47202 Introduction to Future Energy

Energy Storage Technologies

Prof. Ming Chen(minc@dtu.dk)
DTU Energy, Technical University of Denmark

Outline

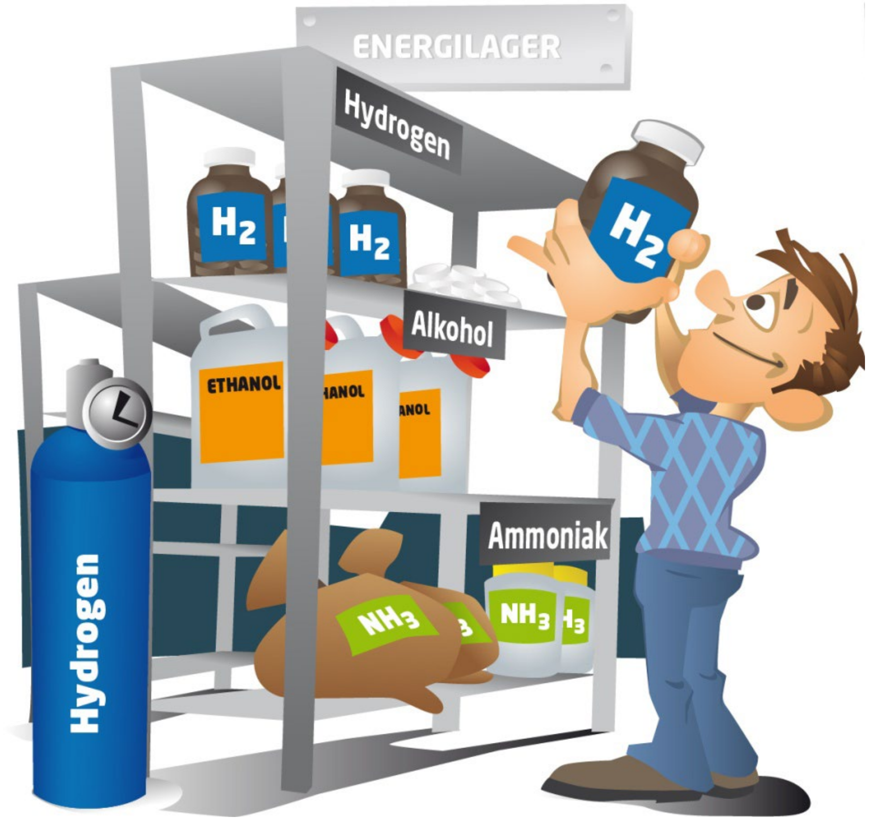
- Introduction to Energy Storage
  - A question of scales
- Economical aspects of Energy Storage
- Mechanical Energy Storage
- Thermal Energy Storage
- Electrochemical Energy Storage
- Summary
- Group exercises
  - Exercise 1: Mechanical Energy Storage
  - Exercise 2: Thermal Energy Storage

Learning objectives

- Discuss the scalability and limits for different energy storage technologies
- Calculate the energy storage capacity in different types of mechanical and thermal energy storage systems
- Discuss and compare the advantages and disadvantages of mechanical, thermal and electrochemical energy storage technologies
- Calculate the levelized cost of storage (LCOS)
- Explain the working principle of thermal energy storage using a phase change materials (PCM)
- Explain the working principle of Compressed Air Energy Storage (CAES)
- Discuss the technical considerations for pumped hydro storage (PHS)
- Assess the relevant time scales for energy storage in flywheels

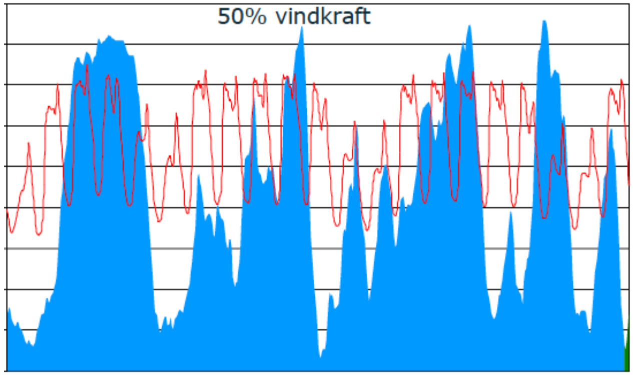
Energy storage – do we need it?

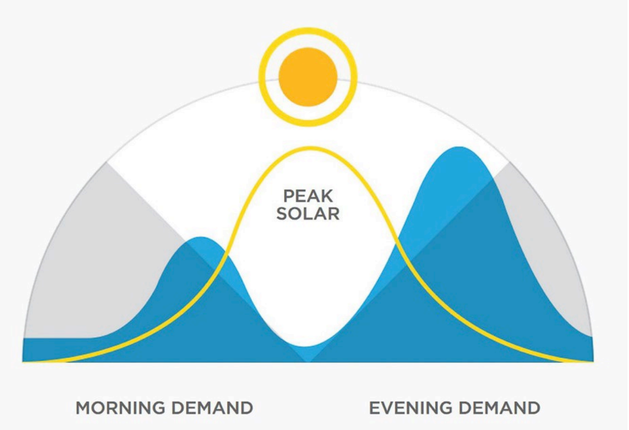
- Why is energy storage needed in the future energy system?
- What are the critical ‘storage parameters‘?
- Are we there yet?
- Let‘s see...



Energy storage – a question of scales

- Different technologies for energy storage are needed for storage on different time- and length scales
- Relevant time-scales
  - Short (seconds-to-minutes)
  - Medium (hours-to-days)
  - Long (weeks-to-seasonal)
- Relevant length-scales
  - Portable devices – i.e. energy you can transport
  - Transportation – energy that transports you
  - Stationary – energy that is transported to you*
- Calls for sustainable storage solutions





Energy storage is the most attractive way to deal with supply/demand mismatches

Energy storage is often the most comfortable and convenient solution – sometimes mandatory
…and increasingly becoming a cheap and affordable option

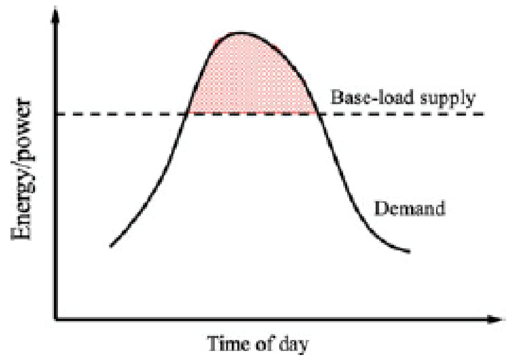


Fig. 1.1 Generic demand and supply of power over the span of a day

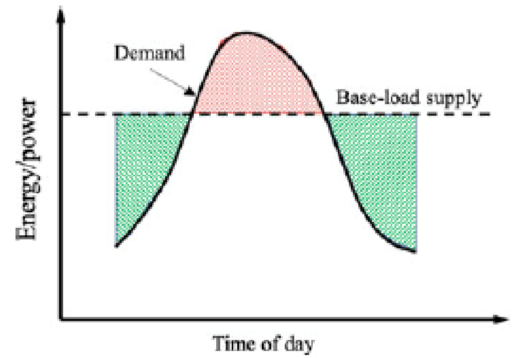


Fig. 1.2 Green areas where storage is permissible to keep power plant operating at baseload

A few facts:

- Energy storage prices (€/kWh) are drastically decreasing
- Energy storage efficiencies are increasing
- LCOE including energy storage is decreasing

Energy storage has been a central part of our energy systems for centuries

- Energy storage has been utilized extensively in the ‘black energy’ economy
- Many European countries are planning for fossil-free – or close to - energy supply by 2050 or earlier
- Since the catastrophe in Fukushima nuclear power has considered a less viable future option – now it’s “green”

- The energy supply is gradually being taken over by renewable sources

solarenergyfactsblog.com

Primary Energy Consumption by Source

- How do you think the war in the Ukraine will change this?

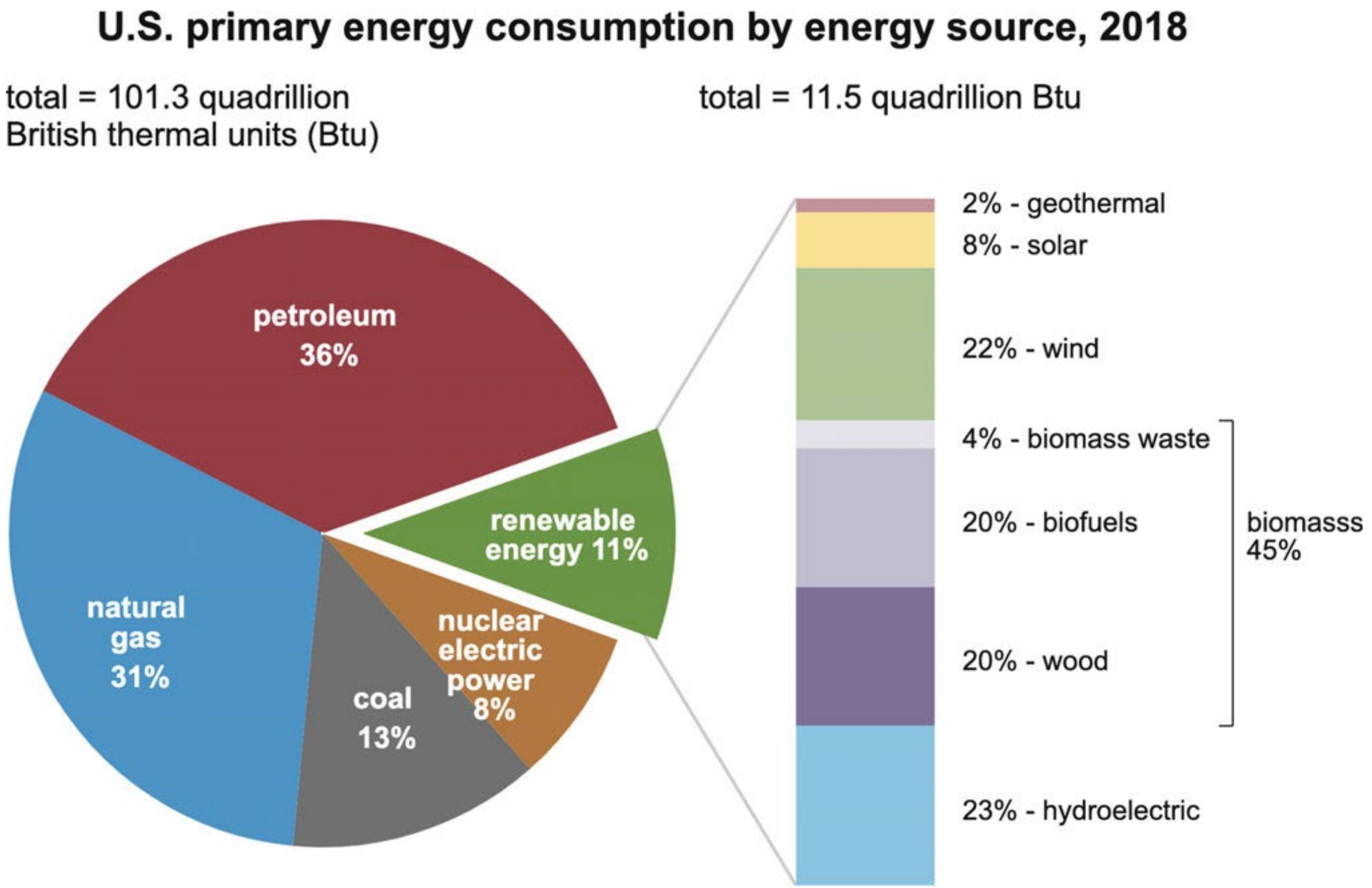


Fig. 1.4 U.S. energy consumption in 2018 classified by energy resource [1]

Abdul Hai Alami, Mechanical Energy Storage for Renewable and Sustainable Energy Resources, Springer (2020)

US Energy Flow

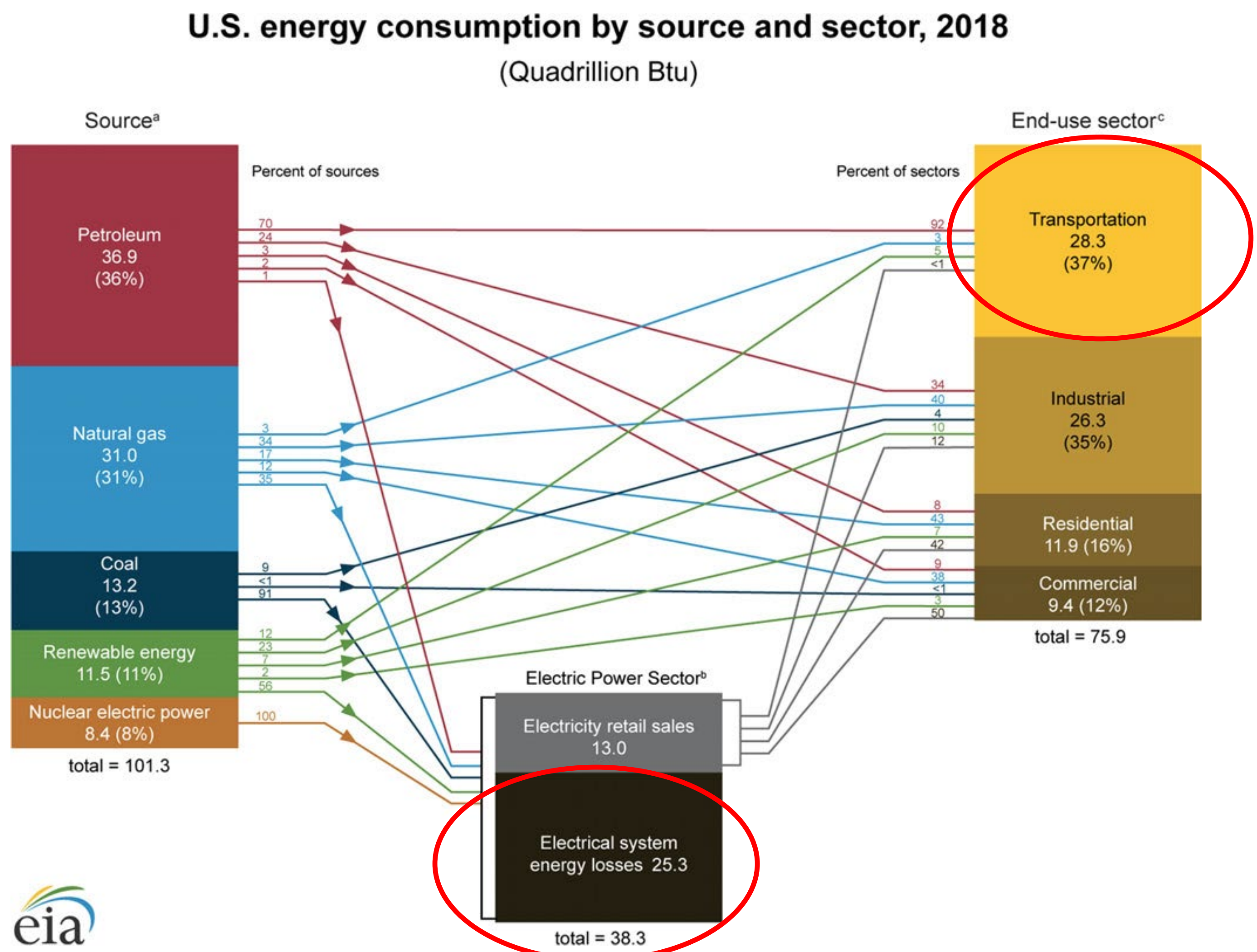
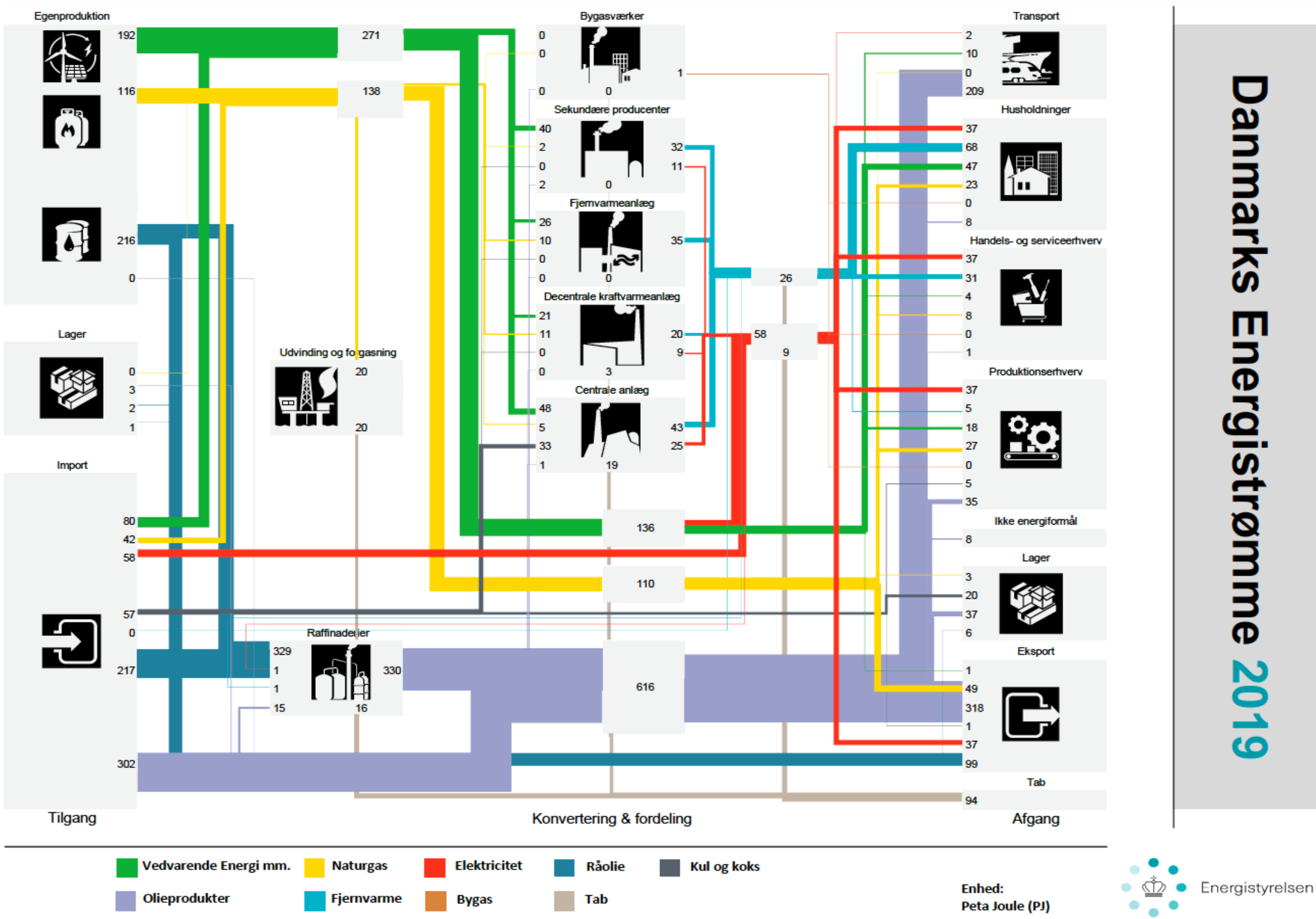


Fig. 1.5 Energy consumption by sector and resource in the United States in 2018 [1]

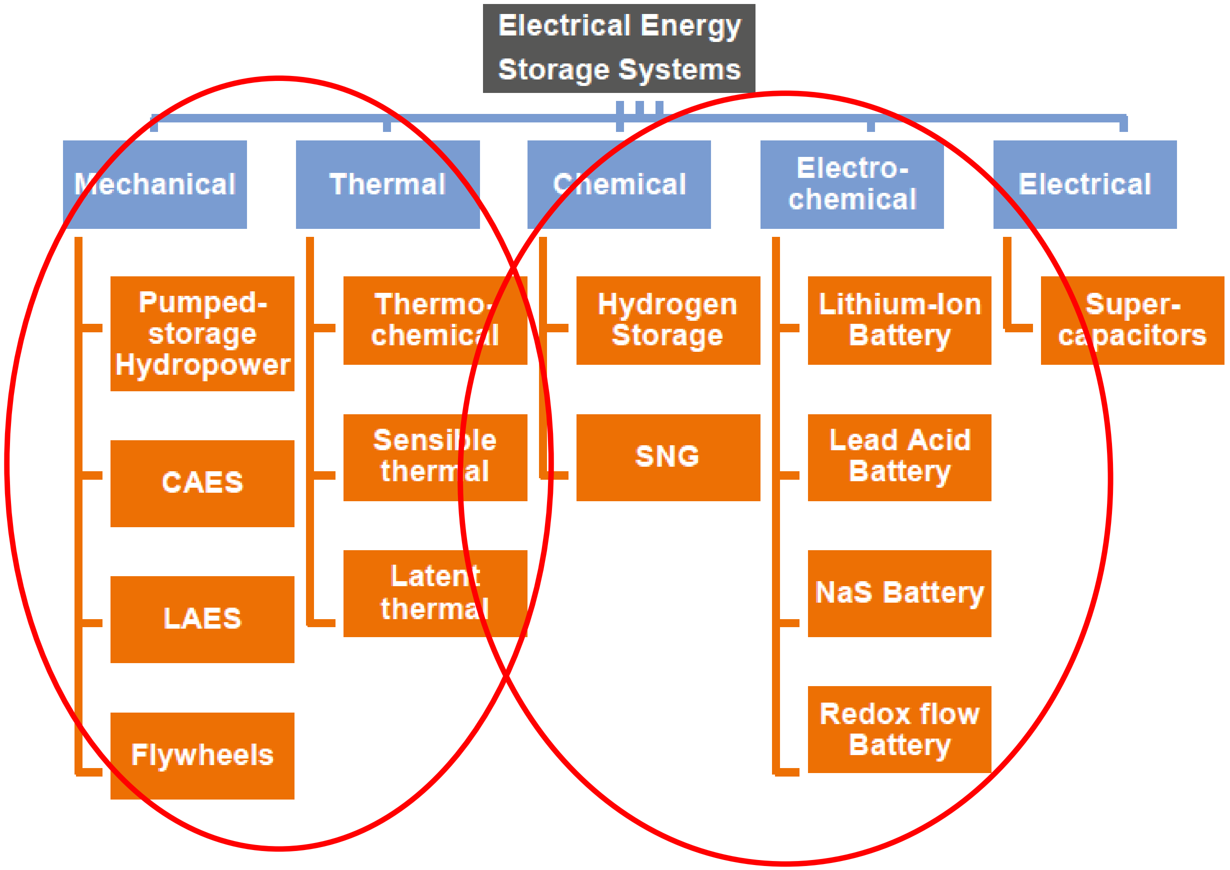
Abdul Hai Alami, Mechanical Energy Storage for Renewable and Sustainable Energy Resources, Springer (2020)

Danish Energy Flow



Energistyrelsen

Different types of energy storage



Source: PwC (2015) CAES is Compressed Air Energy Storage; LAES is Liquid Air Energy Storage; SNG is Synthetic Natural Gas

World Energy Council, World Energy Resources E-Storage (2016)

Time-scales of storage technologies

Duration and frequency of power supply

Time-scale	Technologies
"Seconds to minutes" Short term energy storage systems E2P ratio: 0,25h	Batteries Supercapacitors Flywheels
"Daily storage" Medium term energy storage systems E2P ratio: 1 - 10h	Batteries Pumped hydropower storage CAES / LAES Thermochemical Redox Flow
"Weekly to monthly" Long term energy storage E2P ratio: 50 - 500h	Sensible / Latent thermal Power to Gas

Short and medium term:

- Grid services
- Compensation for day-night load imbalance
- Peak shaving, valley filling, load shifting
- Correction of forecast errors of renewable producers
- Prevention of re-dispatch
- Opportunity of spot market price fluctuations

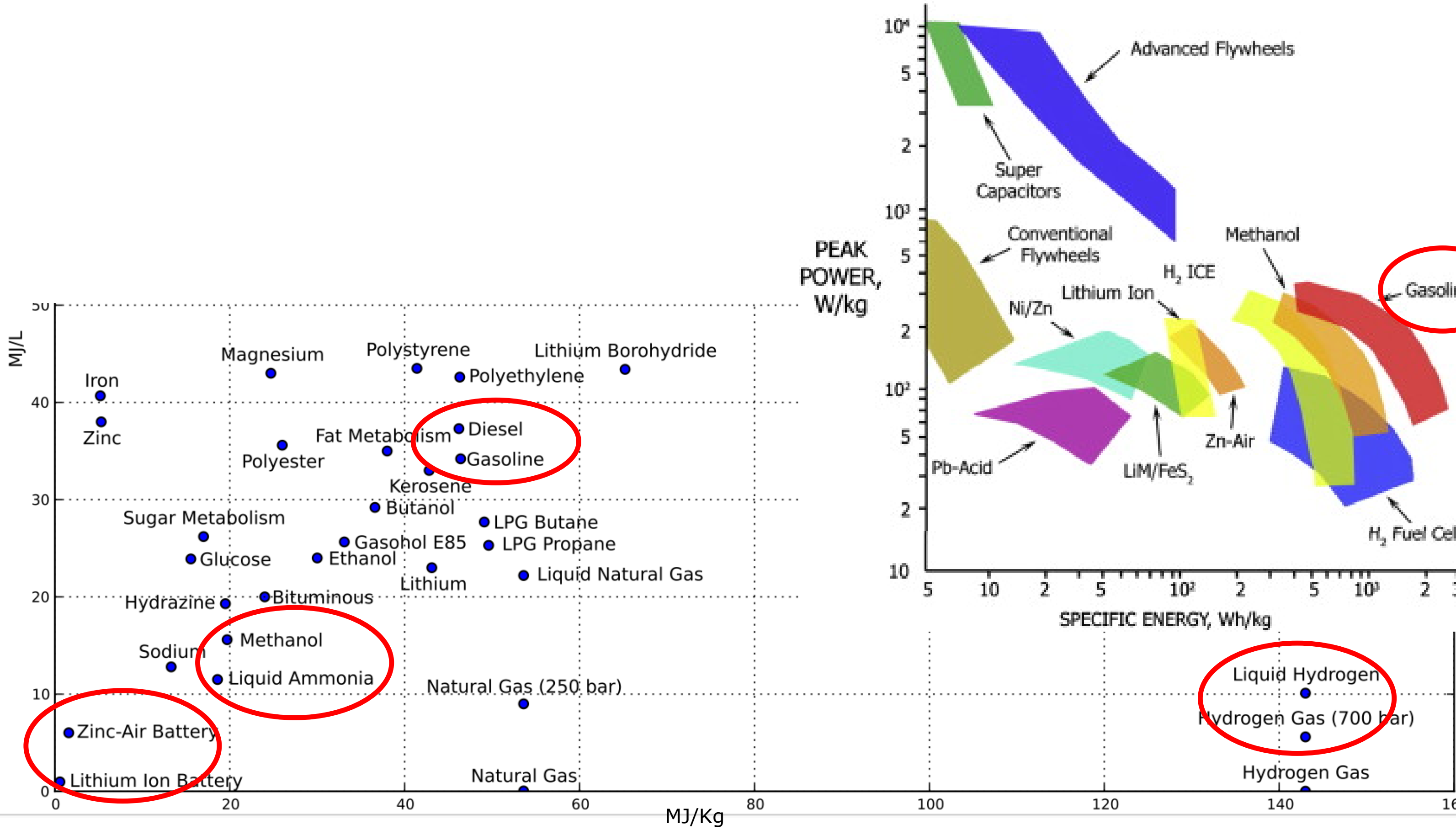
Long term:

- Future application to bridge periods of low wind and photovoltaic generation
- Seasonal storage for thermal energy

World Energy Council, World Energy Resources E-Storage (2016)

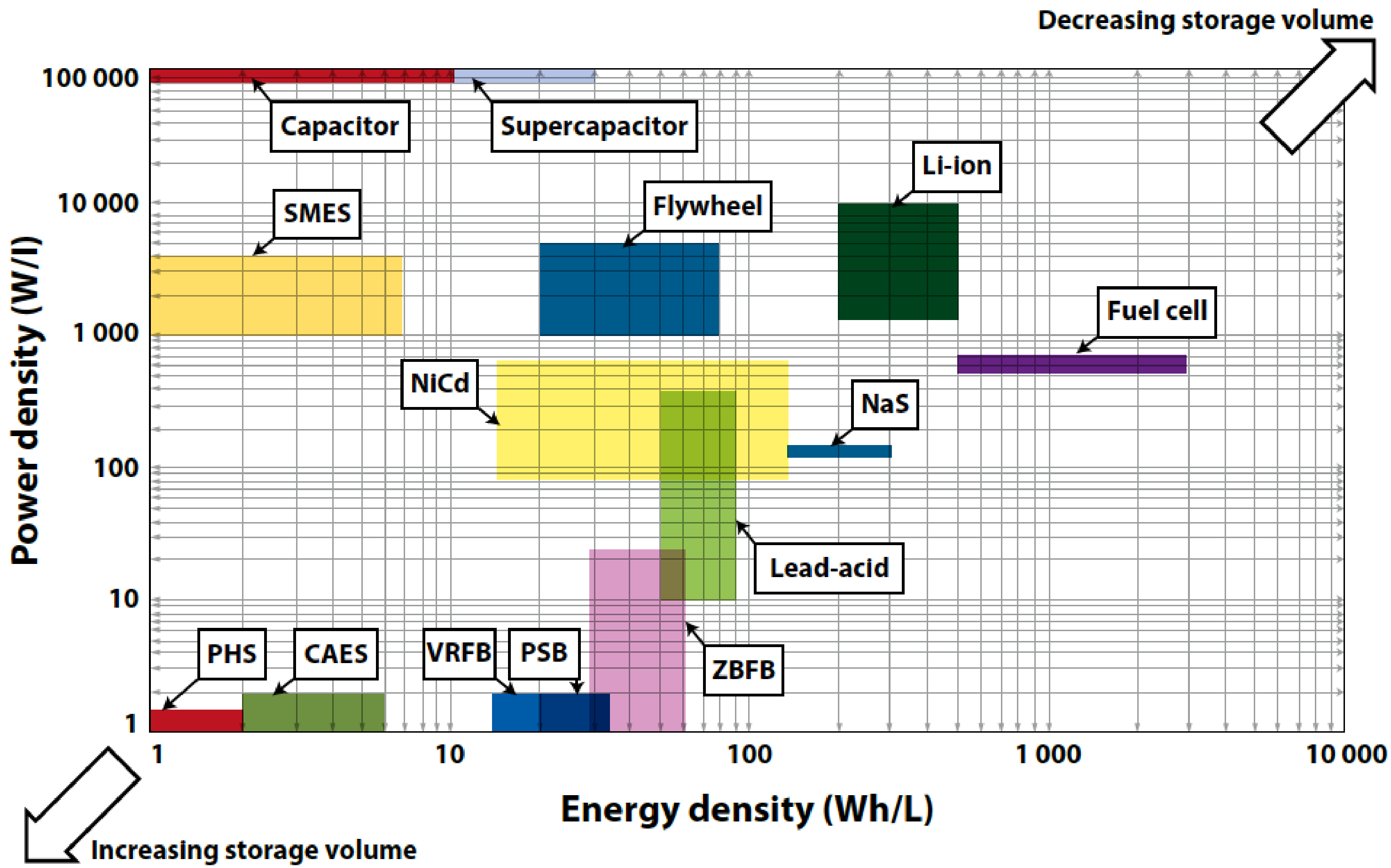
Energy and Power Densities

- What has the highest energy density – batteries or chemical fuels?
- What has the highest peak power – flywheels or fuel cells?



