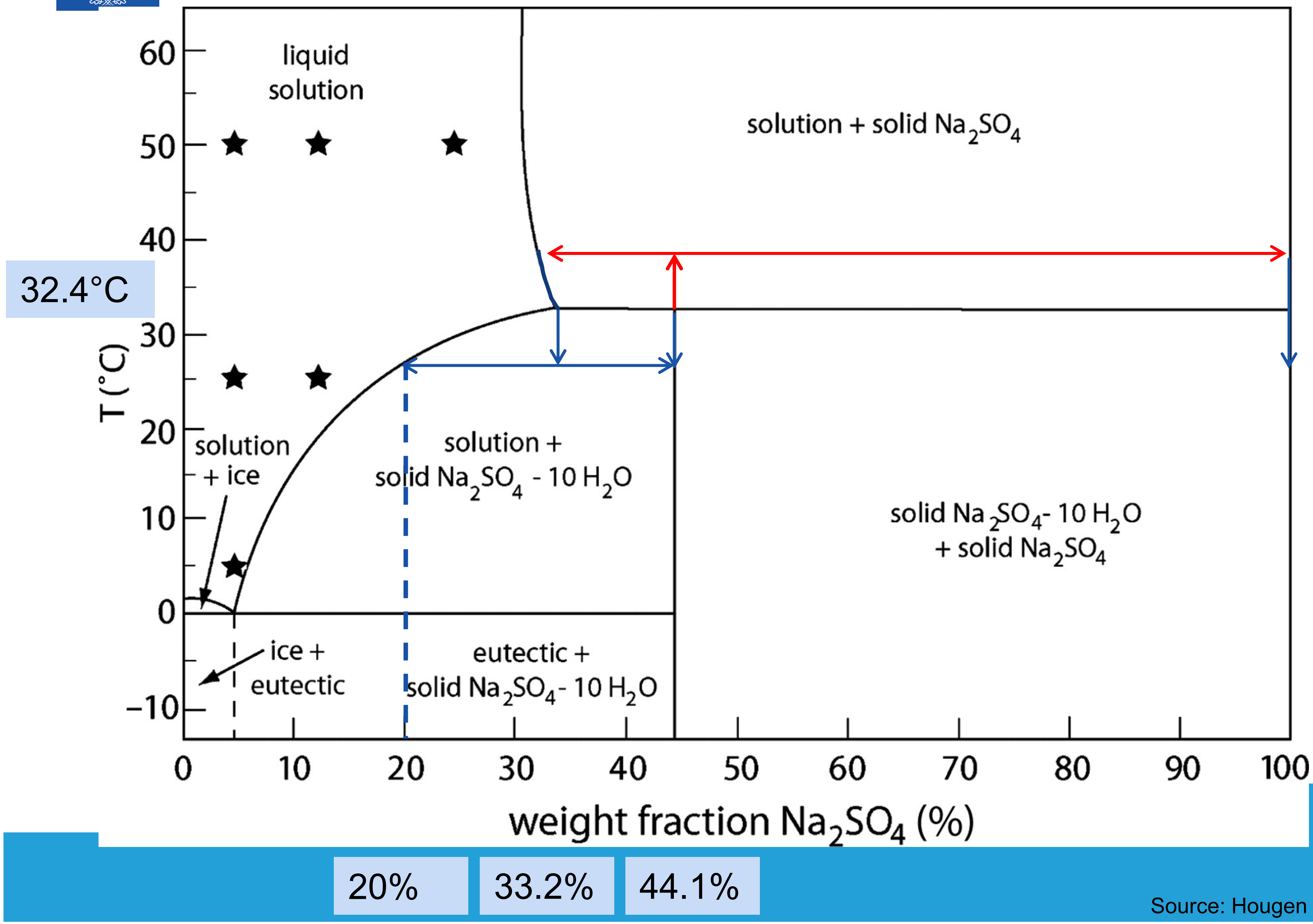
➢ $V_{pcm}/V_{water}= q_{water}/(q_{pcm}$*PF)=0.355 in volume uptake

Discussion

- In reality ρ_liquid ≠ ρ_solid, how does this affect the design?
  - volume expansion is to be taken into account
  - tank has to cope with pressure increase
  - consider if buoyancy mechanism affects the performance

- How is packing factor (PF) linked to the storage performance?
  - higher PF will increase the energy density, but lowers the thermal power rate
  - higher thermal power rate will lower the PF which lowers the energy density

Exercise 2.



Source: Hougen et al. 1954

Exercise 2.

- After cooling molten Glauber's Salt ($Na_2SO_4.10H_20$) from 32.4°C to 26°C, how much Glauber's Salt is left?
- Hint: use the lever rule calculation on the previously shown phase diagram

- m_{GS}.(44.1%-33.2%)=$m_{Solution}$.(33.2%-20%)

➔ $m_{GS} \times 82.6\% = mSolution$

or

- $X_{GS} = \frac{m_{GS}}{m_{total}} = \frac{33.2\% - 20\%}{44.1\% - 20\%} = 54.8\%$

Discussion

- What are the negative impacts of phase segregation?
  - reduced storage capacity
  - alteration of phase change temperature

4. GENERAL DISCUSSIONS

4.1. Design Questions

1. Which storage system to use?
2. What storage characteristics?
   - Storage capacity
   - Volume update, Weight limitation
   - Peak power rate
   - Storage energy loss rate
   - Cyclability of the storage
   - Cycle efficiency
   - Depth of charge/discharge
   - Ramp up time, etc.
3. How can storage fit and operate with existing systems?
4. What are the environmental, social, economic benefits and drawbacks?

Thank you for your attention. Question?

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