Global energy storage power capacity

Figure 12: Comparison of power density and energy density for selected energy storage technologies

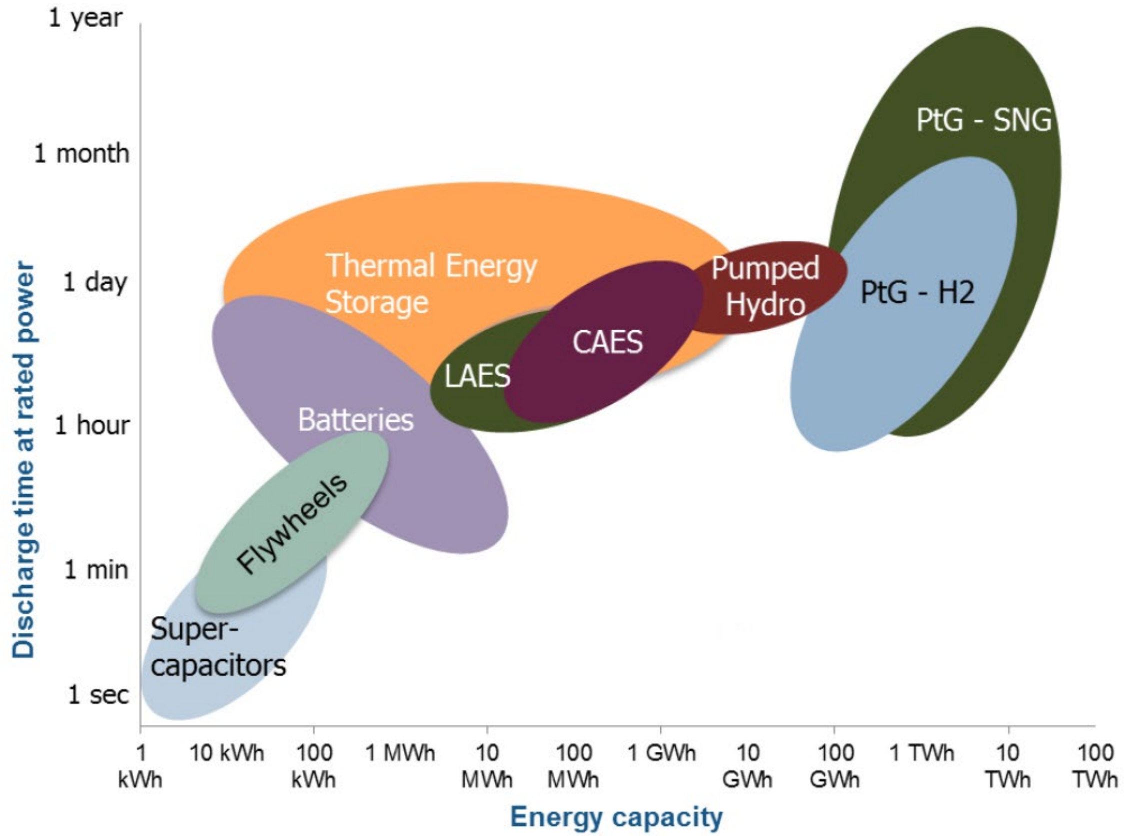


Source: Luo *et al.*, 2015.
Note: SMES = superconducting magnetic energy storage; NiCd = nickel cadmium; NaS = sodium sulphur; PHS = pumped hydro storage; CAES = compressed air energy storage; VRFB = vanadium redox flow battery; PSB= polysulfide bromine flow battery; ZBFB = zinc bromine flow battery.

IRENA, Electricity Storage and Renewables: Costs and Markets to 2030 (2017)

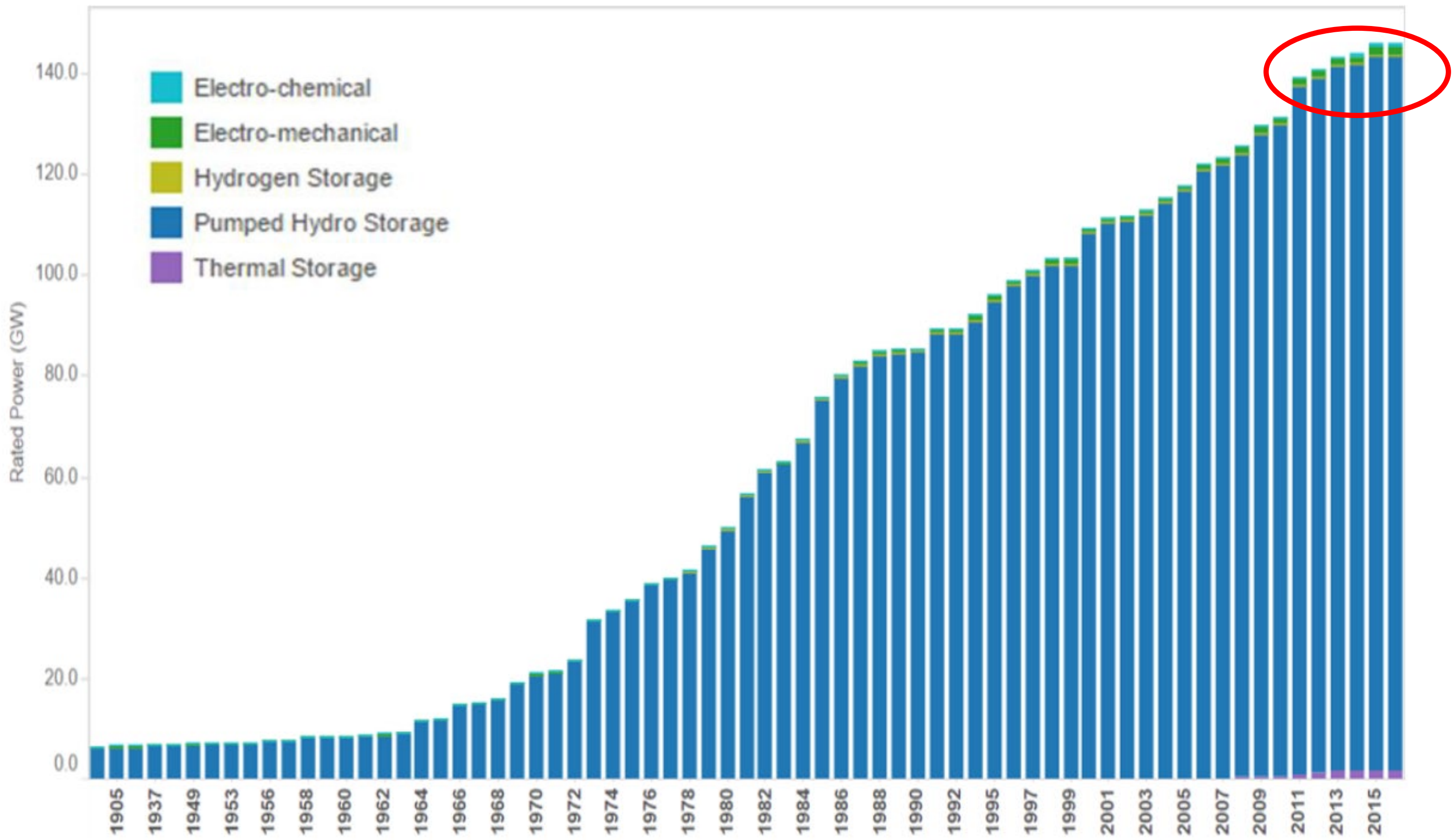
Energy storage on multiple scales

FIGURE 4: MAPPING STORAGE TECHNOLOGIES ACCORDING TO PERFORMANCE CHARACTERISTICS



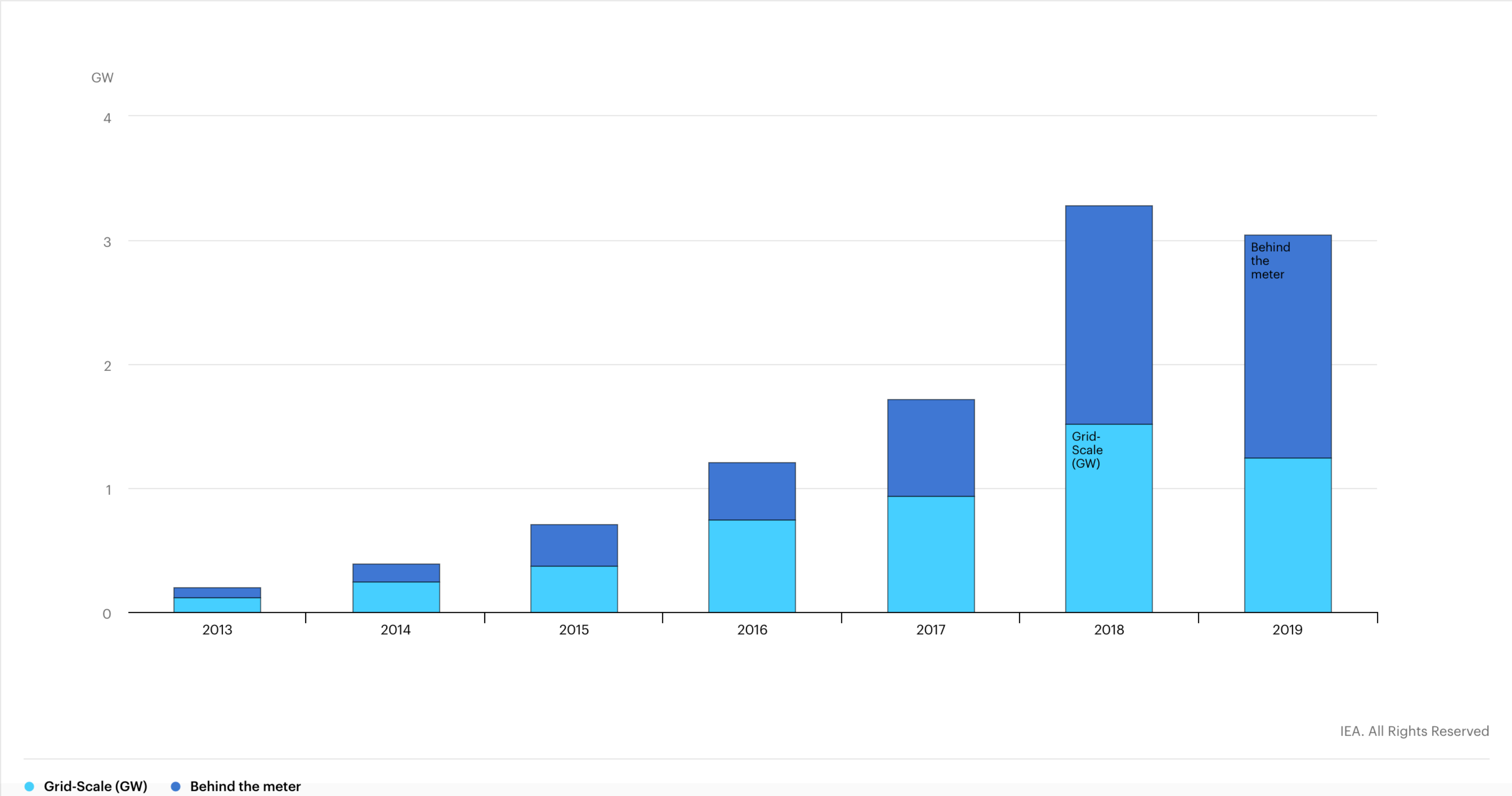
World Energy Council, World Energy Resources E-Storage (2016)

Historic developments in storage capacity



DOE Global Energy Storage Database (2017); IEA (2021)

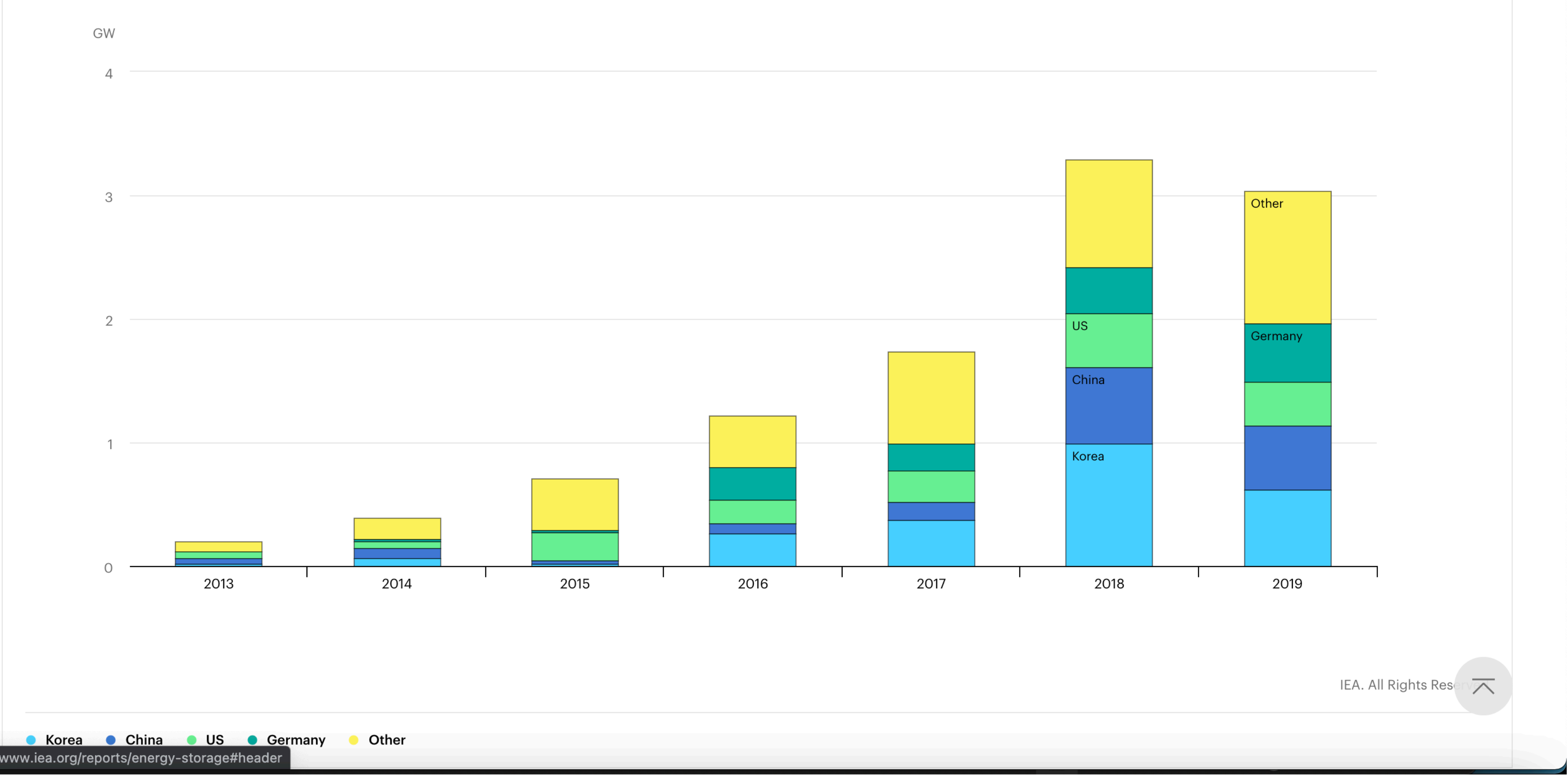
Global deployment of storage technologies



Source: DOE Global Energy Storage Database (2016)

World Energy Council, World Energy Resources E-Storage (2016)

Geographical developments



DOE Global Energy Storage Database (2017); IEA (2021)

Worldwide energy storage reliance on various energy storage technologies

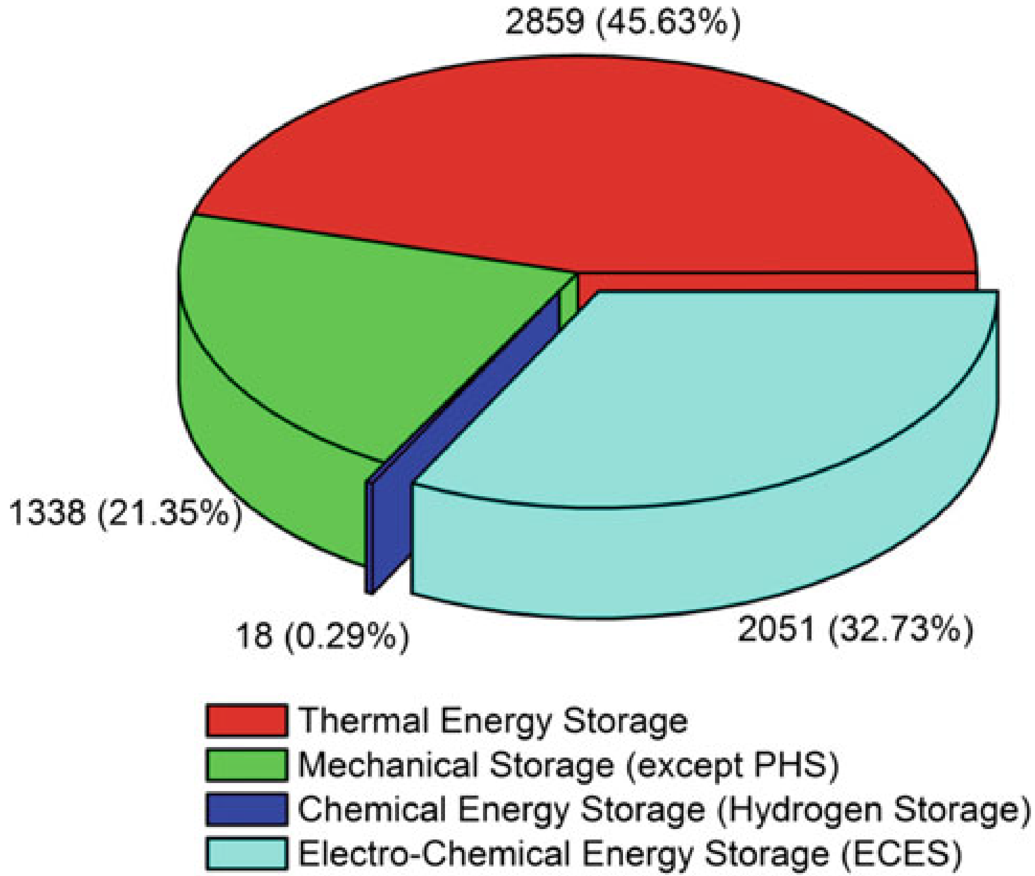


Fig. 1.9 Grid-connected operational capacities of all storage technologies [2]

Abdul Hai Alami, Mechanical Energy Storage for Renewable and Sustainable Energy Resources, Springer (2020)

Comparison on an equal footing

Figure 1 – Sample overview of storage technologies

	ELECTRICAL		MECHANICAL			ELECTROMECHANICAL			CHEMICAL	THERMAL
	Superca-pacitors	SMES	PHS	CAES	Flywheels	Sodium Sulfur	Lithium Ion	Redox Flow	Hydrogen	Molten Salt
Maturity	Develop-ing	Develop-ing	Mature	Mature	Early commer-cialised	Commer-cialised	Commer-cialised	Early commer-cialised	Demon-stration	Mature
Efficiency	90-95%	95-98%	75-85%	70-89%	93-95%	80-90%	85-95%	60-85%	35-55%	80-90%
Response Time	ms	<100 ms	sec-mins	mins	ms-secs	ms	ms-secs	ms	secs	mins
Lifetime, Years	20+	20+	40-60	20-40	15+	10-15	5-15	5-10	5-30 years	30 years
Charge time	s - hr	min - hr	hr - months	hr - months	s - min	s - hr	min - days	hr - months	hr - months	hr - months
Discharge time	ms - 60 min	ms - 8 s	1 - 24 hs+	1 - 24 hs+	ms - 15 min	s - hr	min - hr	s - hr	1 - 24 hs+	min - hr
Environmen-tal impact	None	Moderate	Large	Large	Almost none	Moderate	Moderate	Moderate	Depend-ent of H2 production method	Moderate

World Energy Council, World Energy Resources E-Storage (2020)

Comparison on an equal footing

Figure 1 – Sample overview of storage technologies

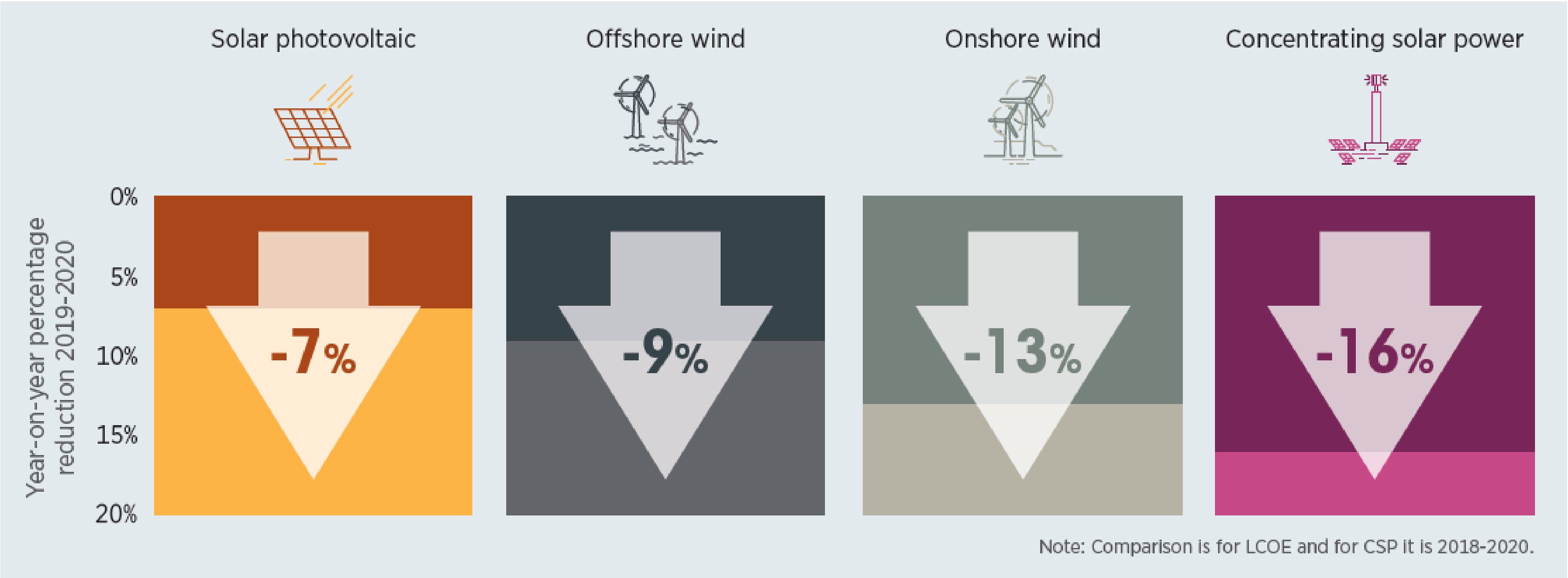
	ELECTRICAL		MECHANICAL			ELECTROMECHANICAL			CHEMICAL	THERMAL
	Superca-pacitors	SMES	PHS	CAES	Flywheels	Sodium Sulfur	Lithium Ion	Redox Flow	Hydrogen	Molten Salt
Possible applications by technologies										
Power quality	✓	✓			✓	✓	✓	🤞		
Energy arbitrage			✓	✓	🤞	✓	✓	✓	🤞	✓
RES integration		✓			✓	✓	✓	✓	✓	
Emergency back-up					✓	✓	✓	✓	🤞	
Peak shaving			✓	✓		✓	✓	🤞	🤞	🤞
Time shifting			✓	✓		✓	✓	🤞	🤞	🤞
Load leveling			✓	✓		✓	✓	🤞	🤞	🤞
Black start						✓	✓	✓	🤞	🤞
Seasonal storage			🤞	✨					🤞	🤞
Spinning reserve		🤞			🤞	✓	✓	🤞	🤞	
Network expansion			✓	🤞		✓	✓	🤞	🤞	🤞
Network stabilisation	🤞	✓			🤞	✓	✓	🤞		
Voltage regultation	🤞	🤞			🤞	✓	✓	✓		
End-user services	🤞	🤞			🤞	✓	✓	🤞		

ECONOMY

Prices on renewables are dropping…

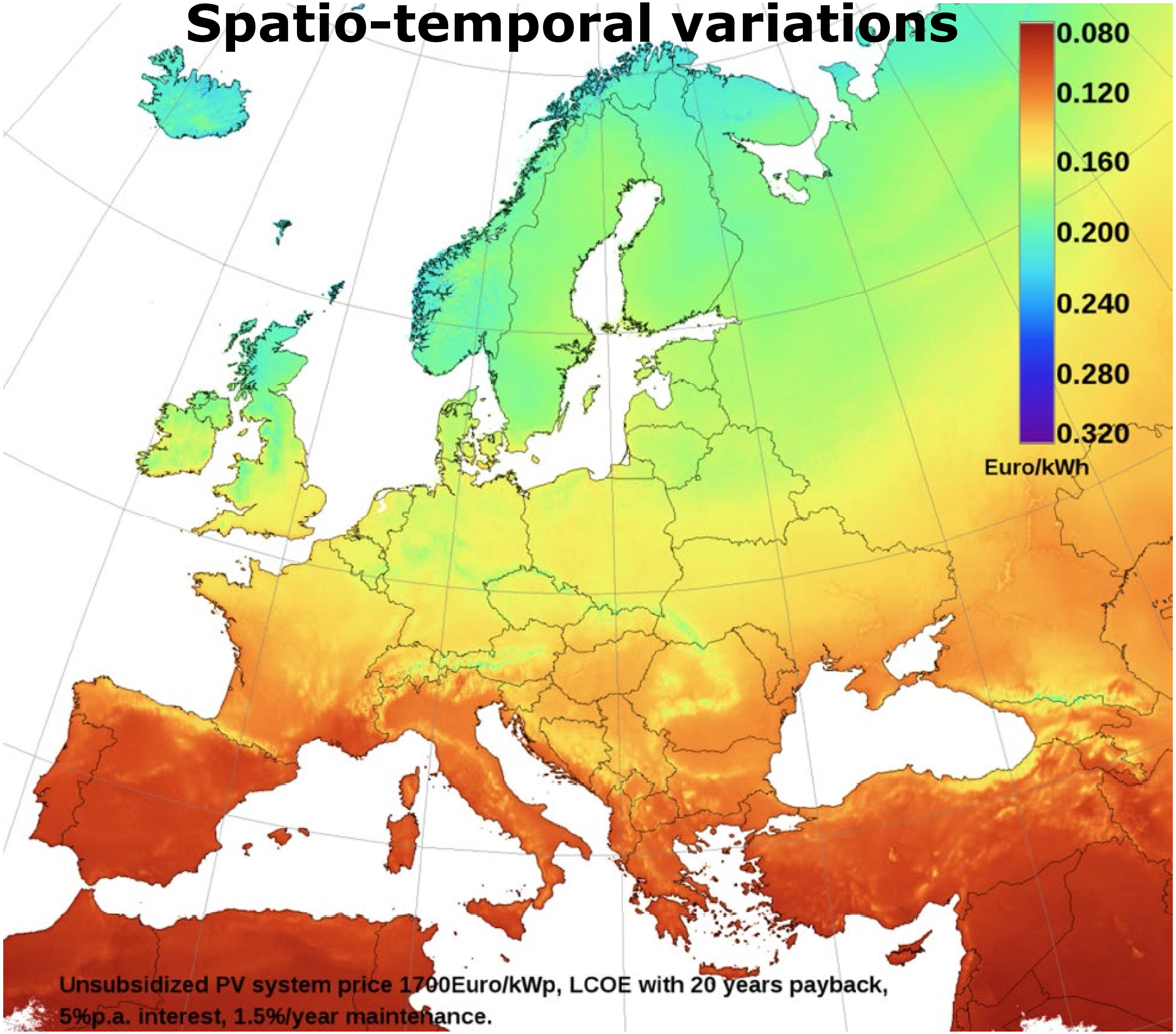
- What about the electricity prices right now?
- What about gas prices?

Figure ES.1 Global weighted-average LCOE from newly commissioned, utility-scale solar and wind power technologies, 2019-2020



Source: IRENA Renewable Cost Database

Spatio-temporal variations



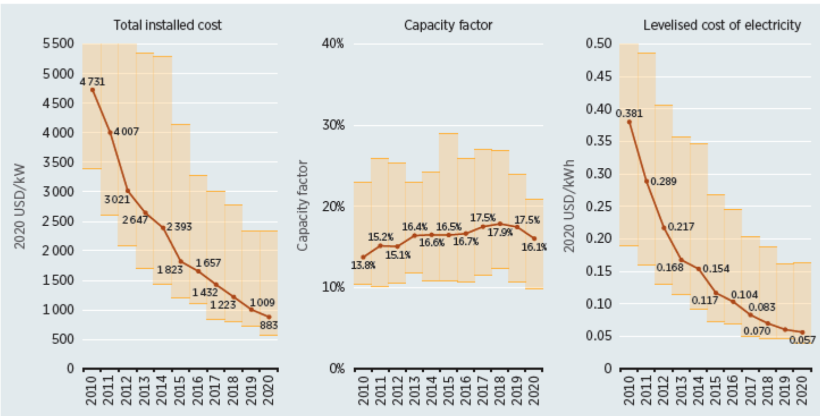
In DK:
~130 EUR/MWh

In ES:
~80 EUR/MWh

Source: Photovoltaic Electricity Cost Maps, JRC, 2013

Electricity from wind and solar

Figure 3.1 Global weighted-average total installed costs, capacity factors and LCOE for PV, 2010–2020



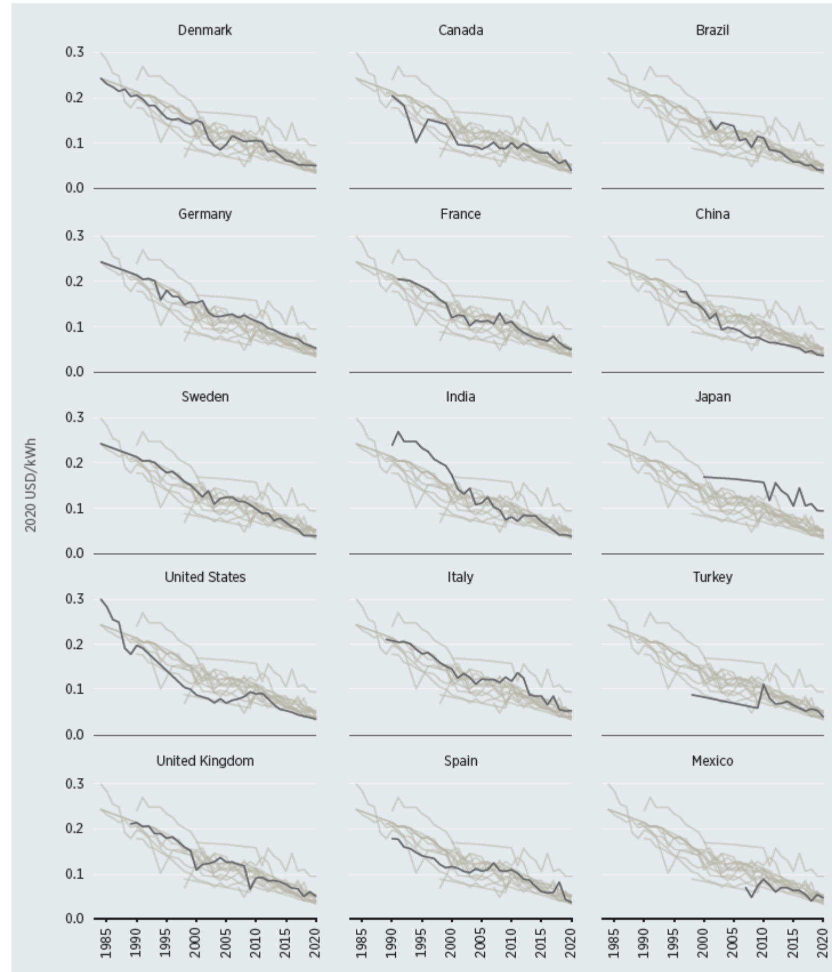
Source: IRENA Renewable Cost Database

Table 2.3 Regional weighted-average LCOE and ranges for onshore wind in 2010 and 2020

	2010			2020		
	5th percentile	Weighted average	95th percentile	5th percentile	Weighted average	95th percentile
	(2020 USD/kW)					
Africa	0.073	**0.091**	0.100	0.041	**0.055**	0.083
Central America and the Caribbean	0.095	**0.095**	0.095	0.059	**0.059**	0.059
Eurasia	0.112	**0.112**	0.112	0.031	**0.047**	0.070
Europe	0.076	**0.113**	0.164	0.035	**0.045**	0.065
North America	0.060	**0.092**	0.124	0.028	**0.037**	0.054
Oceania	0.107	**0.121**	0.132	0.037	**0.052**	0.068
Other Asia	0.103	**0.137**	0.147	0.058	**0.081**	0.113
Other South America	0.087	**0.101**	0.131	0.032	**0.044**	0.063
Brazil	0.110	**0.112**	0.123	0.030	**0.041**	0.062
China	0.058	**0.071**	0.089	0.026	**0.037**	0.047
India	0.053	**0.082**	0.101	0.029	**0.040**	0.051

Source: IRENA Renewable Cost Database.

Figure 2.10 The weighted-average LCOE of commissioned onshore wind projects in 15 countries, 1984–2020



Source: IRENA Renewable Cost Database.

IRENA, Electricity Storage and Renewables: Costs and Markets to 2030 (2020)

LCOE

Levelized Cost Of Energy/Electricity

- Useful for comparing different energy sources on an equal economic footing, but *not* taking dispatchability/reliability into account
- LCOE considers the discounted *lifetime costs* divided by discounted *energy production*
- LCOE provides the *present value* of the total cost of building and operating an energy source over an assumed lifetime
- LCOE can compare an oil well to wind turbine or a coal plant to a nuclear plant

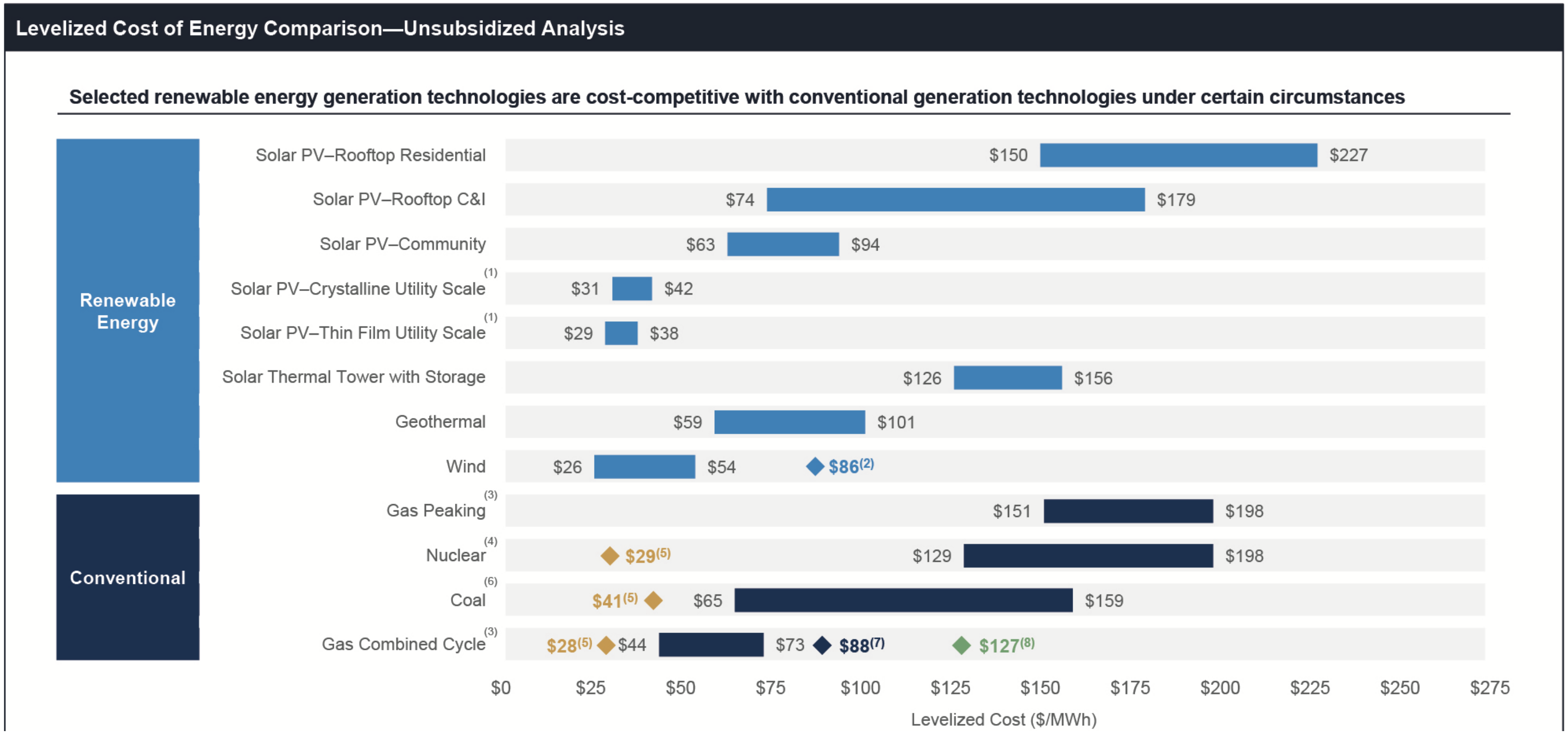
Simple LCOE

- $LCOE = \frac{\sum_{i=1}^{n} \frac{(I_i + M_i + F_i)}{(1+WACC)^i}}{\sum_{i=1}^{n} \frac{E_i}{(1+WACC)^i}} = \frac{(Negative)DCF}{Discounted\ Energy\ Flow}$
- I_i = Investment in year *i*
- M_i = Operation and maintenance in year *i*
- F_i = Fuel cost in year *i*
- E_i = Electricity (or energy) produced in year *i*
- n = Lifetime of the installation
- One might include decommissioning costs to I_n.

- Calculation:
  - https://www.nrel.gov/analysis/tech-lcoe.html
  - ”NPV” formula in spread sheet
  - Python, Maple, etc.

Levelized Cost of Energy/Electricity (LCOE)

- 'LCOE' provides a fair comparison of the economics of different energy production technologies
- The weighed average cost of capital (WACC) impacts long term

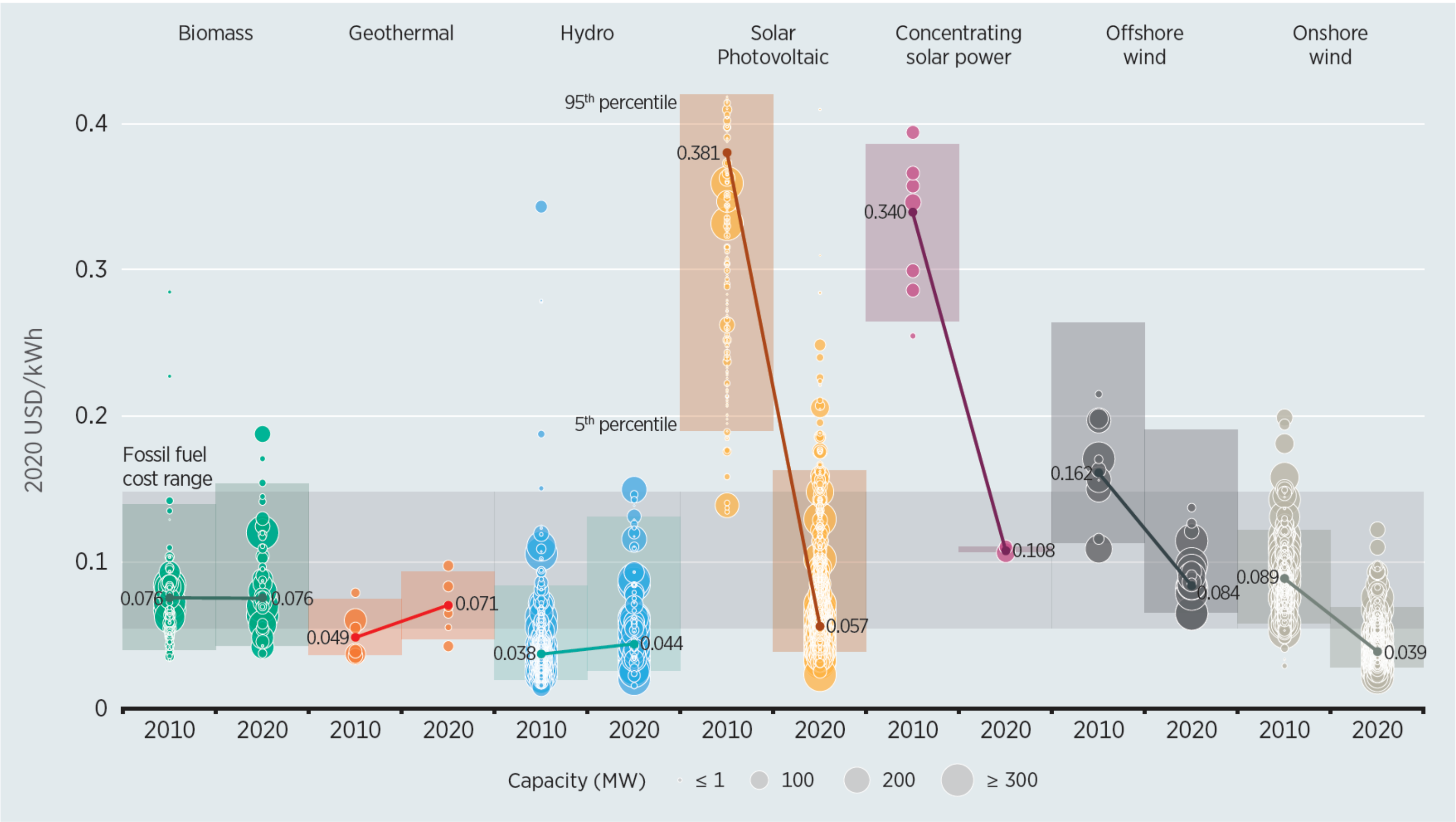


Lazard's Levelized Cost of Energy Analysis – version 11.0 (2017) and 14.0 (2021); IEA (2021)

Global LCOEs from renewables

- What about the storage?

Figure 1.2 Global LCOEs from newly commissioned, utility-scale renewable power generation technologies, 2010-2020



Source: IRENA Renewable Cost Database

Selected long duration storage solutions

- What about the cost of storage?

Selected Long Duration Storage Technologies—Overview

A variety of long-duration energy storage technologies are in various stages of development and commercial viability

	Flow	Thermal	Mechanical
Typical Technologies	• Zinc Bromine • Vanadium	• Latent Heat • Sensible Heat	• Gravity Energy Storage • Compressed Air Energy Storage ("CAES")
Description	• Energy storage systems generating electrical energy from chemical reactions, often stored in liquid tanks	• Solutions storing thermal energy by heating or cooling a storage medium	• Solutions that store energy as a kinetic, gravitational potential or compression medium
Advantages	• No degradation • Cycling throughout the day • Modular options available • Limited safety concerns	• Able to leverage mature industrial cryogenic technology base • Materials are generally inexpensive • Power and energy capacity are independently scalable	• Mechanical is proven via established technologies (e.g., pumped hydro) • Attractive economics • Limited safety concerns
Disadvantages	• Relatively expensive membrane materials • Relatively more difficult to scale production capacity • Lower energy density • Slightly higher O&M costs	• Lower energy density vs. competing technologies • Challenging to increase capacity in modular increments after installation • Operating performance is sensitive to local climatic conditions • Limited track record at larger scale	• Substantial physical footprint vs. competing technologies • Difficult to modularize • Cycling limited to once per day • Lower efficiency (e.g., CAES systems)

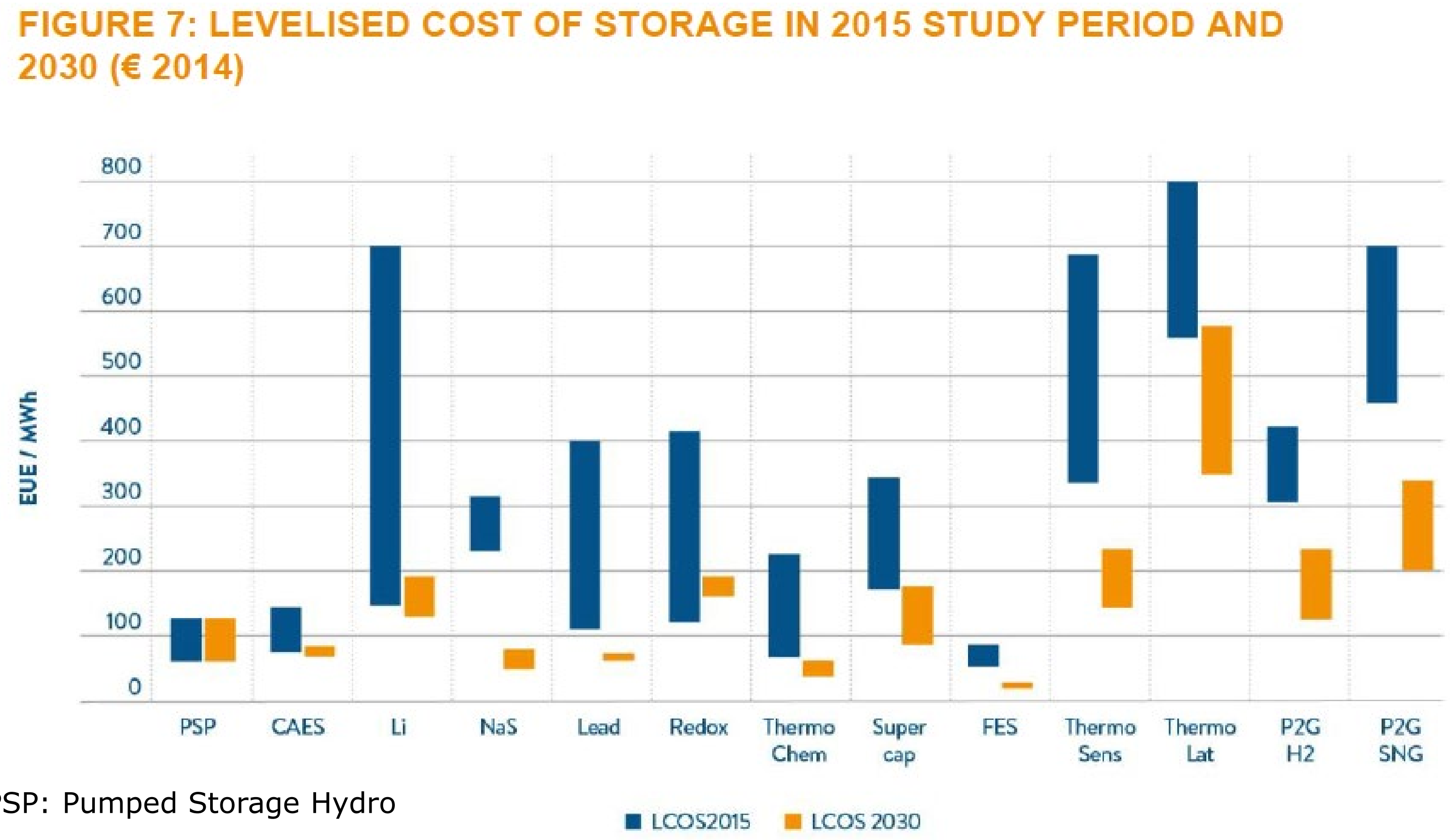
Levelized Cost of Storage (LCOS)

$$LCOS = \frac{\mathrm{I}_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{el}}{(1+i)^t}}$$

$LCOS$	$Levelized\ cost\ of\ energy\ [€/kWh]$
I_0	$Investment\ costs\ [€]$
A_t	$Annual\ total\ costs\ in\ year\ t\ [€]$
M_{el}	$Generated\ electricity\ in\ each\ year\ [kWh]$
n	$Technical\ lifetime\ [years]$
t	$Year\ of\ technical\ lifetime\ (1, \ldots, n)$
i	$Discounted\ rate\ (WACC)[\%]$

World Energy Council, World Energy Resources E-Storage (2016)

Levelized Cost of Storage (LCOS)



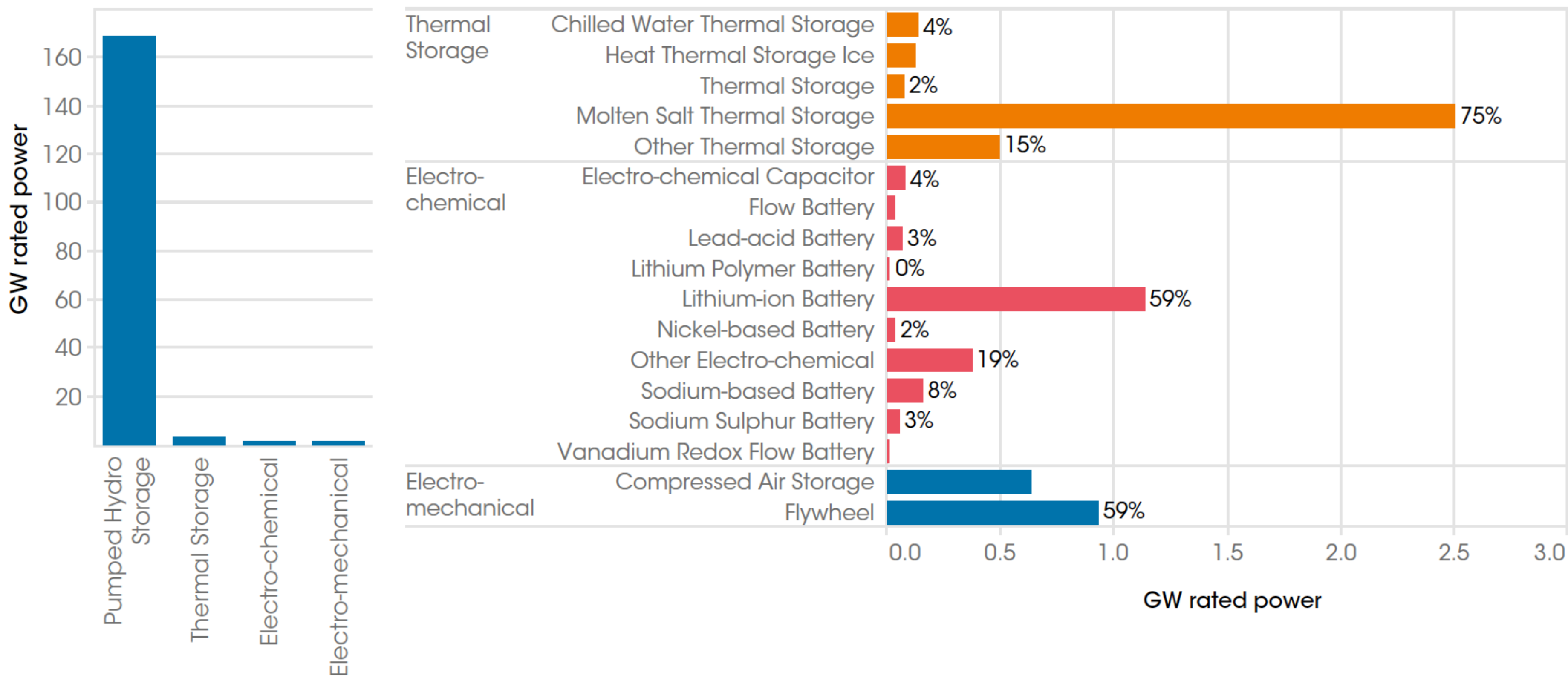
PSP: Pumped Storage Hydro

World Energy Council, World Energy Resources E-Storage (2016)

Globaly accessible E-storage power capacity

- Massive projected increase in storage capacity (12 GW in 2024)
- Can any of these technologies can be scaled to 17 TW?

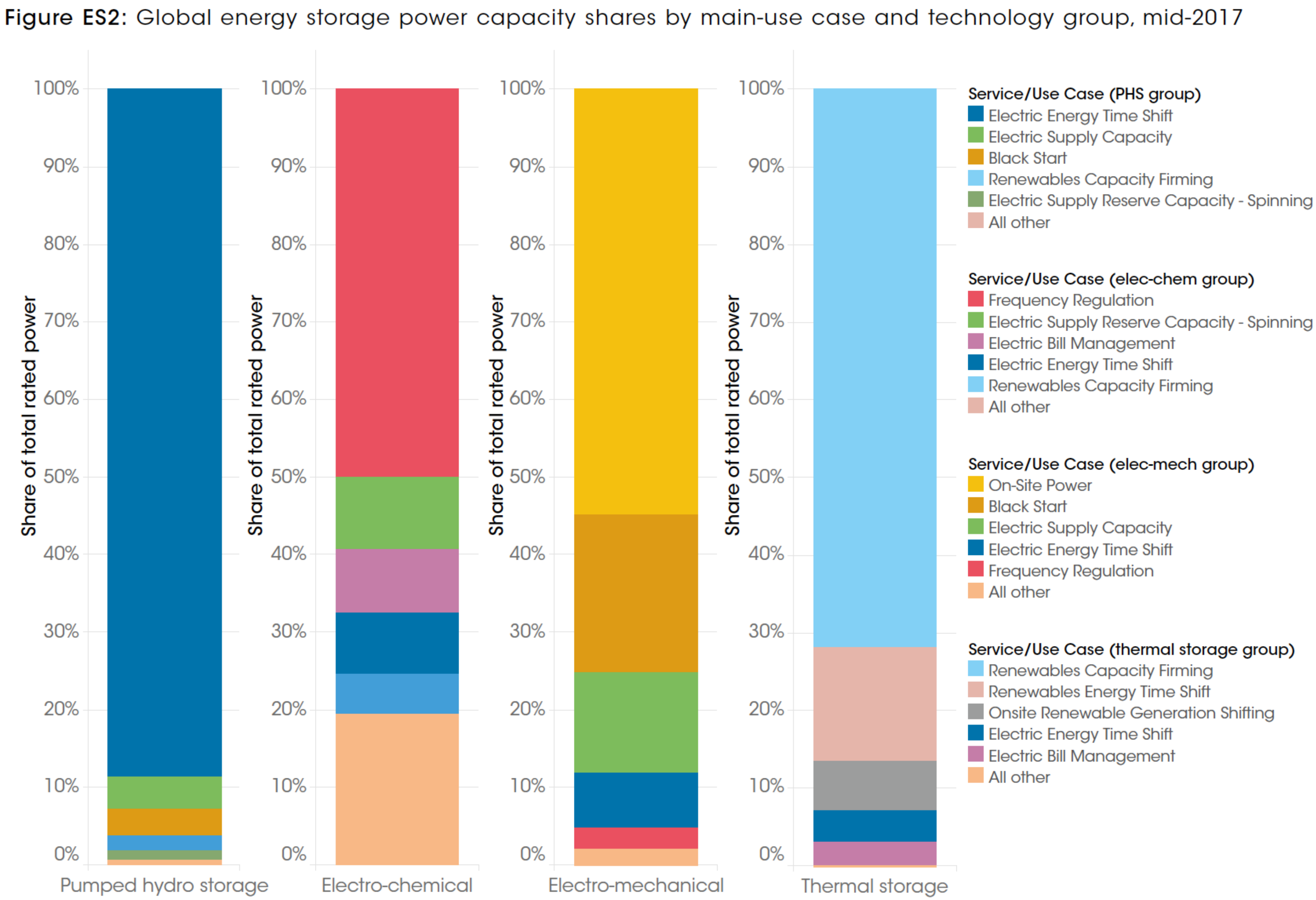
Figure ES8: Global operational electricity storage power capacity by technology, mid-2017



IRENA, Electricity Storage and Renewables: Costs and Markets to 2030 (2017)

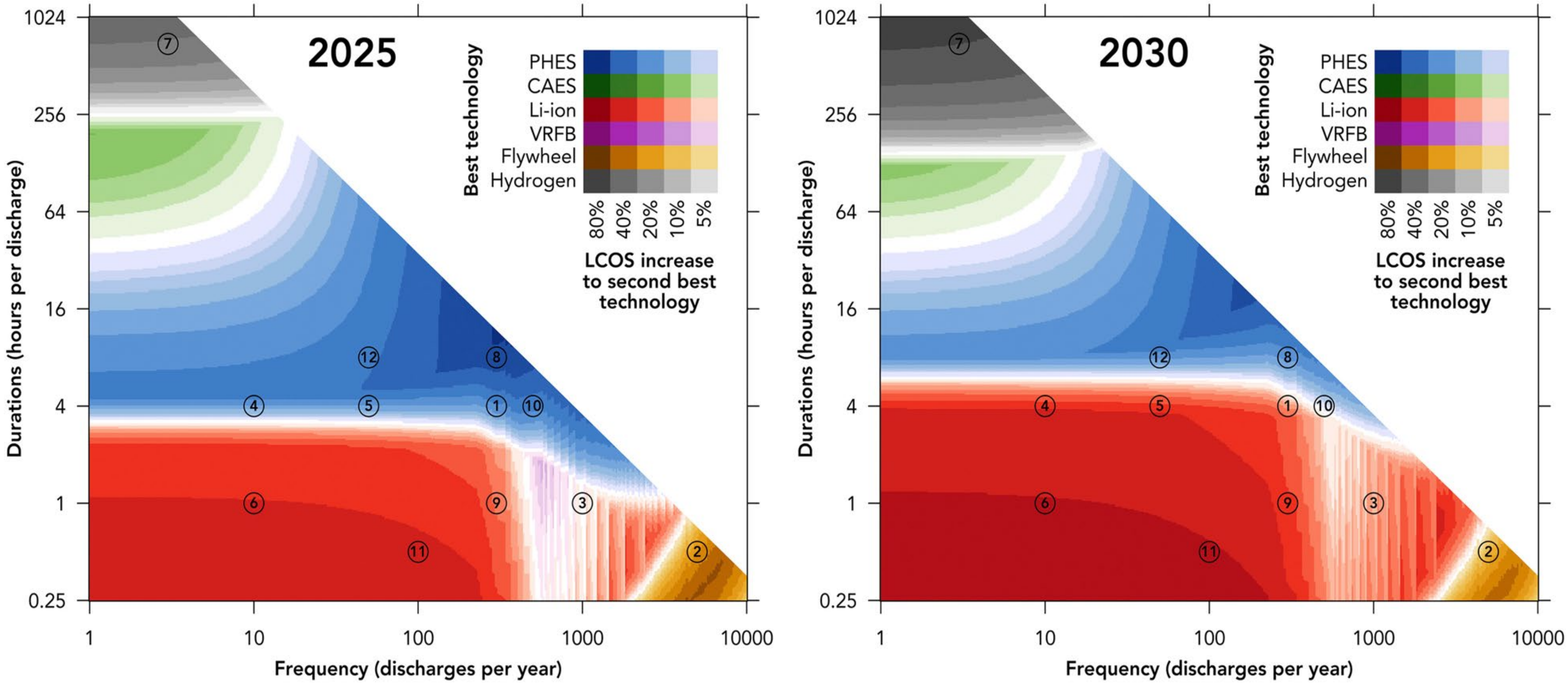
Energy Storage World Forum, Navigant Research (2017)

Global energilagring - power capacity



IRENA, Electricity Storage and Renewables: Costs and Markets to 2030 (2017)

Your own LCOS calculator



Schmidt et al, Joule 3, 81-104 (2019)

Figure 3. Most Cost-Efficient Technologies Relative to Discharge Duration and Annual Cycle Requirements (All Technologies)

Chart displays technologies with lowest LCOS relative to discharge duration and annual cycle requirements for all modeled technologies from 2015 to 2040. Circled numbers represent the requirements of the 12 applications introduced in Table 1: 1, Energy Arbitrage; 2, Primary Response; 3, Secondary Response; 4, Tertiary Response; 5, Peaker Replacement; 6, Black Start; 7, Seasonal Storage; 8, T&D Investment Deferral; 9, Congestion Management; 10, Bill Management; 11, Power Quality; 12, Power Reliability. Colors represent technologies with lowest LCOS. Shading indicates how much higher the LCOS of the second most cost-efficient technology is, meaning lighter areas are contested between at least two technologies, while darker areas indicate a strong cost advantage of the prevalent technology. White spaces mean LCOS of at least two technologies differ by less than 5%. The sawtooth pattern above 1,000 cycles reflects the marked lifetime reductions at more frequent discharges that affect competitiveness of individual technologies. The modeled electricity price is 50 US$/MWh. See Video S1 for an animated version. All technology input parameters can be found in Tables S4–S8. Refer to Figure S5 for a similar overview of most cost-efficient technologies based on annuitized capacity cost (US$/kW$_{year}$).

MECHANICAL

Pumped Hydro Energy Storage (PHS)

Vattenfall 1060 MW PHS plant Goldisthal, Germany

- > 180 GW (~95% of world electricity storage)
- Market: 6 GW/year – Europe 1.5 GW/year
- ~100 years – “unlimited” no. of cycles
- 200 – 1.000 $/kW
- Approx. 75-80(85)% cycle efficiency

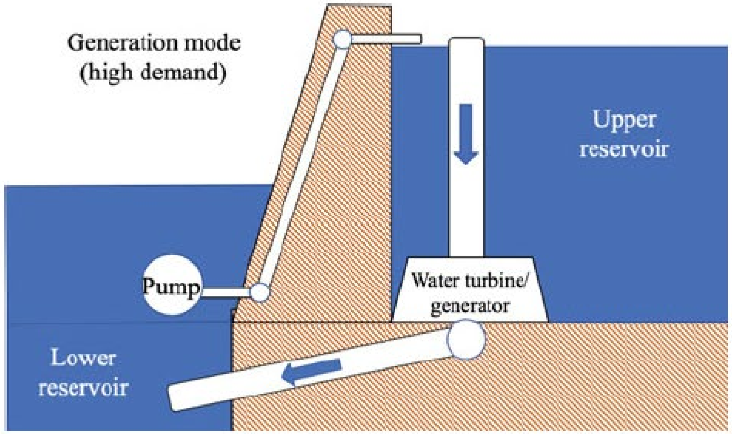


Fig. 6.1 Generation operation mode where water is routed through the turbines

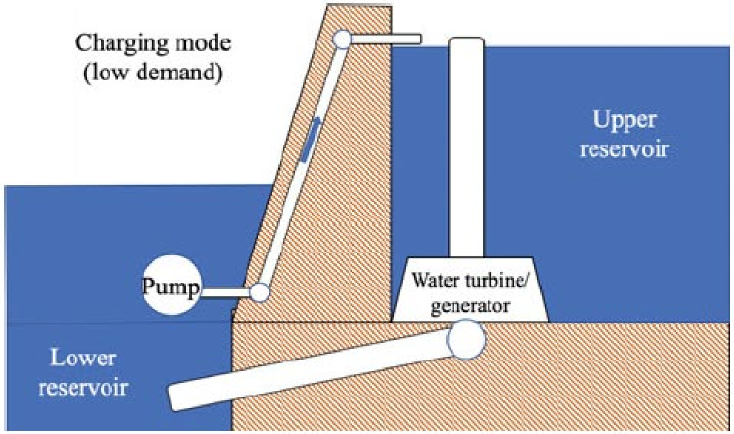


Fig. 6.2 Charging operation mode where water driven by pumps from lower reservoir to upper reservoir

PHS – Installed Capacity

- The global PHS capacity is increasing, but too slowly to match the growth in, e.g., wind and solar capacity
- Why is this?
  - Finances?
  - Geography? - [open or closed loop]

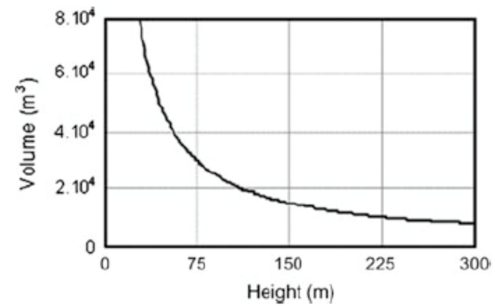
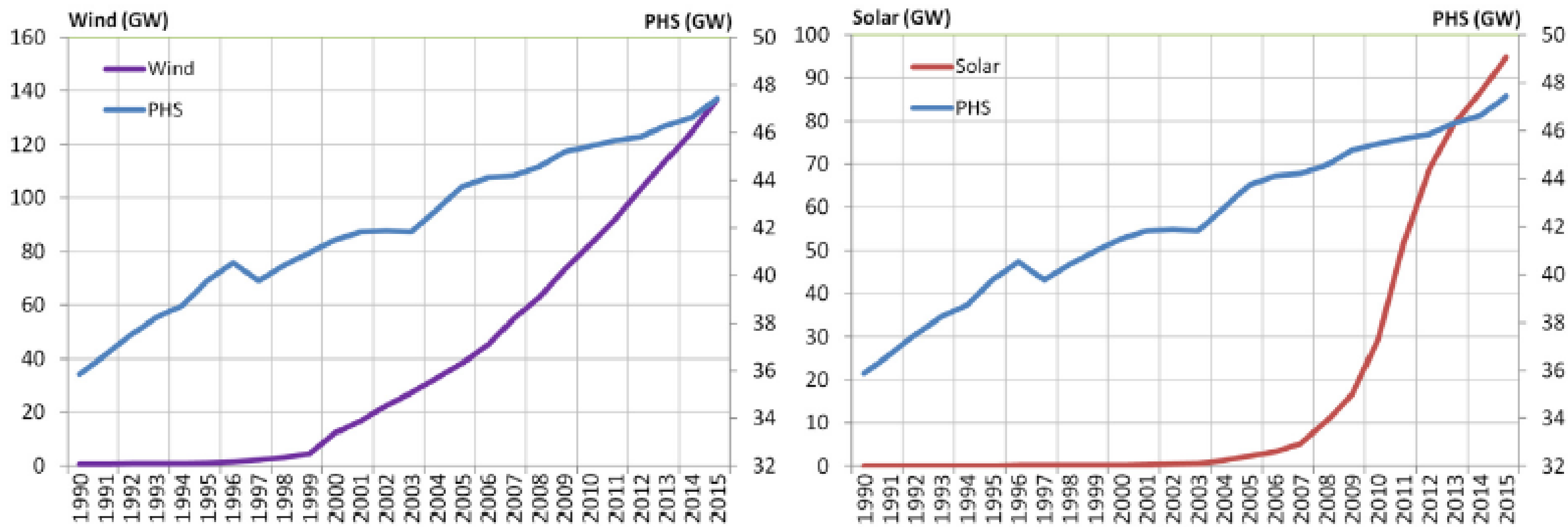


Fig. 6.6 Water volume needed at a given height to store 6 MWh [2]



(a) Wind, pure PHS cap. in EU28 (b) Solar, pure PHS cap. in EU28

Kougias and Szabó, Energy 140, 318 (2017)

PHS – Energy and power capacity

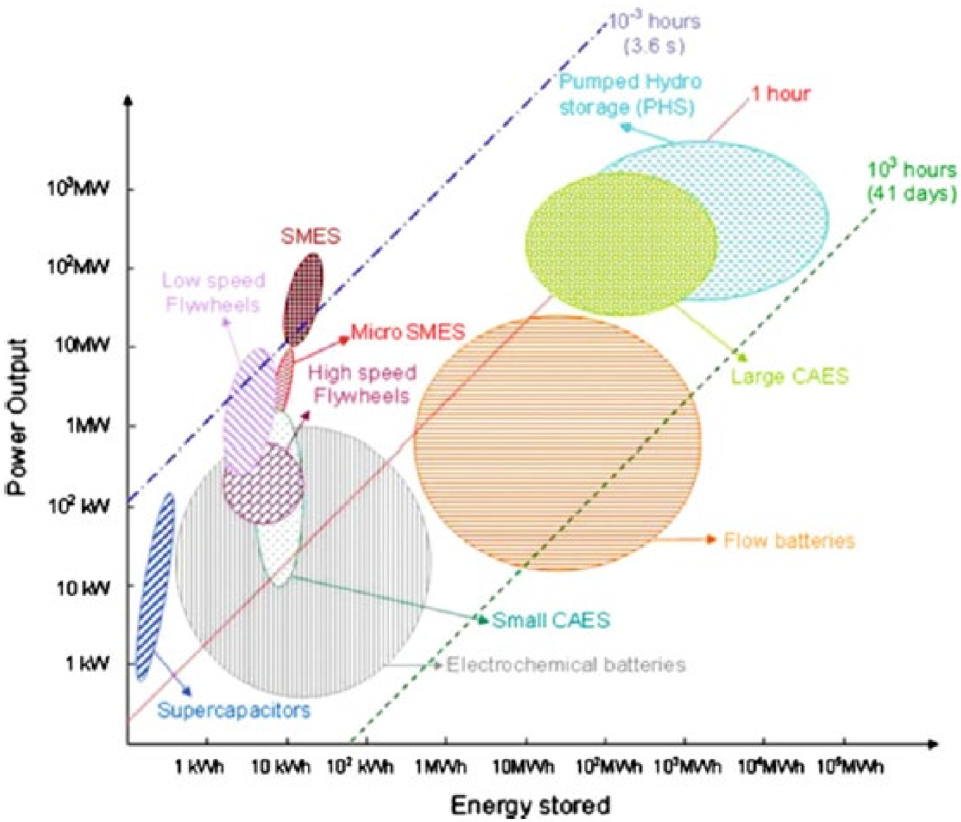


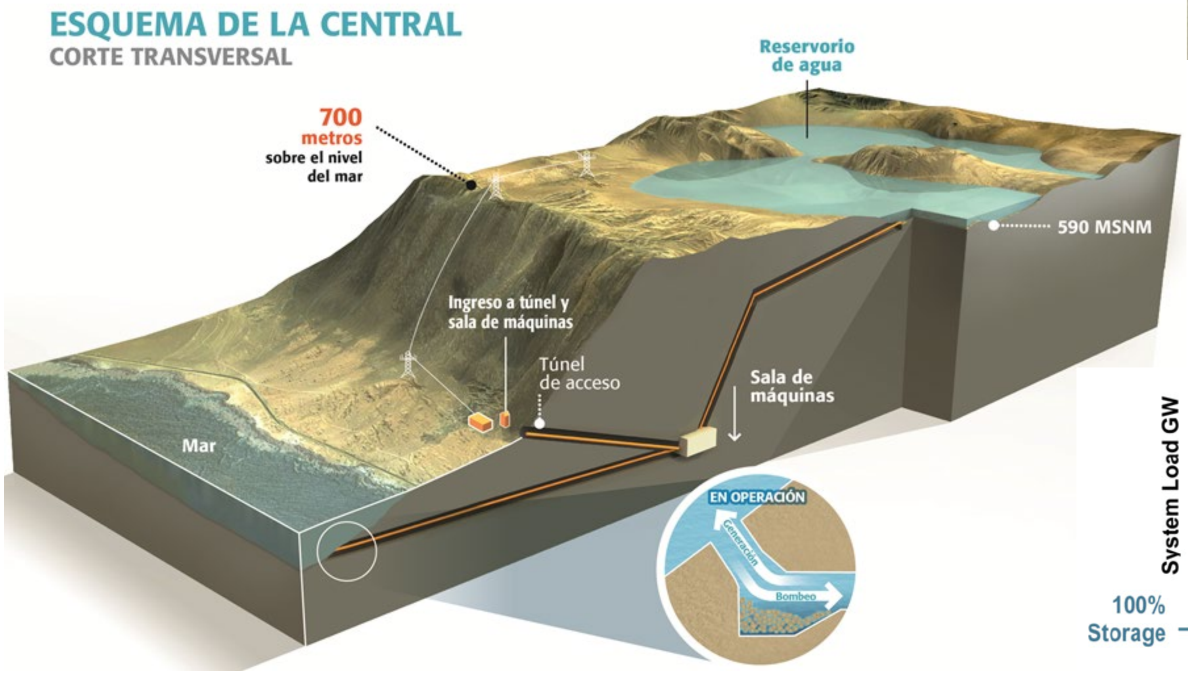
Table 6.1 Examples of pumped hydropower stations around the world [2]

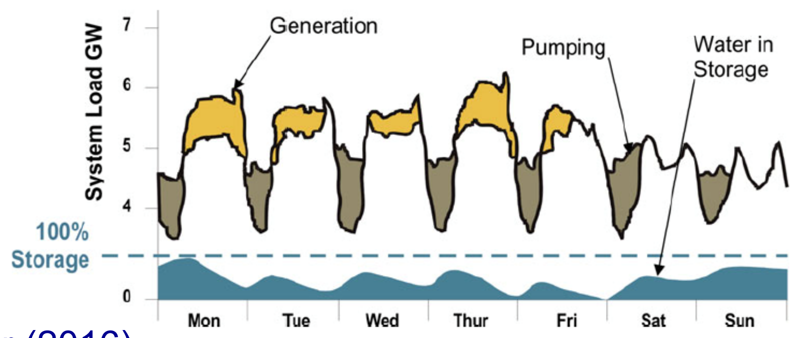
Country	Station name	Capacity (MW)
Argentina	Rio Grande-Cerro Pelado	750
Australia	Tumut Three	1,500
Austria	Malta-Haupsufe	730
Bulgaria	PAVEC Chaira	864
China	Guangzhou	2,400
France	Montezic	920
Germany	Goldisthal	1,060
	Markersbach	1,050
India	Purulia	900
Iran	Siah Bisheh	1,140
Italy	Chiotas	1,184
Japan	Kannagawa	2,700
Russia	Zagorsk	1,320
Switzerland	Lac des Dix	2,099
Taiwan	Mingtan	1,620
United Kingdom	Dinorwig, Wales	1,728
United States	Castaic Dam	1,566
	Pyramid Lake	1,495
	Mount Elbert	1,212
	Northfield Mountain	1,080
	Ludington	1,872
	Mt. Hope	2,000
	Blenheim-Gilboa	1,200
	Raccoon Mountain	1,530
	Bath County	2,710

Abdul Hai Alami, Mechanical Energy Storage for Renewable and Sustainable Energy Resources, Springer (2020)

Pumped Hydro Storage – 2021

- High efficiency, but high CAPEX and long return on investment
- Low LCOE: ”Valhalla solar/PSP”: 531MW/300MW and ~$10*/kWh
- Project cost: ~1 billion US$

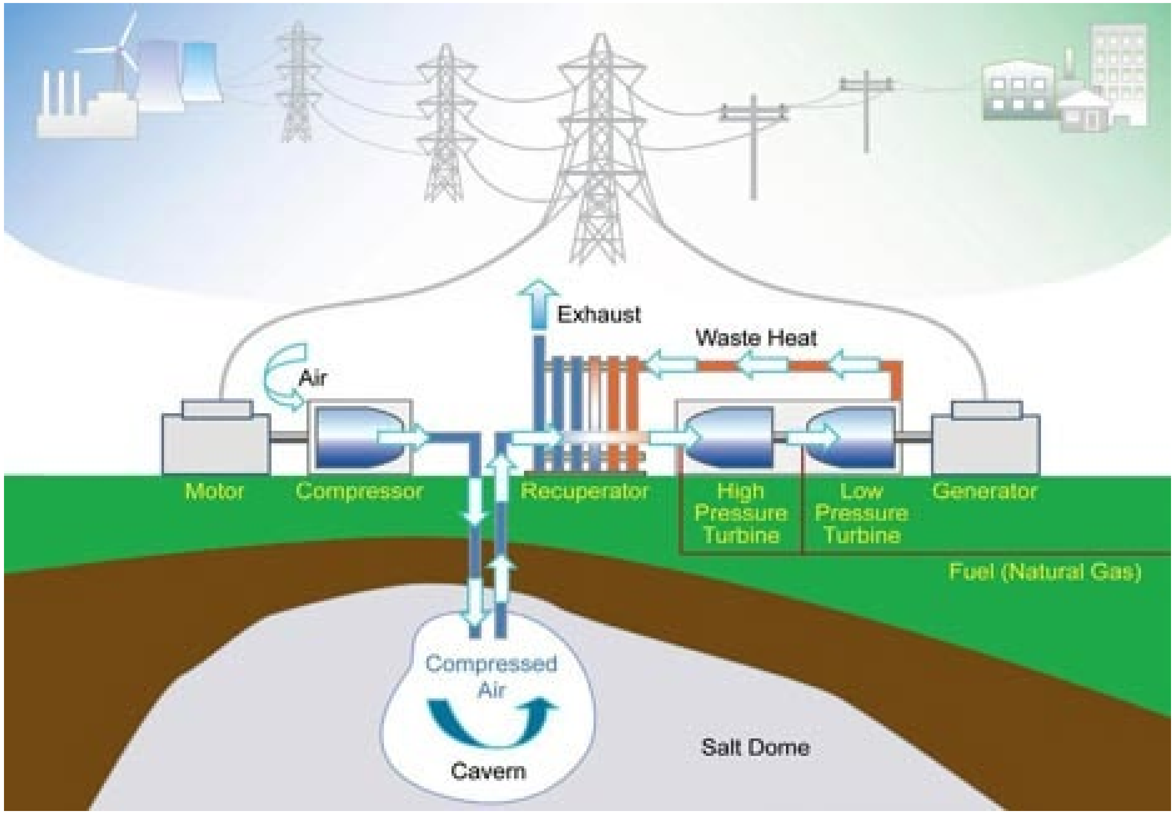




World Energy Council, World Energy Resources Hydropower (2016)

Compressed Air Energy Storage (CAES)

- Mechanical compression using electricity
- Storage of high pressure gas in underground caverns
- Re-electrification through pressure turbines



Visualization: gridflexenergy.com/energy-storage-technologies/

Concepts for grid-connected Compressed Air Energy Storage

- Traditional CAES
- Traditional CAES with heat recuperation
- Adiabatic CAES (A-CAES)

- CAES builds on well-known technology
- Suitable in a Danish environment because of salt dome availability in many geographic locations

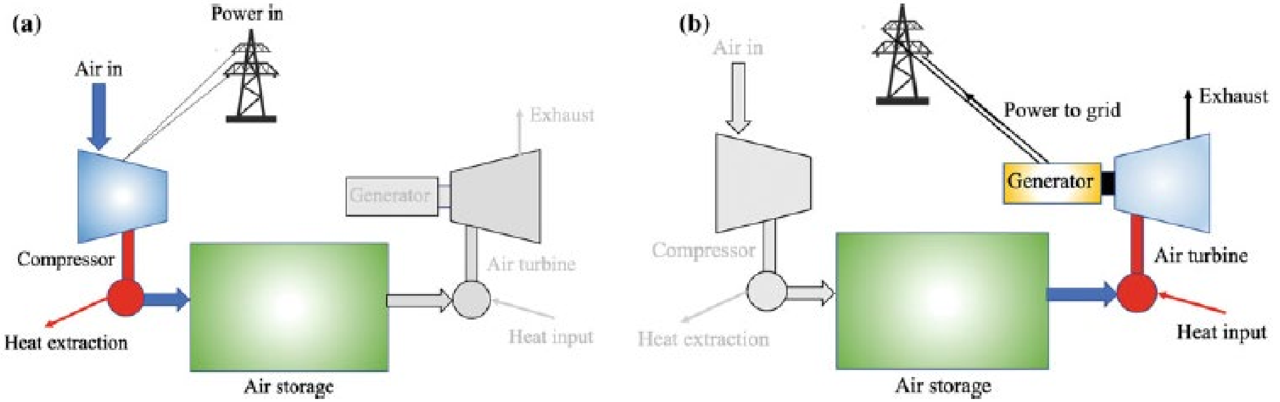
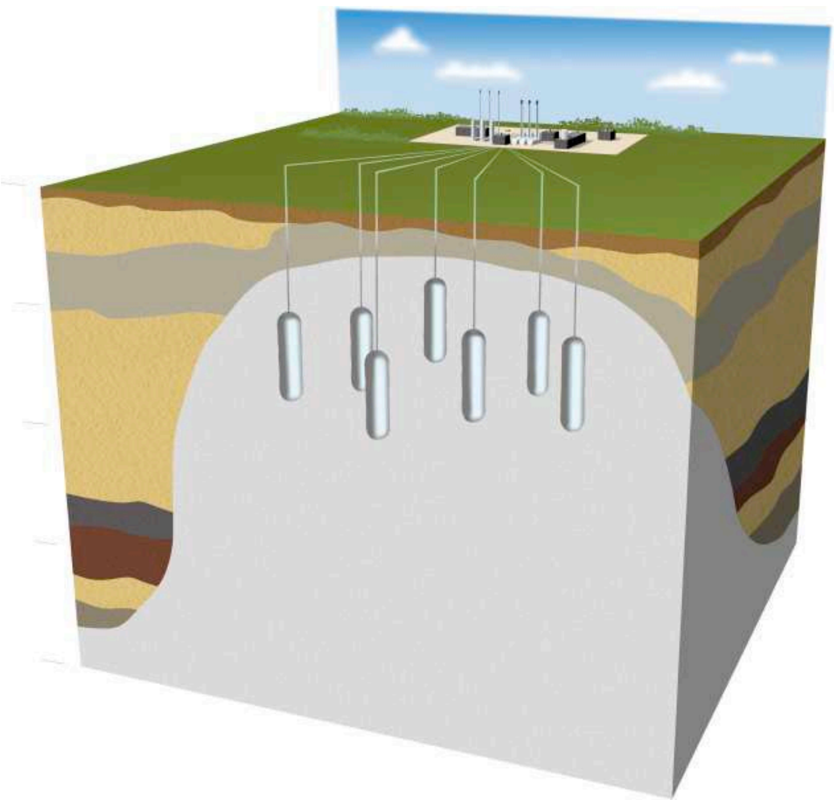


Fig. 7.1 Depiction of operation of a large-scale CAES system in a charging mode and **b** discharge mode

Danish underground gas storage potential

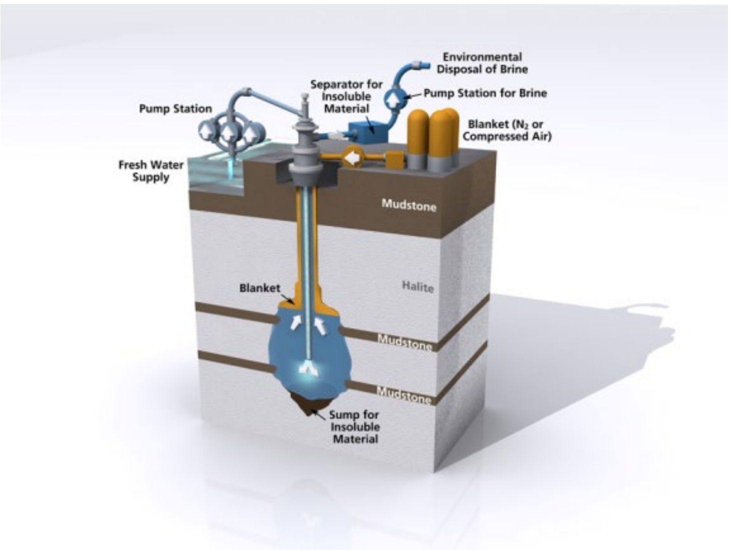
- Denmark has suitable geological conditions for salt caverns



Energinet.dk

Existing capacity:

- 440 mill. Nm^3 natural gas
- 5.300 GWh
- DK consumption:
  3100 mill. Nm^3



www.tunneltalk.com/Technological-developments-Apr11-Salt-cavern-storage.php

Realized grid-connected CAES systems

Only two systems have been constructed until now

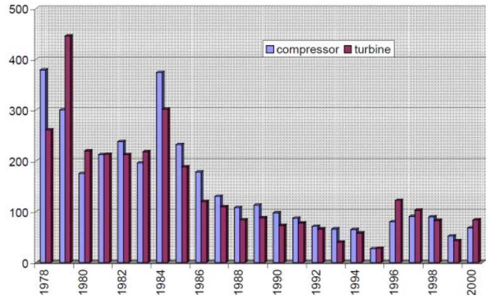
- Huntorf operated since 1978
- McIntosh operated since 1991

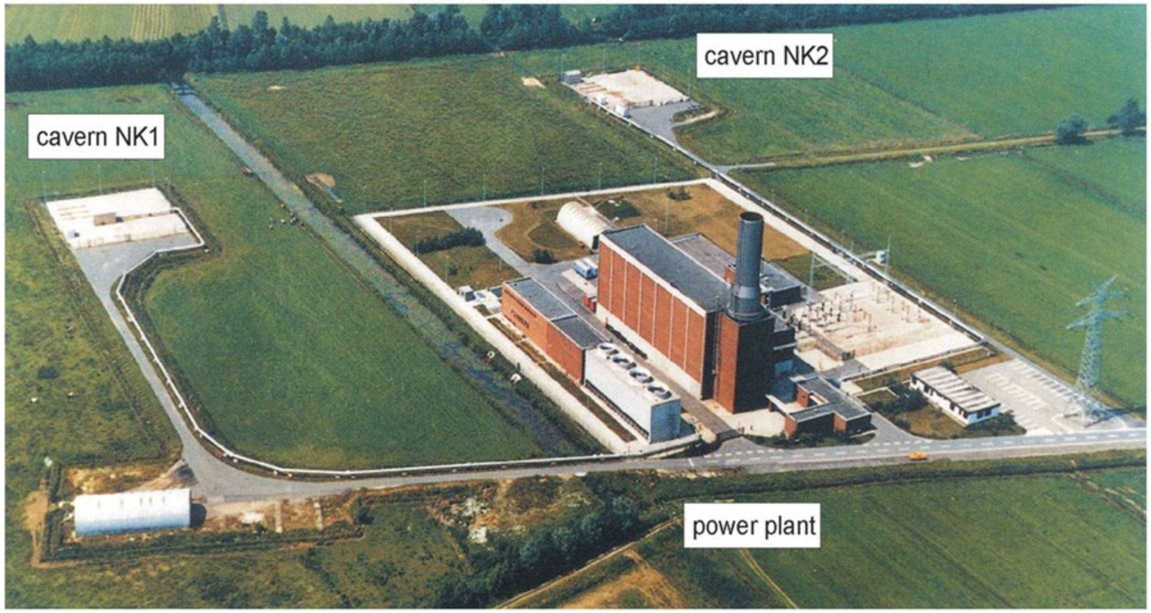
- Numerous plans for building new plants, but none realized so far

- Plans for A-CAES were taken quite far by German utilities

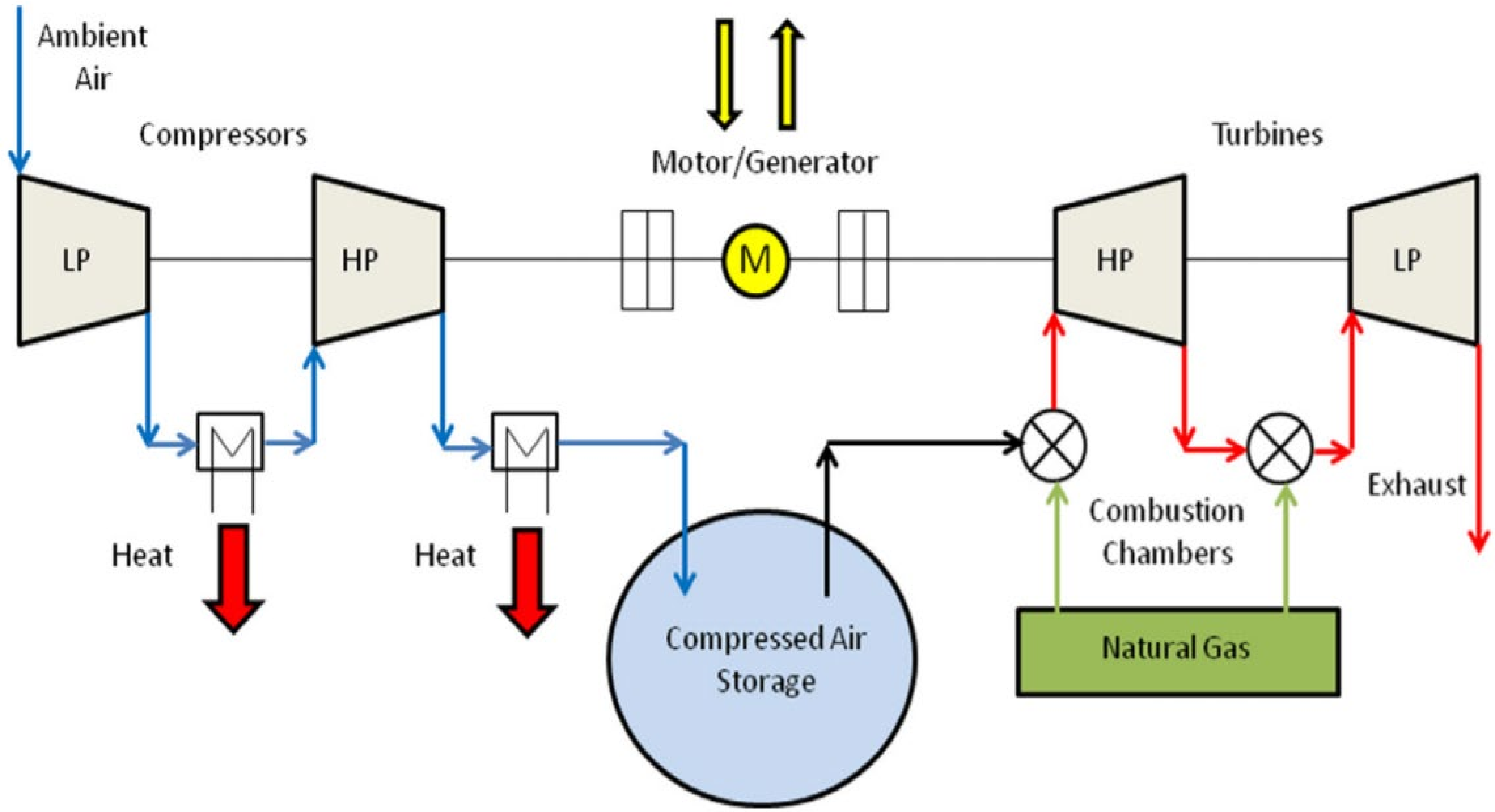
The Huntorf plant, North Germany

- Charging 60 MW_{el} (8 hrs)
- Discharging 321 MW_{el} (1.5 hrs)
- Commissioned 1978
- Developed to provide black-start for nearby nuclear plant
- Still operational today
- Total cavern volume: 310.000 m3
- Hundreds of stops/starts per year

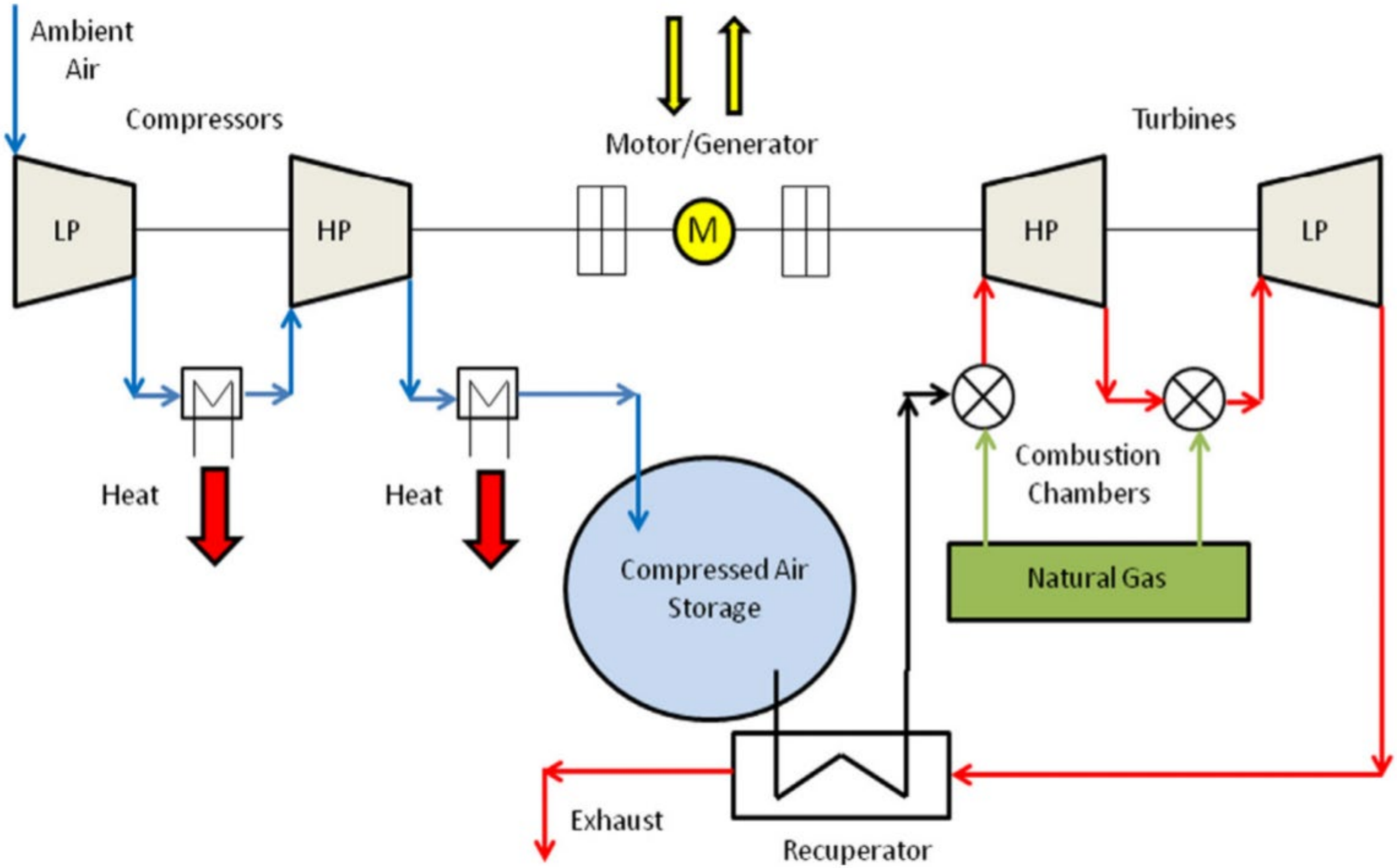




Huntorf CAES plant schematic, Germany



McIntosh CAES plant schematic, USA



Differences between Huntorf and McIntosh

- What are the main differences between the two systems?
  - Cycle efficiency?
  - Charge time?
  - Output power?
  - …

(a) (b)

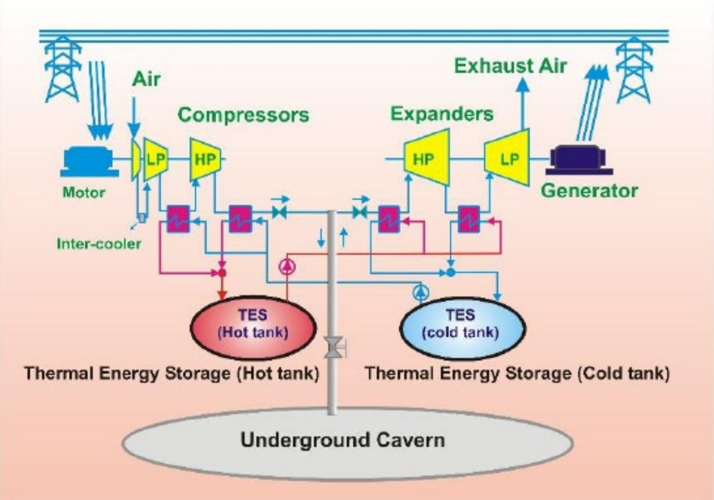
Fig. 7.3 **a** The PowerSouth energy cooperative McIntosh CAES power plant and **b** the pertinent salt cavern dimensions [2]

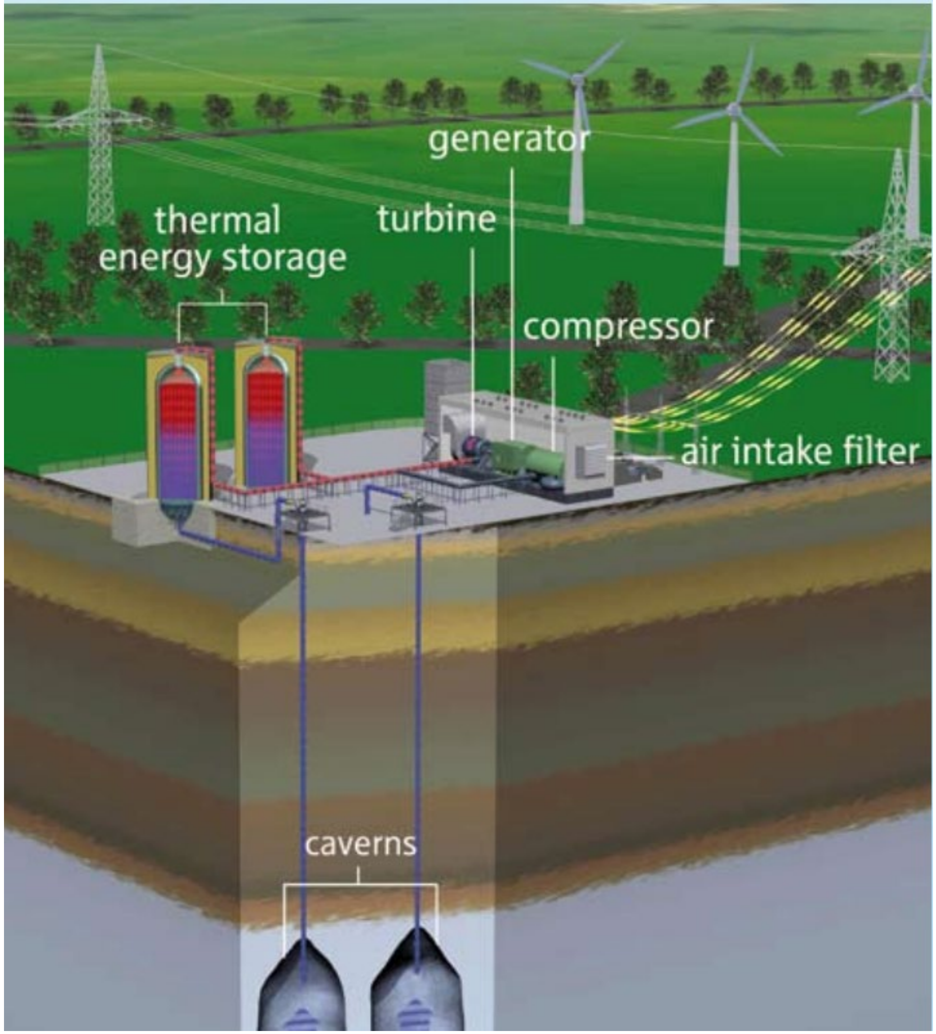
Table 7.1 Operational parameters for the Huntorf and McIntosh CAES facilities [3]

	Huntorf	McIntosh
Cycle efficiency (%)	42	54
Maximum electrical input power (MW)	60	50
Maximum air mass rate (kg/s)	108	~90
Charge time (h)	8	38
Discharge time (h)	2	4
Cavern pressure range (bar)	46–72	46–75
Cavern volume (m^3)	310,000	538,000
Maximum electrical output power (MW)	321	110
Control range (output) (MW)	100–321	10–110
Setup time (normal/emergency) (min)	14/8	12/7
Maximum mass flow rate (kg/s)	455	154
High-pressure turbine inlet (bar)	41.3 @ 490 °C	42 @ 538 °C
Lower pressure turbine inlet (bar)	12.8 @ 945 °C	15 @ 871 °C
Exhaust gas temperature (°C)	480	370 (before recuperator)

Adiabatic Compressed Air Energy Storage (A-CAES) – a vision

- Main drawback is loss of heat during compression
- Intermediate storage of heat is needed, e.g. ceramic materials for heat storage
- Potential efficiency 70% and 20% cost reduction



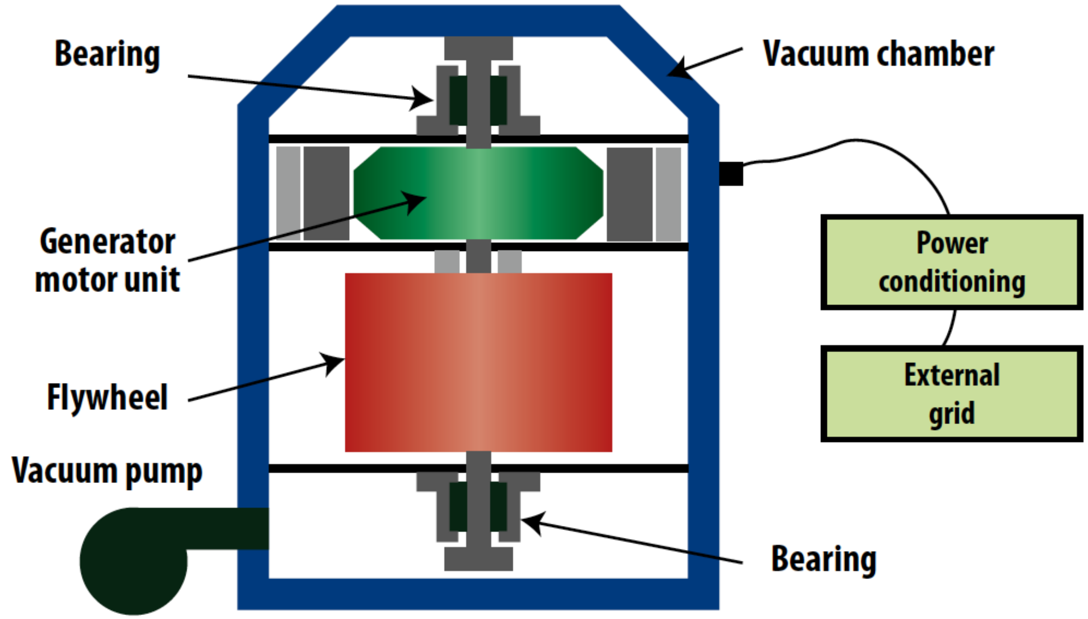


ADELE adiabatic CAES (2018); Huang et al., Energy Procedia 105, 4034 (2017)

Flywheels

- Old technology, but still relevant – why?
- Simple electro-mechanical concept for energy storage on small scale
- Spinning at many thousand rpm in a vacuum environment

Figure 20: Key components of a high-speed flywheel energy storage system



Source: International Renewable Energy Agency, based on Luo *et al.*, 2015.

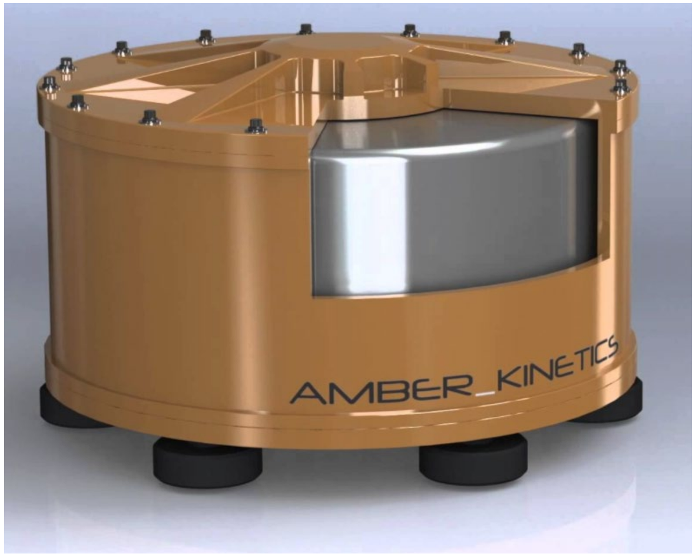
IRENA, Electricity Storage and Renewables: Costs and Markets to 2030 (2017)

Grid-connected Flywheels

- Stores energy as rotational, kinetic energy: $E_{kin} = ½ \cdot I \cdot \omega^2$
- Extremely fast reacting technology – comparable to, e.g. batteries
- Suitable for fast reserves, frequency and voltage stabilization
- Limited/no degradation
- Prices are decreasing fast

Flywheels

- New geometries



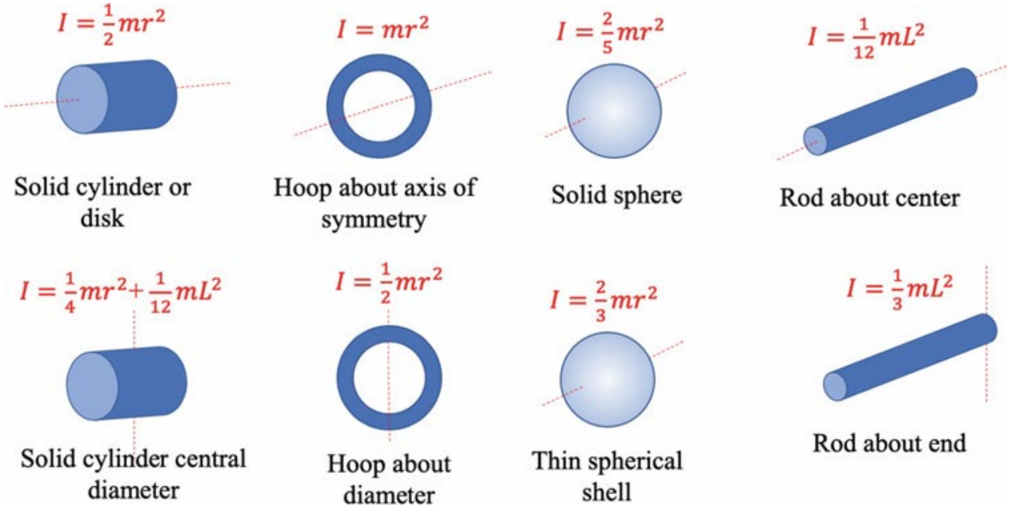


Fig. 5.2 Moment of inertia for common shapes around various axes [4]

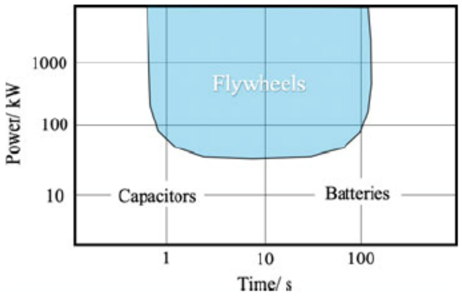


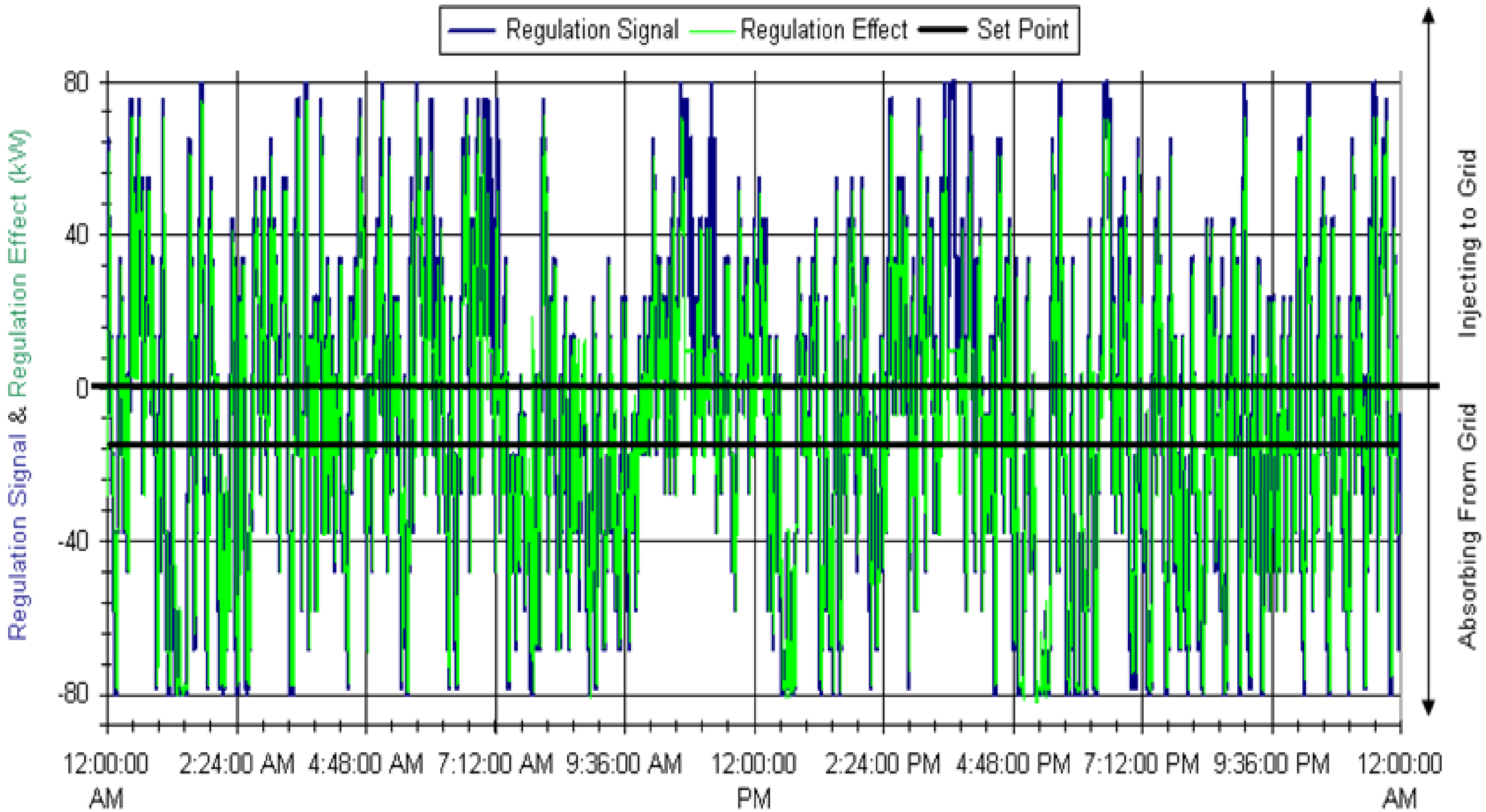
Table 5.1 Example of flywheel characteristics [5]

Object	Mass (kg)	Diameter (m)	Angular velocity (rpm)	Energy stored (J)	Energy stored (kWh)
Bicycle wheel	1	0.7	150	15	4×10^{-7}
Flintstone wheel	245	0.5	200	1680	4.7×10^{-4}
Train wheel (60 km/h)	942	1	318	65,000	1.8×10^{-2}
Large truck wheel (60 km/h)	1000	2	79	17,000	4.8×10^{-3}
Train braking flywheel	3000	0.5	8000	33×10^6	9.1
Electrical power backup flywheel	600	0.5	30,000	92×10^6	26

Flywheels

- Quotation 2009 (Beacon Power) 11.000 $/kWh
- Selling price 2017 (WattsUp Power) 350 €/kWh – 35 €/kW
- Efficiency 90-95% (in 2009 85%)
- Units may be combined to many MW and MWh
- Already used for grid stabilization
- Applicable also for short term energy storage

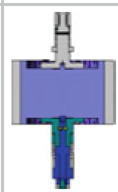
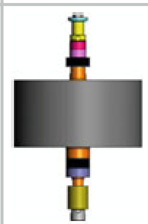
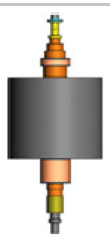
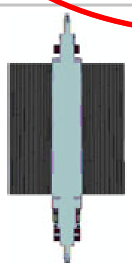
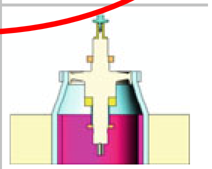
Reaction of a flywheel (MW input/output) in response to signals from the AGC in the New York ISO grid.



Source: Beacon Power.

NASA Flywheel technologies

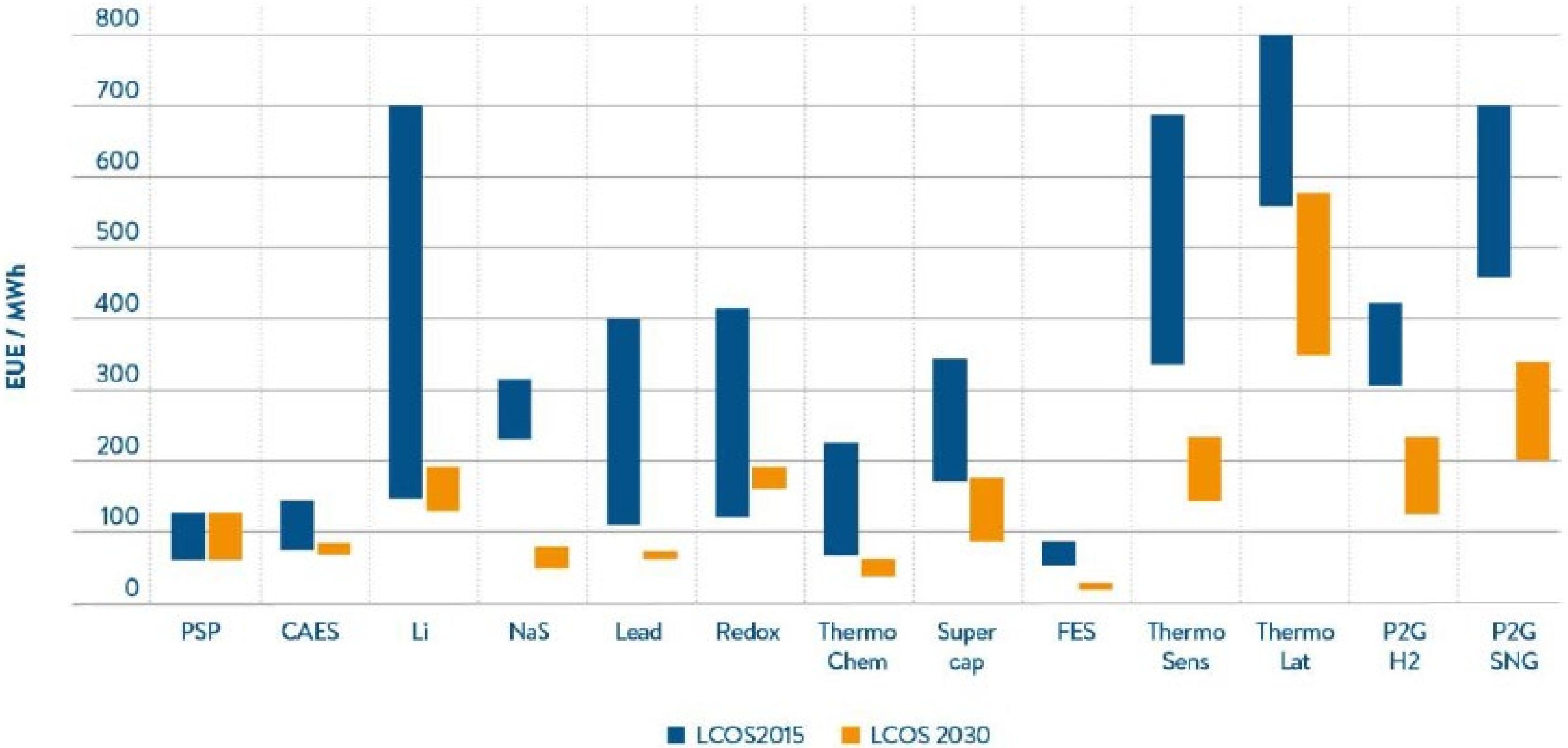
Table 5.9 NASA rotor development for flywheel energy storage onboard the ISS [12]

Flywheel	HSS	Dev1	D1	G2	FESS	G3
Features	Steel hub	Single-layer composite	Multilayer composite 750 m/s	Multilayer composite 750 m/s	Multilayer composite 950 m/s	Composite arbor 1100 m/s
Energy (Wh)	17	300	350	581	3000	2136
Specific energy/ ($Whkg^{-1}$)	1	23	20	26	40	80
Life (yr)	NA	<1	1	1	15	15
Temperature (°C)	NA	NA	25–75	25–75	NA	–25–95
Illustration						

Abdul Hai Alami, Mechanical Energy Storage for Renewable and Sustainable Energy Resources, Springer (2020)

LCOS

FIGURE 7: LEVELISED COST OF STORAGE IN 2015 STUDY PERIOD AND 2030 (€ 2014)



THERMAL

Basic laws of thermodynamics

- Zeroth law of thermodynamics: If two systems are in thermal equilibrium with a third system, they are in thermal equilibrium with each other.

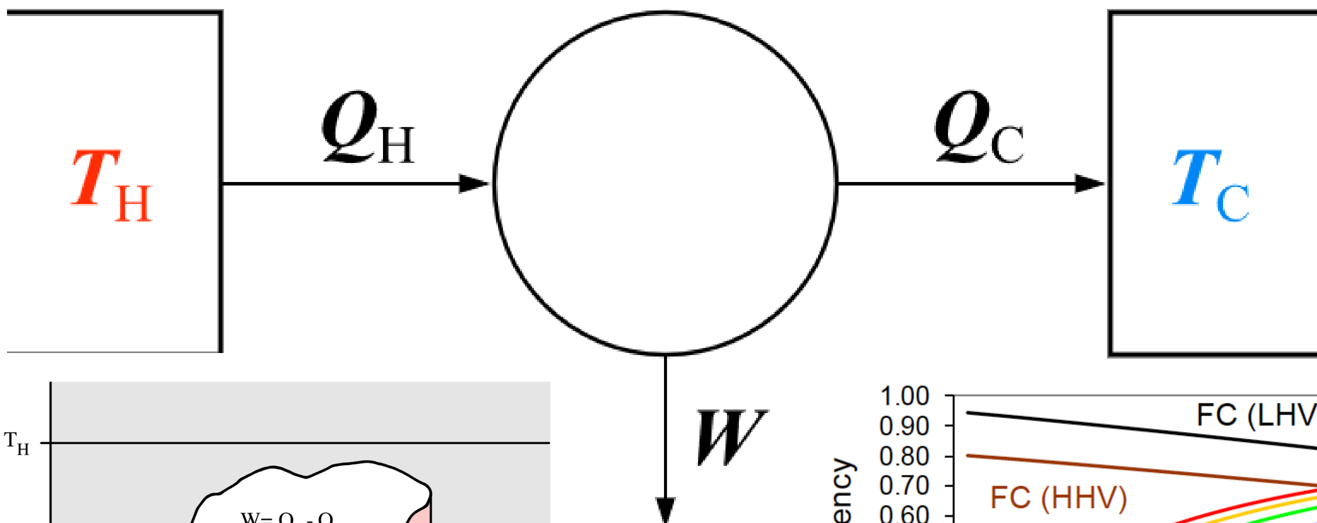
- First law of thermodynamics: When energy passes, as work, as heat, or with matter, into or out from a system, the system's internal energy changes in accord with the law of conservation of energy.

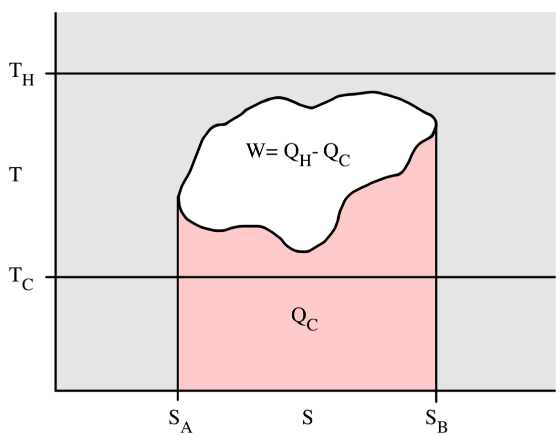
- Second law of thermodynamics: In a natural thermodynamic process, the sum of the entropies of the interacting thermodynamic systems increases.

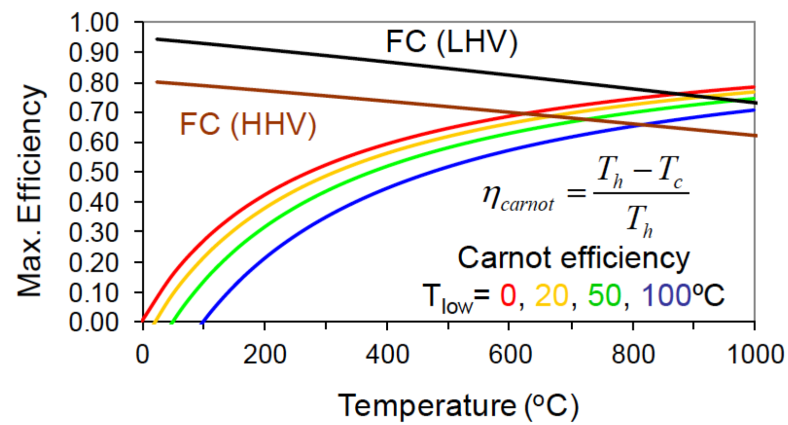
- Third law of thermodynamics: The entropy of a system approaches a constant value as the temperature approaches absolute zero.

Laws of thermodynamics – the Carnot engine

- A theoretical engine that operates on the reversible Carnot cycle
- Upper limit on the efficiency that any classical thermodynamic engine can achieve during the conversion of heat into work

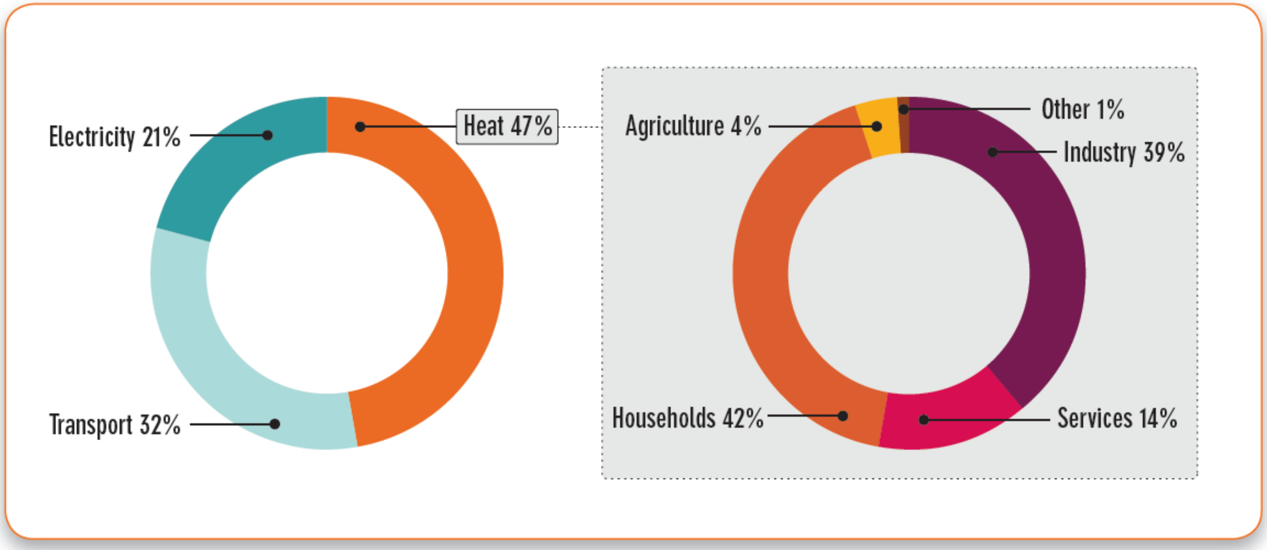






Let´s not forget about heat storage

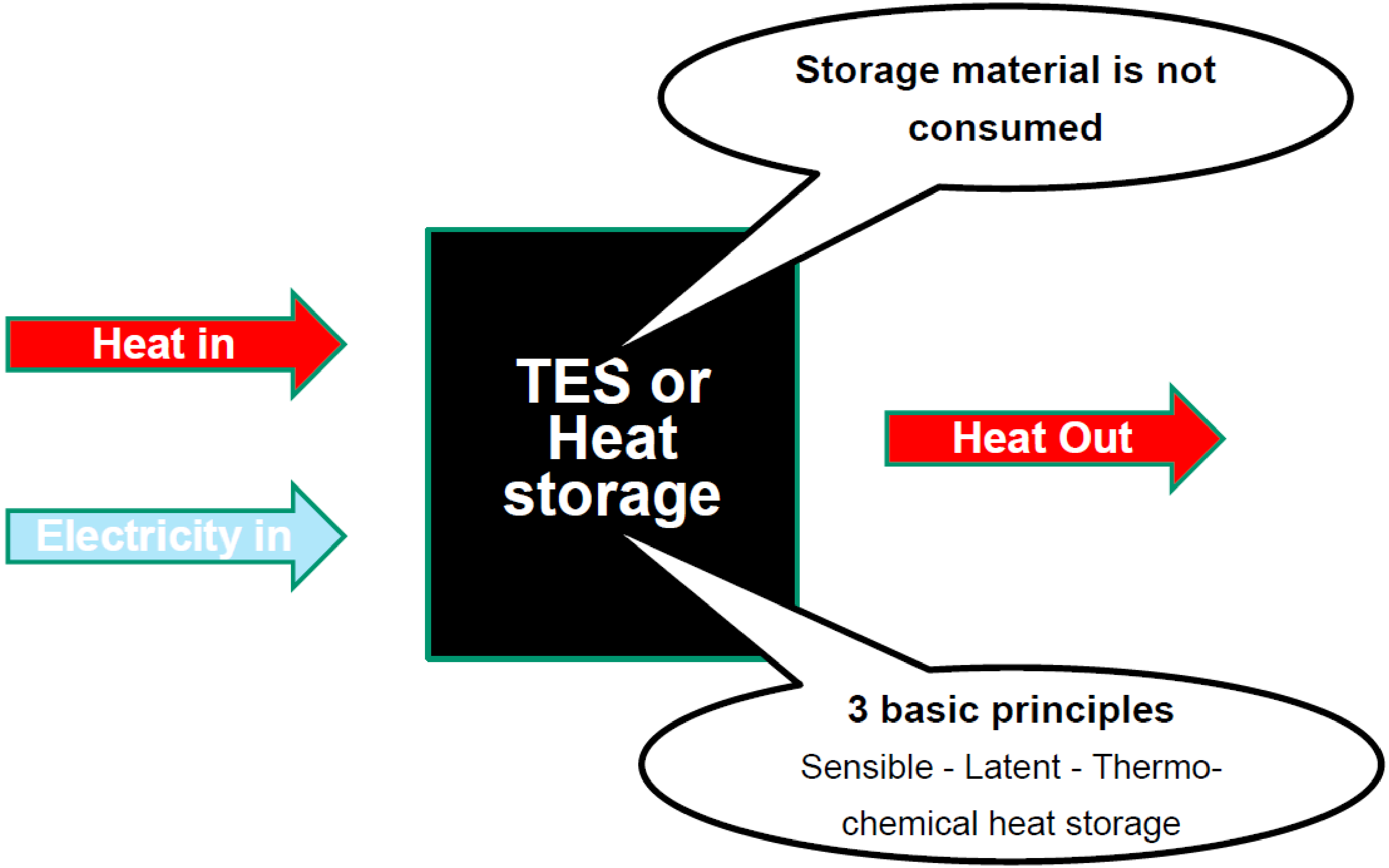
- Worldwide heat accounts for almost 50% of energy consumption
- Electricity is (currently) 18% in DK and 21 % in EU
- In Denmark approx. 60% of households are supplied by district heating
- Power-to-heat including heat pumps is anticipated to grow significantly in Denmark
- Large-scale heat storage can be foreseen



Final energy use in the EU27 by type of use (left) and by sectors (right)

Source: European Technology Platform on Renewable Heating and Cooling

Definition


Storage material is not consumed
Heat in
Electricity in
TES or Heat storage
Heat Out
3 basic principles
Sensible - Latent - Thermo-chemical heat storage

Fundamental principles to store heat

Sensible Heat

Sensible Heat Storage 20 – 200 kWh/m³
(depending on temperature difference)

Latent Heat

Latent Heat Storage 50 – 150 kWh/m³
(for small temperature difference)

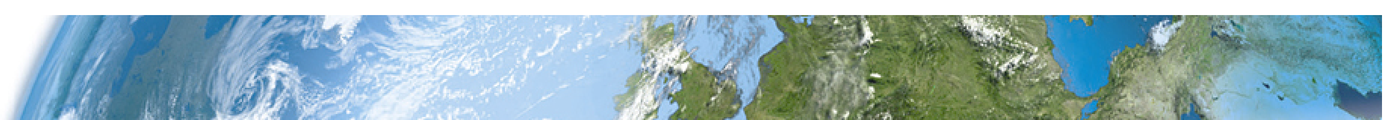
Heat of Reaction

Thermo-chemical Storage 100 – 400 kWh/m³
(depending on driving gradient (temperature or pressure))

Energy density [kWh/m³]
low → high

Development status
low → high

DLR



Solar-thermal heat store for district heating in DK

Vojens Fjernvarme – operation started in 2015

70.000 m^2 solar heating - 203.000 m^3 storage volume

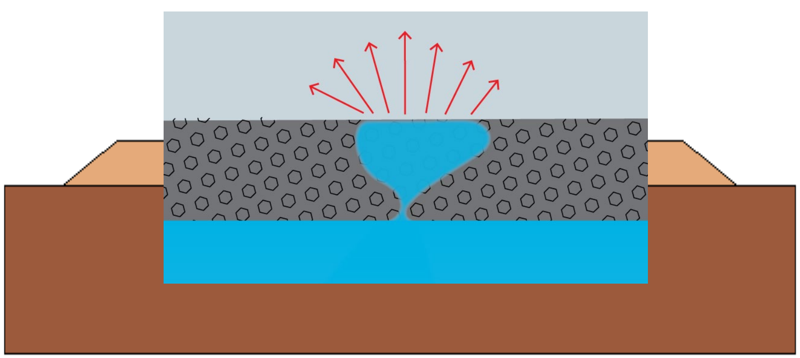
23.500 m^2 - 14 m deep, 200 m wide - 70 cm lid (Leca)

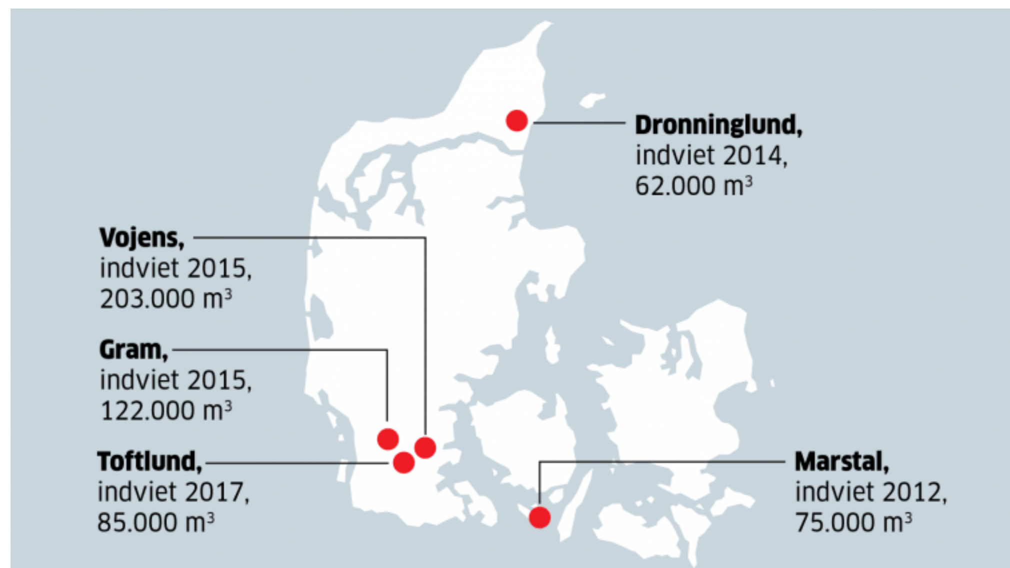
45% of annual consumption for 2000 consumers – Target: 10-15% saving on bill

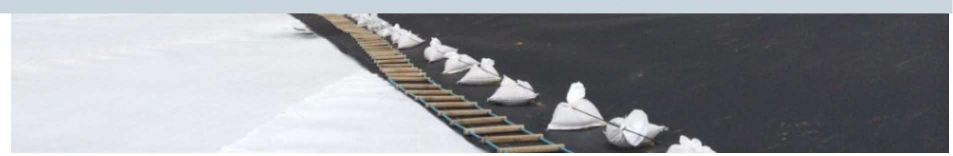
Charge Apr - Sep: 80-90 ºC

Discharge Oct – Jan: 40-45 ºC

Hot water in and cold water out





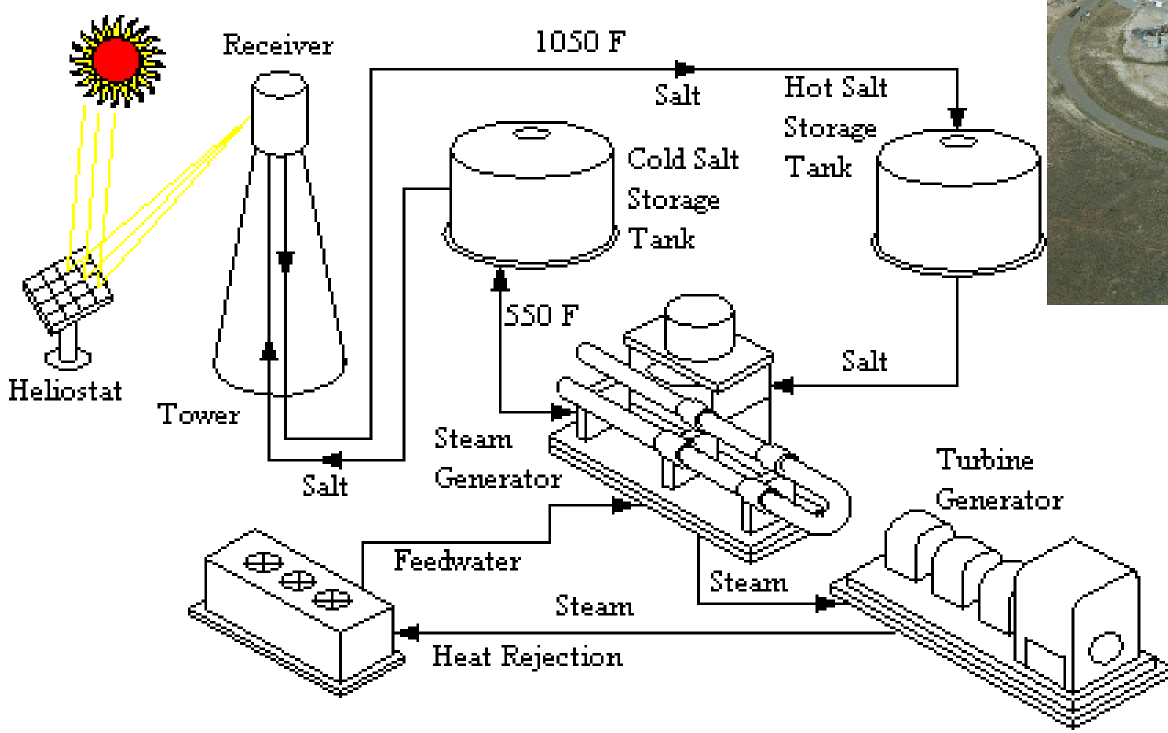


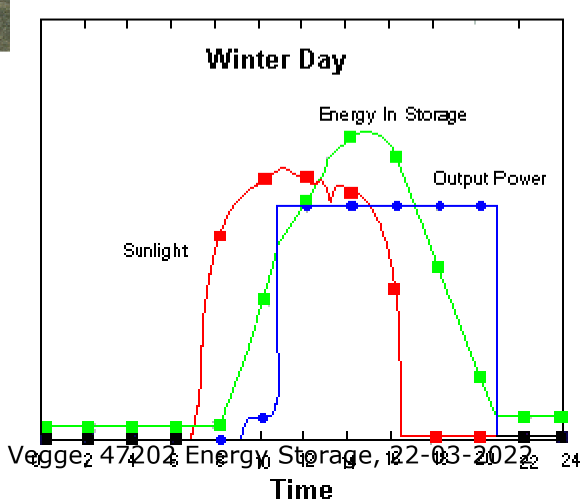
Holes have resulted in 35-45% heat loss

Molten Salt Sensible Heat Storage at National Solar Thermal Test Facility at Sandia Lab.

5 MW thermal power, 60 MW test plants

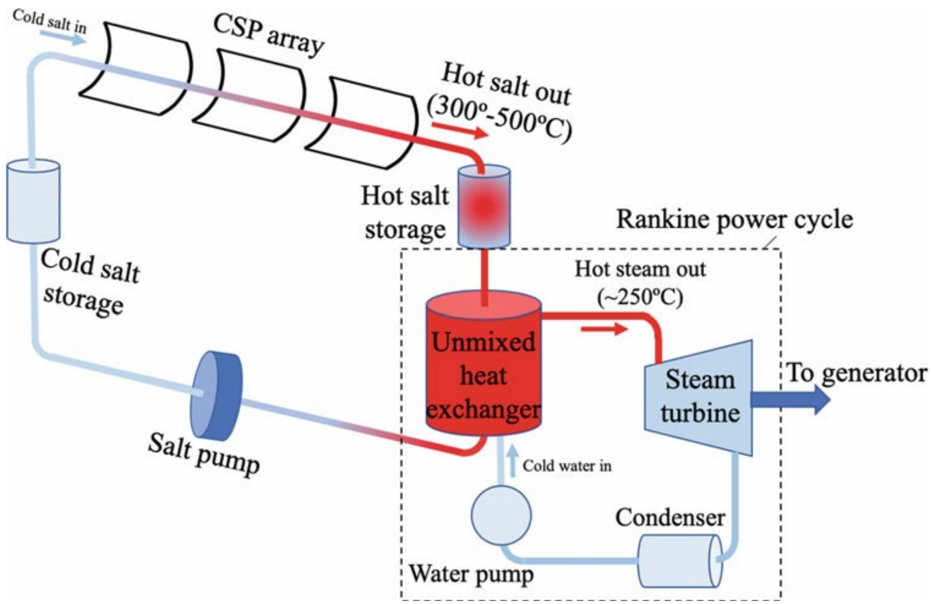
300-500 MW hybrid





Molten Salt Sensible Heat Storage at Heliostat & Solar Reserve

- Solar Reserve is now bankrupt…
- The potential is large, but the business plans are challenging



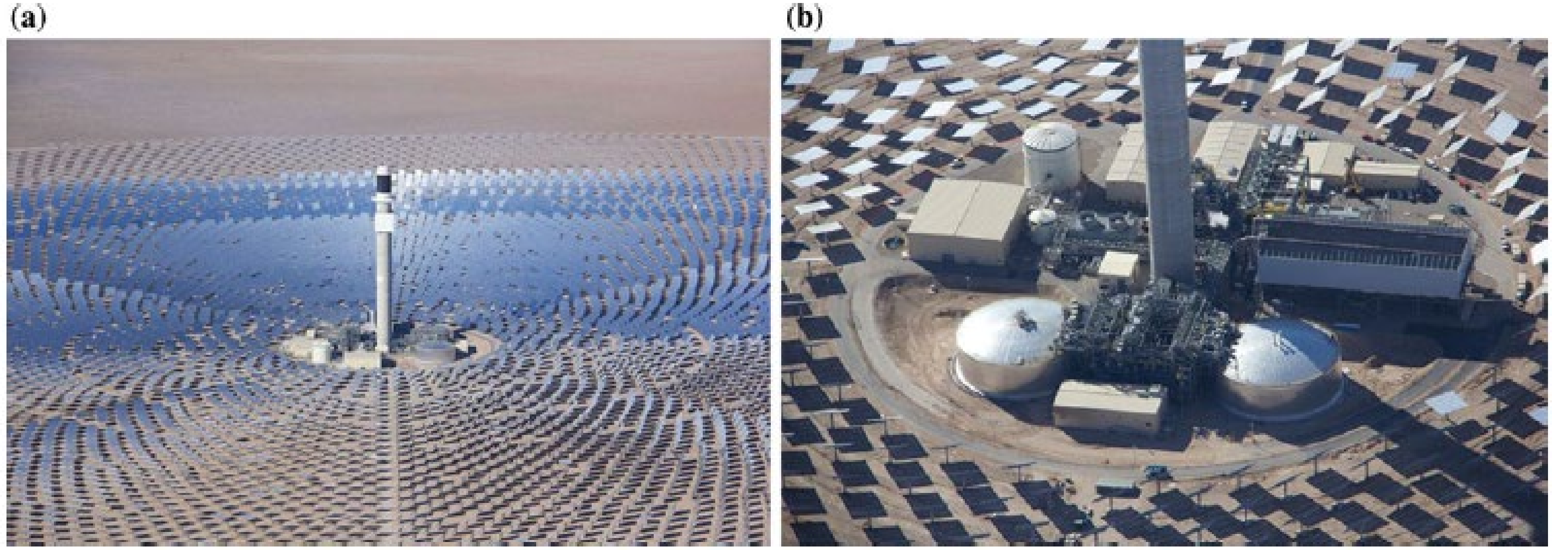
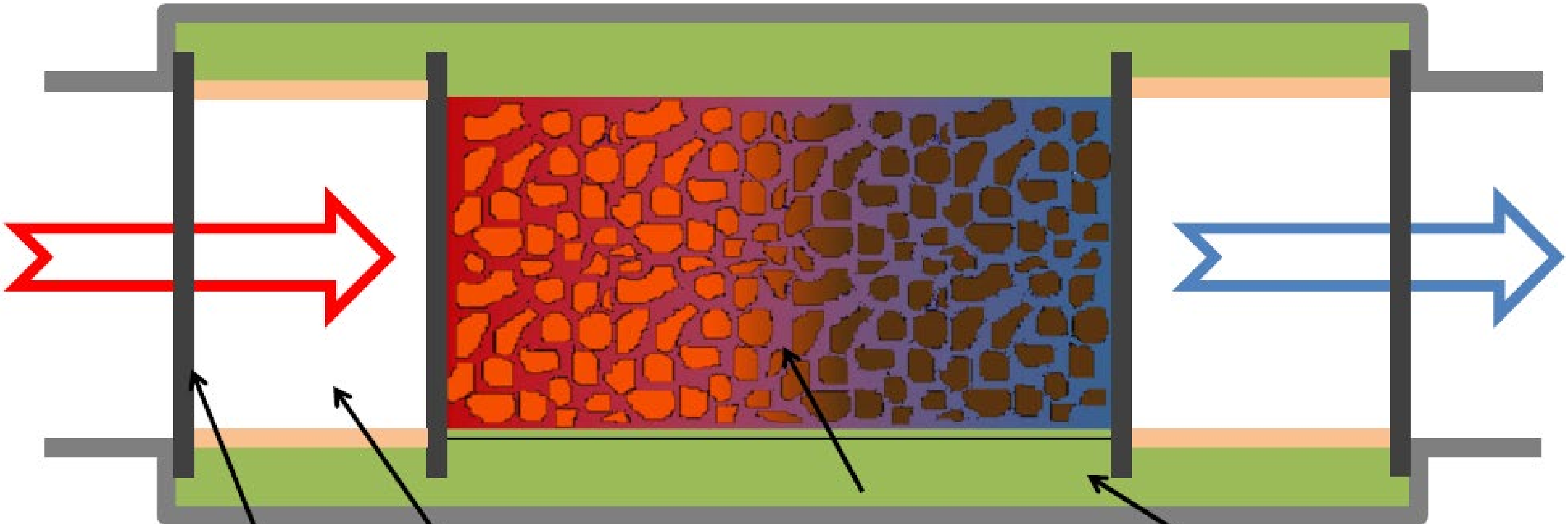


Fig. 4.6 a Heliostat field of Solar Reserve where b molten salt storage tanks are shown [1]

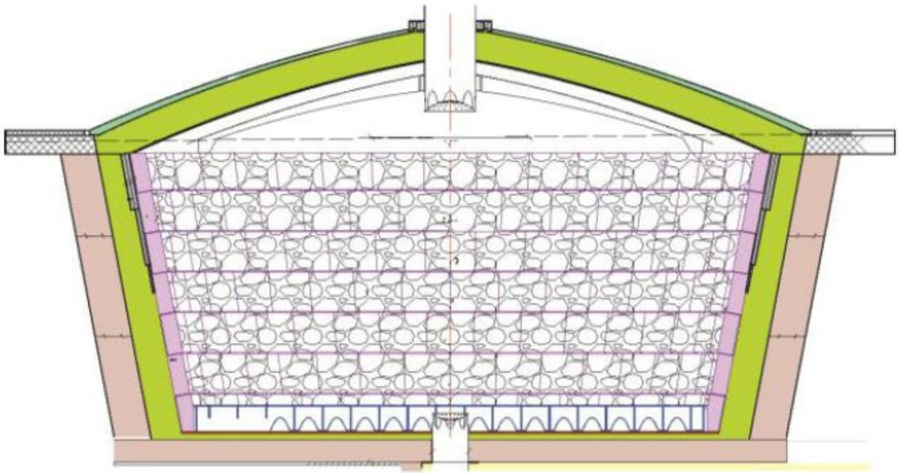
Thermal energy storage at high temperature



- Sensible heat: $Q = mc_p\Delta T$
- Approx. 300 kWh/m^3 for many rock materials if heated to 600 C
- Combined with steam turbine
- Estimated price for storage facility <u>in demo-version </u>50-100 €/kWh

High Temperature Thermal Energy Storage

G. Zanganeh et al. / Energy Procedia 49 (2014) 1071 – 1077



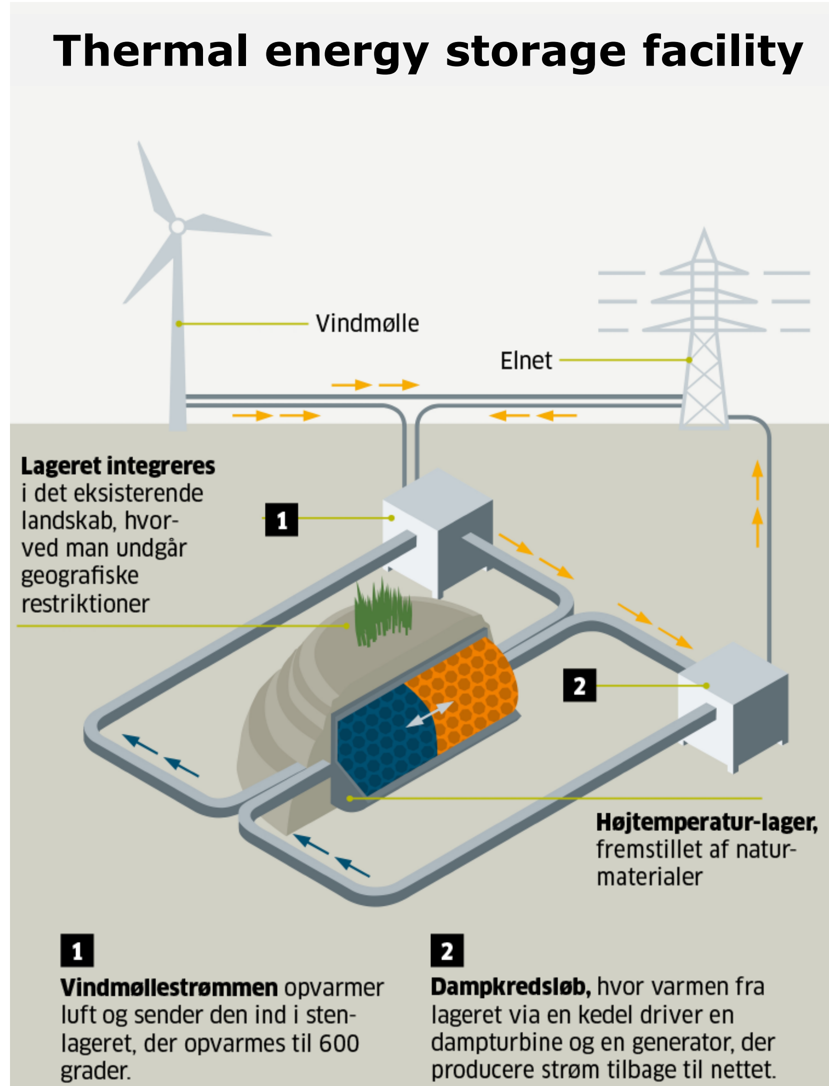
Operating conditions	
$t_{charging}$ [h]	10
$t_{discharging}$ [h]	4.5
T_{idle} [h]	9.5
$T_{charging}$ [°C]	640
$T_{discharging}$ [°C]	280

Energy density (depending on material): approx. 430 MJ/m^3 equal to 120 kWh/m^3

High Temperature Thermal heat store for re-electrification

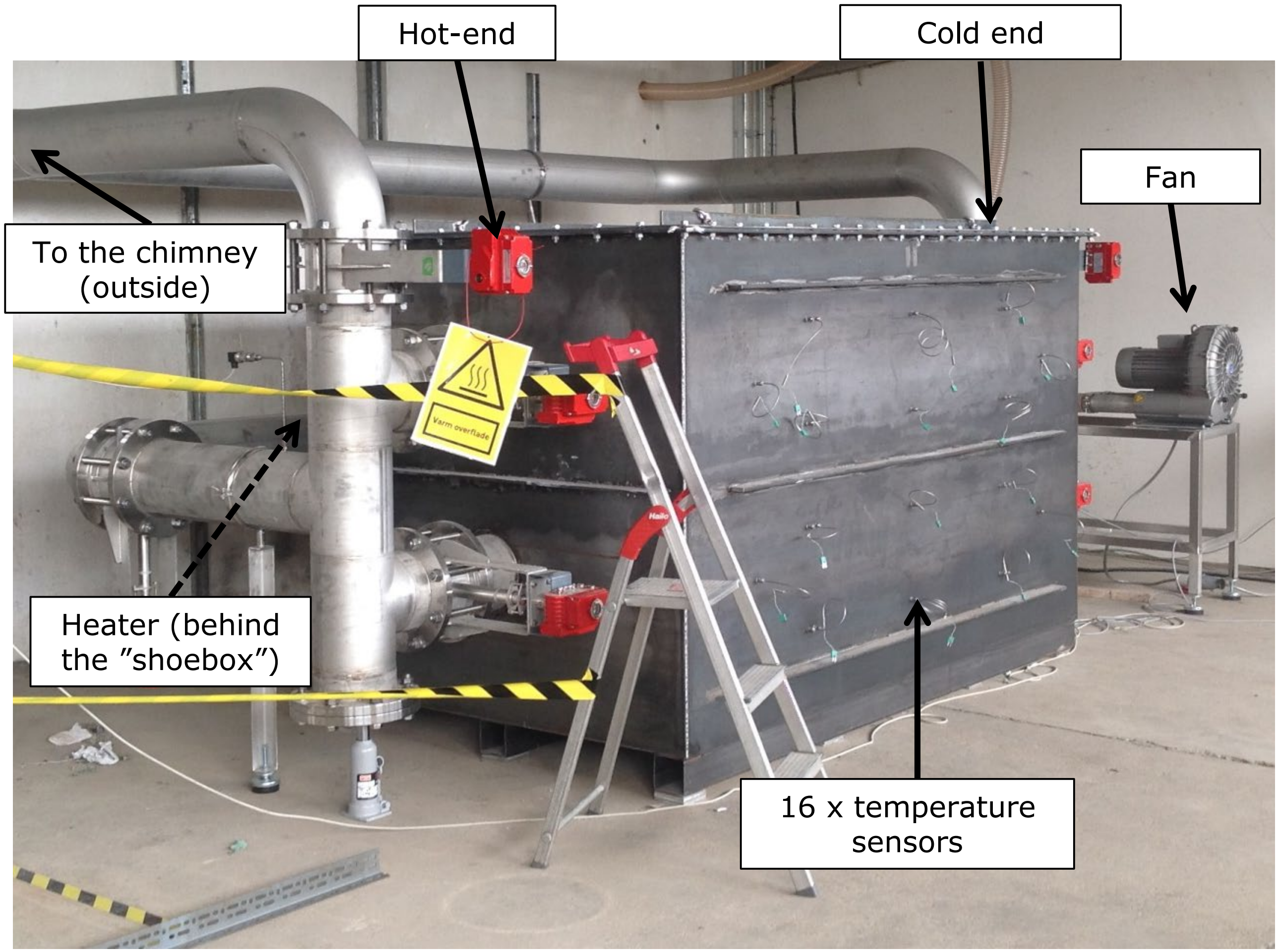
Pilot plant at DTU

- 850 kWh
- 100 kW
- 400-600 C
- High-temperature thermal energy storage (HT-TES)



Graphic: Ingeniøren

Experimental setup “shoebox” at DTU



Size = 1.5 m^3 of rocks ~ 450 kWh_{th} Max. charging rate = 25 kW

Experiments – effect of buoyancy forces

- The effect of the **buoyancy forces** can be clearly **detected** in the charging, storage, and discharging cycles

- **Charging**: the hot air tends to occupy the upper part of the bed

- **Discharging**: the cold airflow tends to sink in the bottom part of the bed

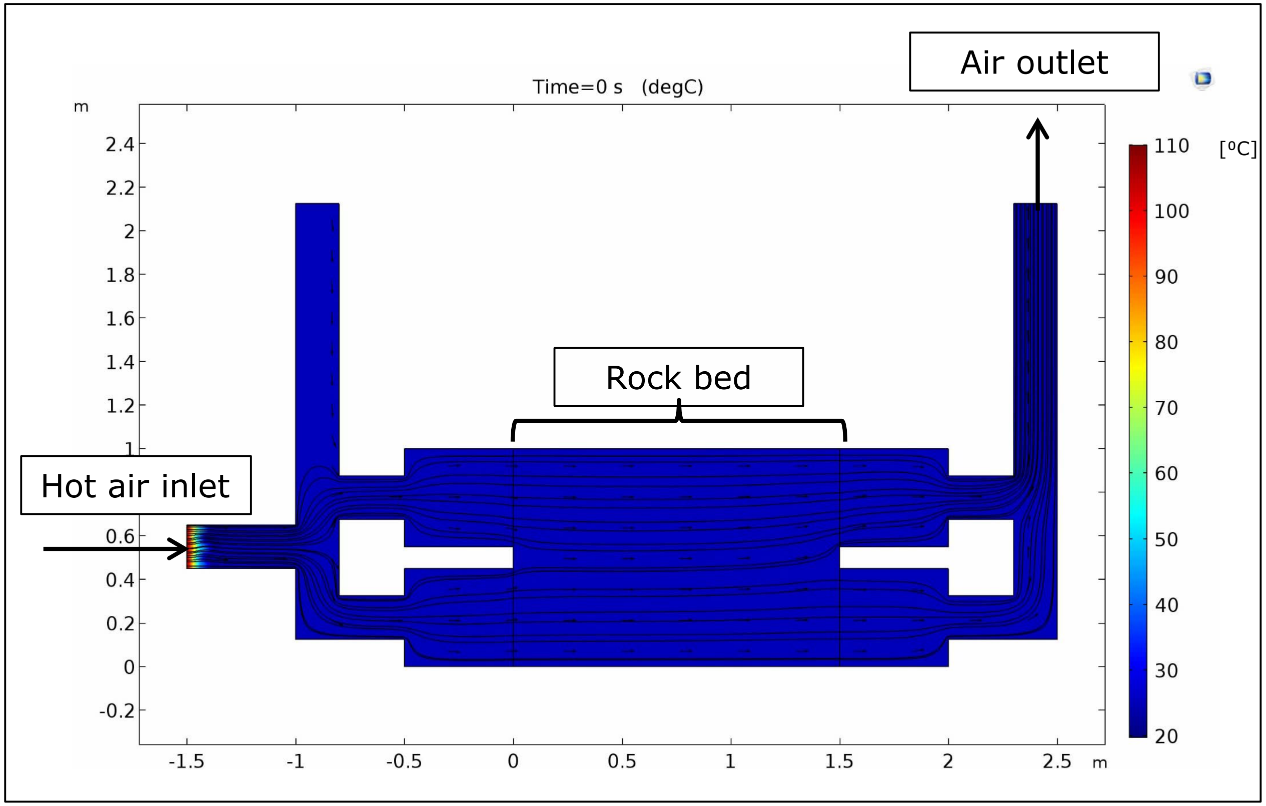
- **Storage**: buoyancy forces create a stratification

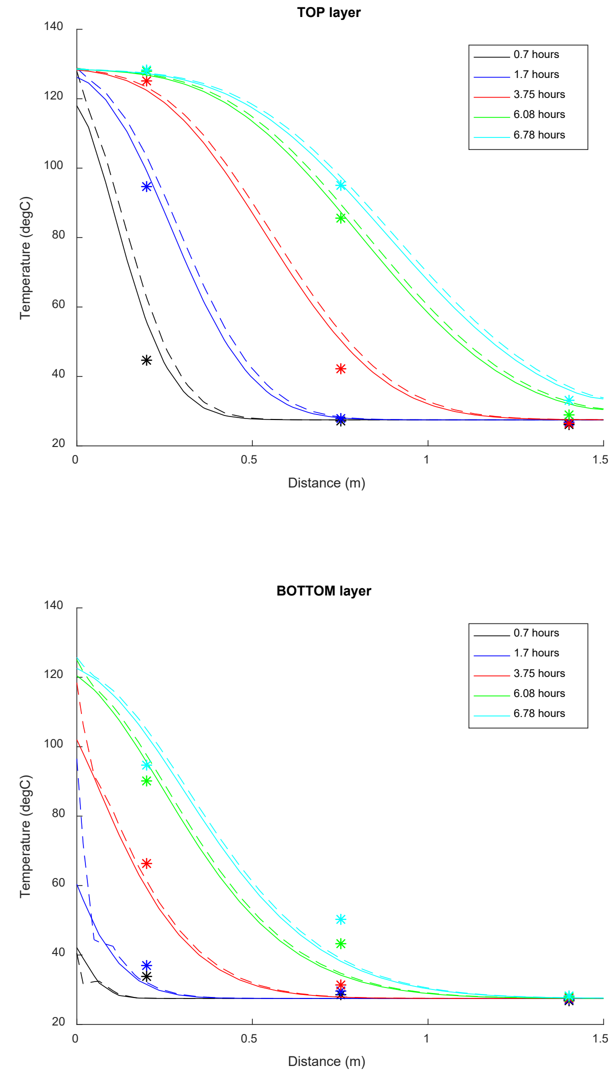
- Buoyancy acts **against the storage efficiency**

Experiments vs Modelling

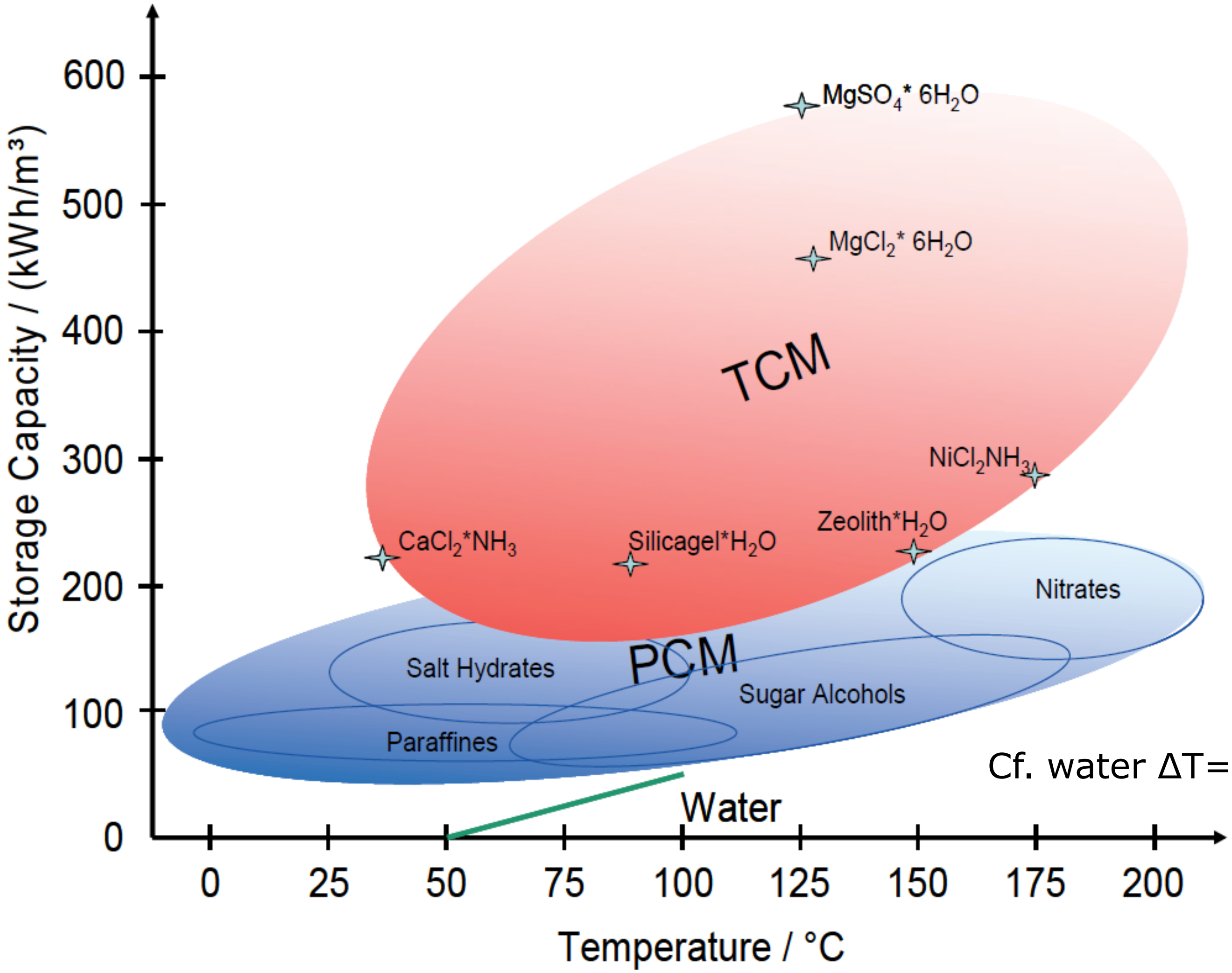
- **2D model (COMSOL)**

Simulation of a charging cycle of 12 hours at 110 ºC.





Storage Capacity vs. Temperature for Sensible, Latent and Thermochemical Energy Storage

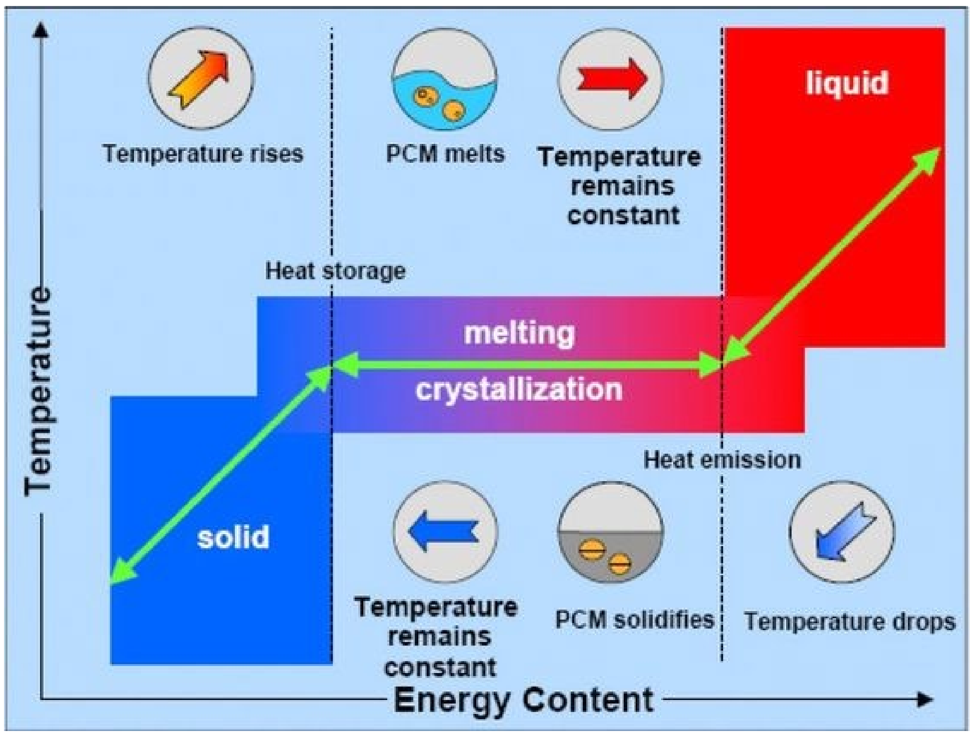


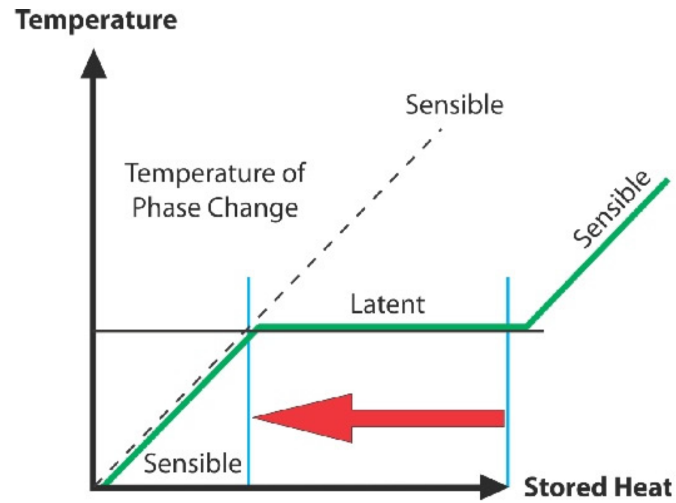
Cf. water ΔT=50 °C: 58 kWh/m^3

Source: Laevemann, E., Thermische Energiespeicher, Theoretische Grenzen und Beurteilungskriterien, Experten-Workshop „Thermische Speicher: Potentiale und Grenzen der Steigerung der Energiespeicherdichten", DFG/PTJ, Berlin, June 2010

Principle of a phase change material (PCM)

- Latent heat utilizing a phase change, e.g., solid-liquid or liquid-gas
- In principle at constant temperature





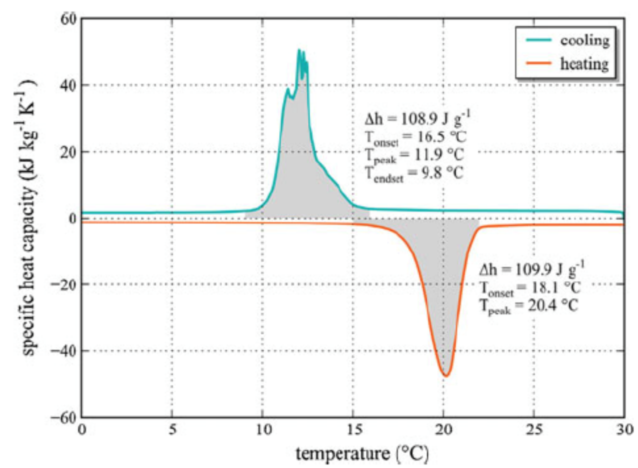


Fig. 4.2 DSC measurement for the eutectic salt hydrate mixture $Zn(NO_3)_2 \cdot 6H_2O$, $Mn(NO_3)_2 \cdot 4H_2O$, and KNO_3 [3]

- $Q = mc_p\Delta T + mh_{fg}$ (h_{fg} is the latent heat of fusion)

Thermal properties of selected materials

Table 4.1 Thermal properties of common materials [4]

Material	Density ($kg\,m^{-3}$)	Specific heat ($J\,kg^{-1}\,K^{-1}$)	Thermal conductivity ($J\,m^{-1}\,K^{-1}$)	Thermal diffusivity ($10^6\,m^2 s^{-1}$)
Clay	1,458	879	1.4	1.10
Brick	1,800	837	1.3	0.86
Sandstone	2,200	712	1.7	1.08
Wood	700	2,390	0.17	0.10
Concrete	2,000	880	1.8	1.02
Glass	2,710	837	1.05	0.46
Aluminum	2,710	896	237	97.60
Steel	7,840	465	54	14.81
Air	1.27	1006	0.024	18.8
Water	988	4,182	0.6	0.14

Table 4.2 Latent heat values for inorganic materials [4]

Phase	Melting point (°C)	Heat of fusion ($MJ\,kg^{-1}$)
NH_4NO_3	170	0.12
$NaNO_3$	307	0.13
NaOH	318	0.15
$Ca(NO_3)_2$	561	0.12
LiCl	614	0.31
$FeCl_2$	670	0.34
$MgCl_2$	708	0.45
KCl	776	0.34
NaCl	801	0.50

Thermal properties of selected PCMs

Table 4.3 Solid-state phase transformation and melting entropy data for some materials [4]

Material	Transition temperature (°C)	Melting temperature (°C)	Transition entropy ($J.mol^{-1}.K^{-1}$)	Melting entropy ($J\ mol^{-1}\ K^{-1}$)
FeS	138	1,190	4.05	21.51
AgI	148	558	14.61	11.33
Ag_2S	177	837	8.86	7.01
Na_2SO_4	247	884	12.5	18.2
Ag_2SO_4	427	660	26.66	19.19
Li_2SO_4	577	860	29.2	7.9
$LiNaSO_4$	518	615	31.2	Small

Table 4.4 Latent heat values for organic PCMs [4]

Material	Melting point (°C)	Heat of fusion ($k.J.kg^{-1}$)
Paraffin wax	64	173.6
Polyglycol E400	8	99.6
Polyglycol E600	22	127.2
Polyglycol E6000	66	190.0

Table 4.5 Latent heat values for fatty acids used as PCMs [4]

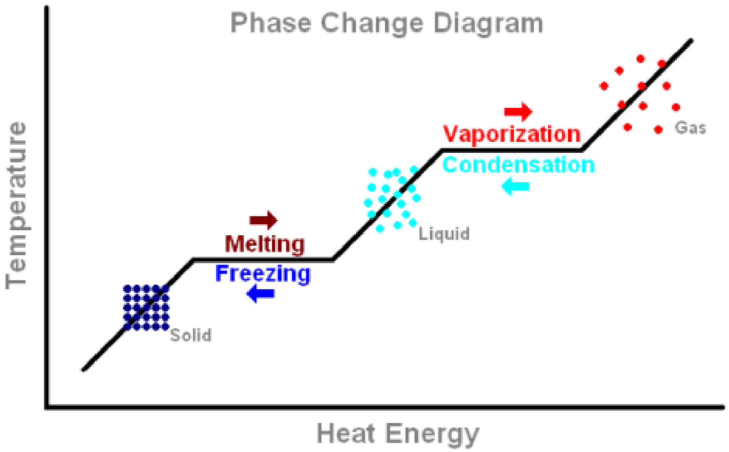
Material	Melting point (°C)	Heat of fusion ($k.J.kg^{-1}$)
Stearic acid	69	202.5
Palmitic acid	64	185.4
Capric acid	32	152.7
Caprylic acid	16	148.5

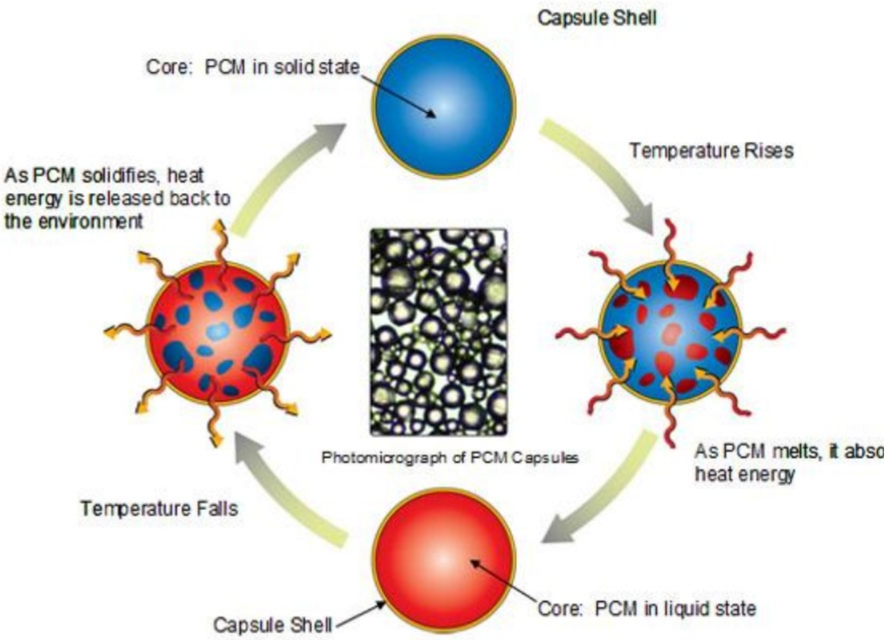
Table 4.6 Latent heat values for aromatic materials used as PCMs [4]

Material	Melting point (°C)	Heat of fusion ($k.J.kg^{-1}$)
Biphenyl	71	19.2
Naphthalene	80	147.7

PCM in Buildings: How does it work

- Melting 1 g of ice requires same energy as heating 1 g of water from 0 to 80 °C





www.microteklabs.com

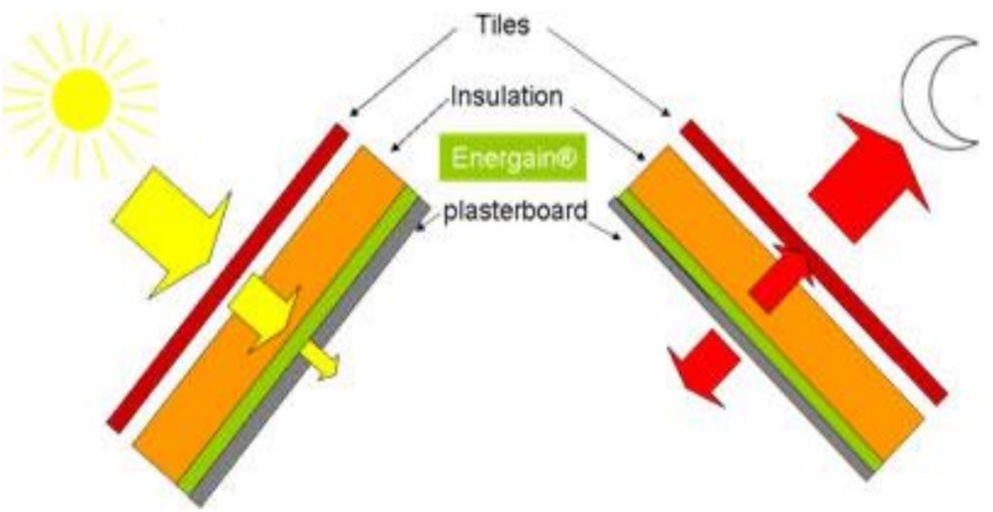


Figure 4 – The Ideal Configuration of Insulation with PCM, a variation of Trombe walls. Image from energain.co.uk

Reversible Gas-Solid Reactions in TCM/TCS

- High storage density
- Lossless long-term storage possible
- Possible heat transformation
- Large temperature range (RT to > 1000 °C)
- Detachment of storage capacity and thermal power
- Cost efficient storage materials

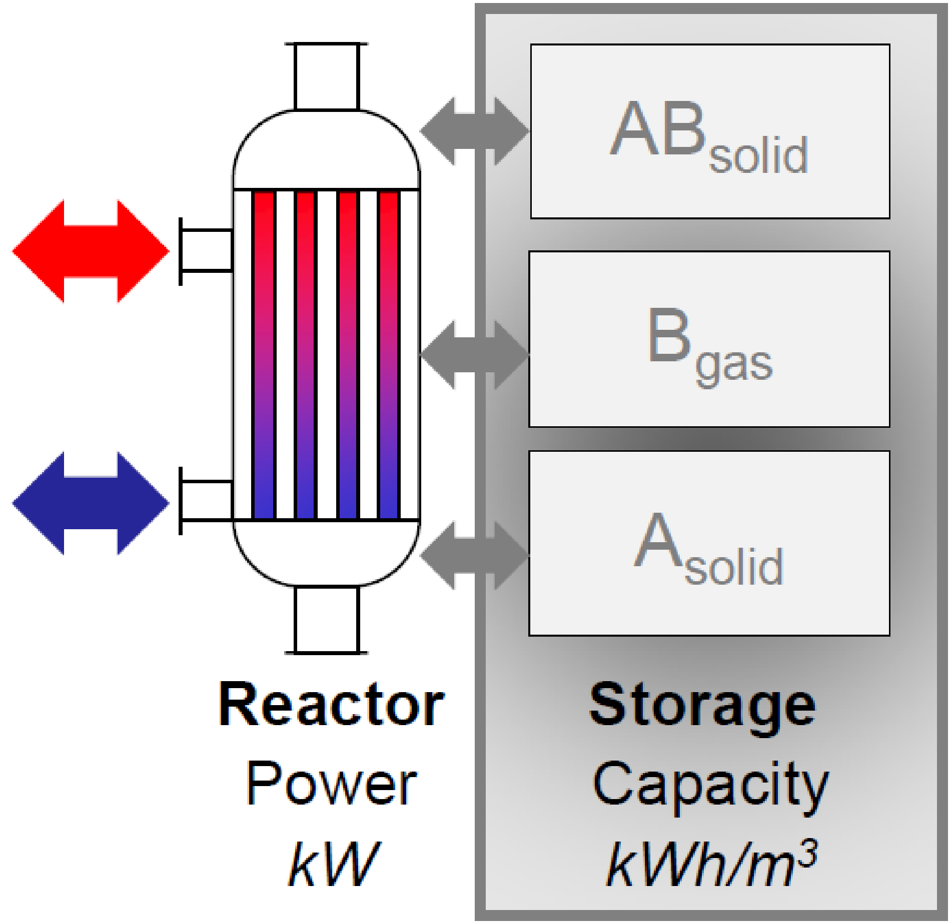
$$AB \underset{\text{exothermal}}{\overset{\text{endothermal}}{\rightleftharpoons}} A + B$$

- Reactions:
  - Dehydration: $CaCl_2{*}6H_2O = CaCl_2 + 6\ H_2O$
  - Metalhydroxide/Metaloxide: $Ca(OH)_2 = CaO + H_2O$
  - Redox cycles of Metaloxides: $2\ MnO_2 = Mn_2O_3 + ½\ O_2$

Source: DLR, Germany

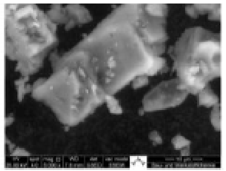
Reversible Gas-Solid Reactions (TES)

- **Closed loop operation** requires storage of gaseous reactant
- **Open loop operation** possible for steam or oxygen reaction systems
- Transport of solid reactant enables **detachment of power from capacity**
- **Integration** of storage system with process important

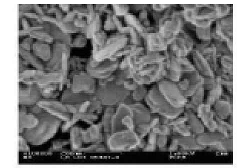


Source: DLR, Germany

Examples of TCM materials



Cf. water ΔT=50 °C: 58 kWh/m³



Calcium Hydroxide

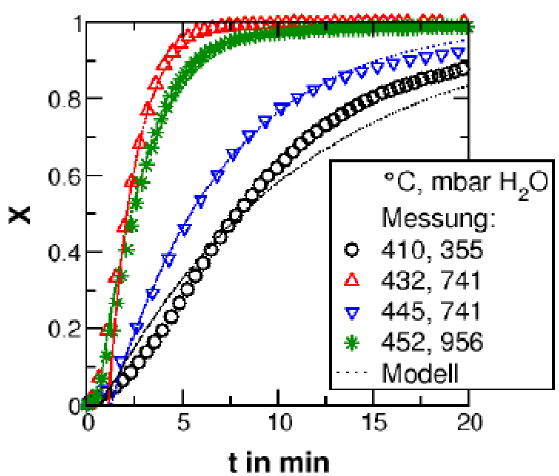
$Ca(OH)_2 + \Delta H \leftrightarrow CaO + H_2O$

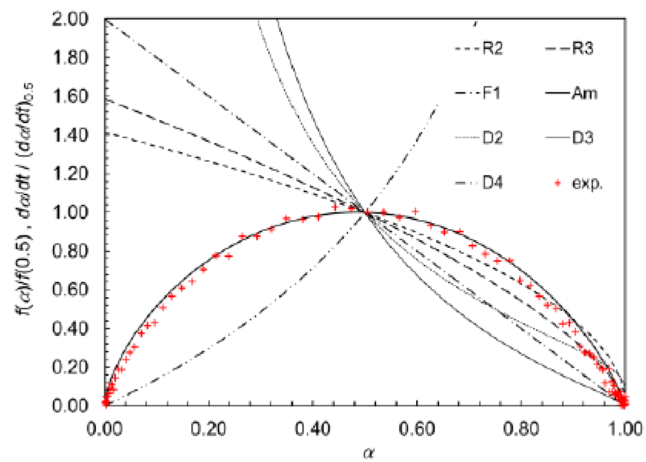
T_{eq} = 507°C at 1 bar
ΔH = 100 kJ/mol
Storage density*) = 410 kWh/m³

Manganese Oxide

$6\ Mn_2O_3 + \Delta H \leftrightarrow 4\ Mn_3O_4 + O_2$

T_{eq} = 980°C at 1 bar
ΔH = 31.8 kJ/mol
Storage density*) = 126 kWh/m³





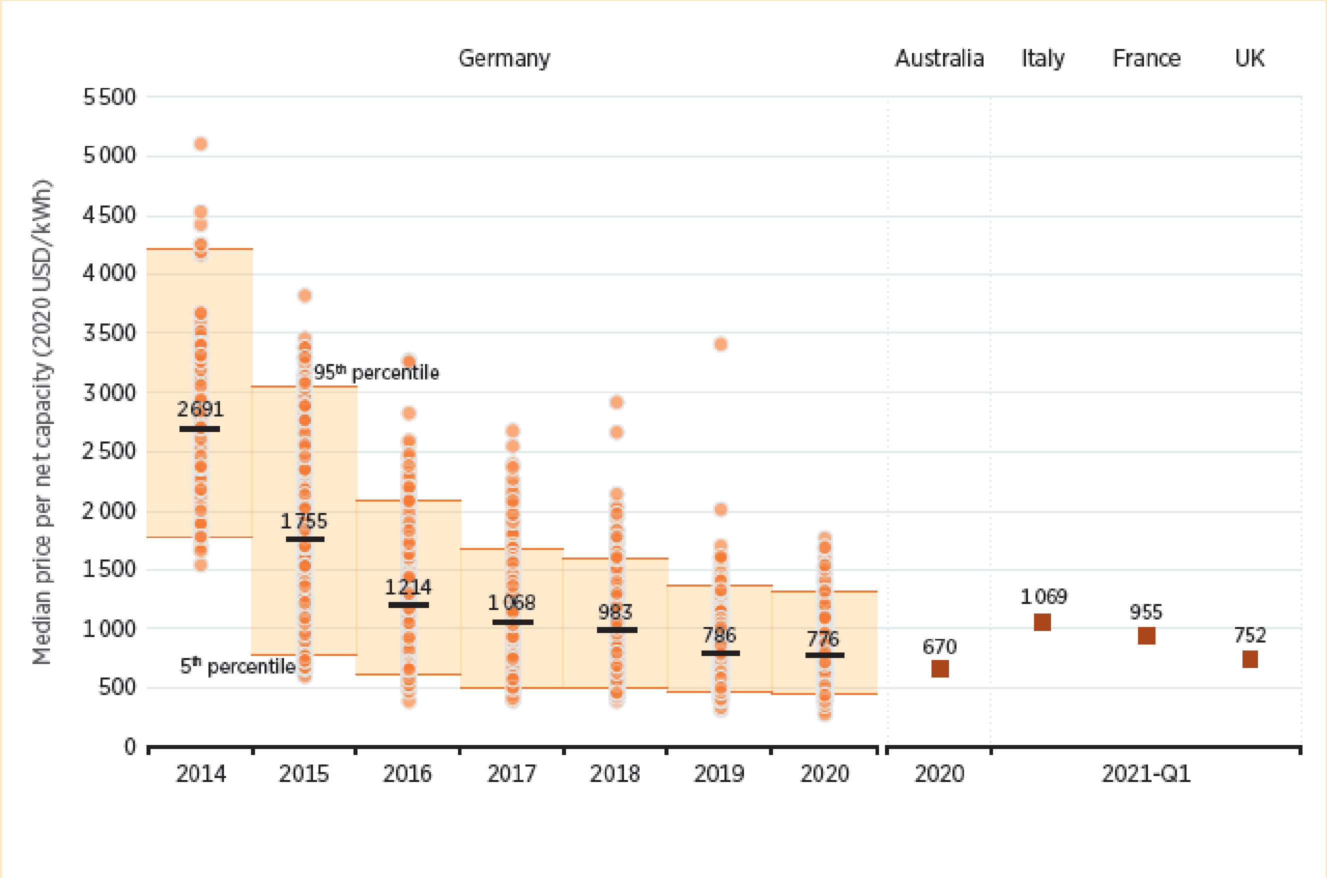
*) open loop, bulk porosity ε = 0.5

Source: DLR, Germany

ELECTRO(CHEMICAL)

Li-ion battery cost - utility

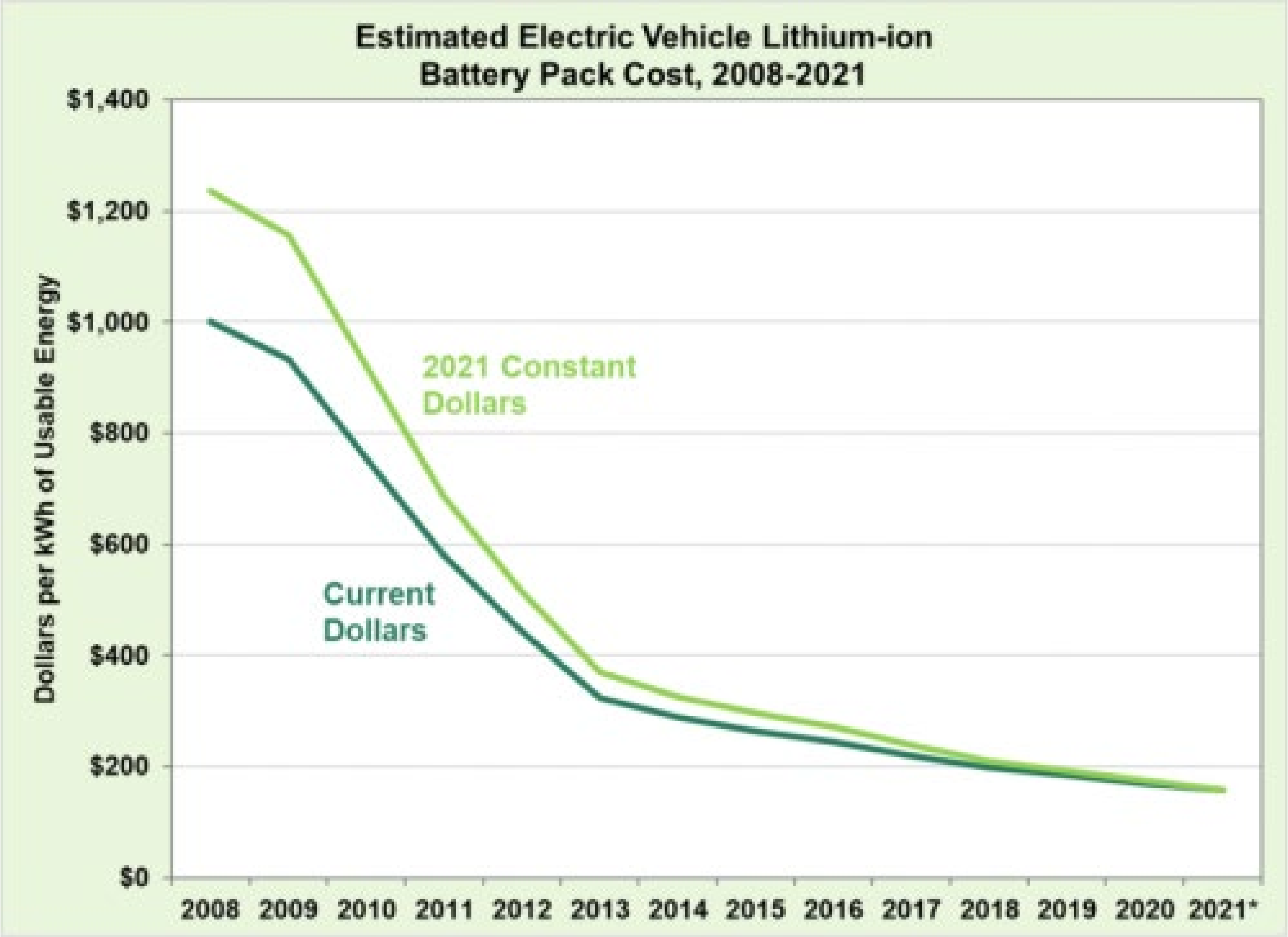
Figure B3.1 Behind-the-meter residential lithium-ion battery system prices in Germany, Australia, France, Italy and the United Kingdom, 2014-2020



Source: IRENA and EUPD Research GmbH, 2021; and Solar Choice, 2021

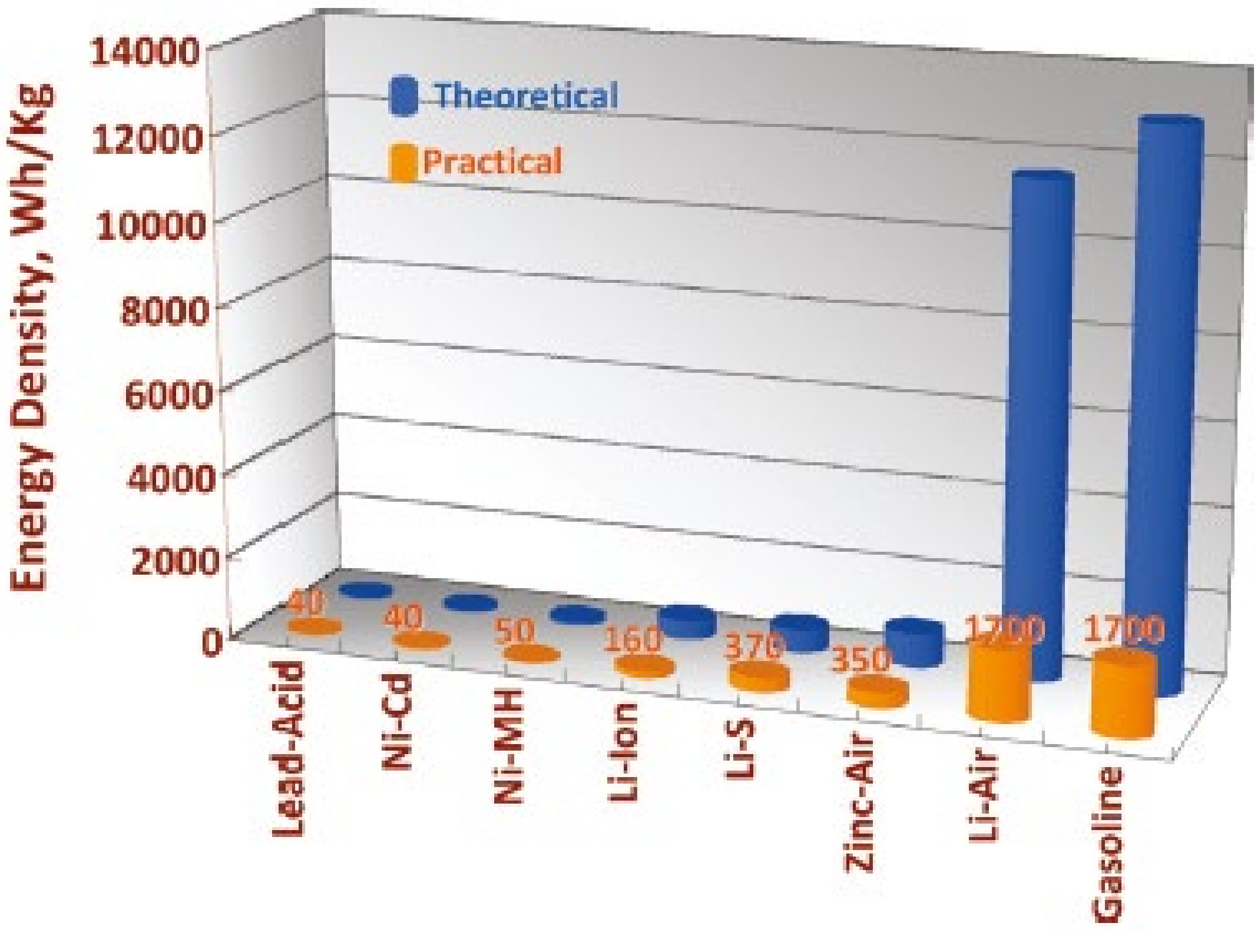
IRENA, Electricity Storage and Renewables: Costs and Markets to 2030 (2020)

Li-ion battery cost - automotive



Greencongresscar (2021)

The fundamental problem about batteries: the energy density. Can we improve?



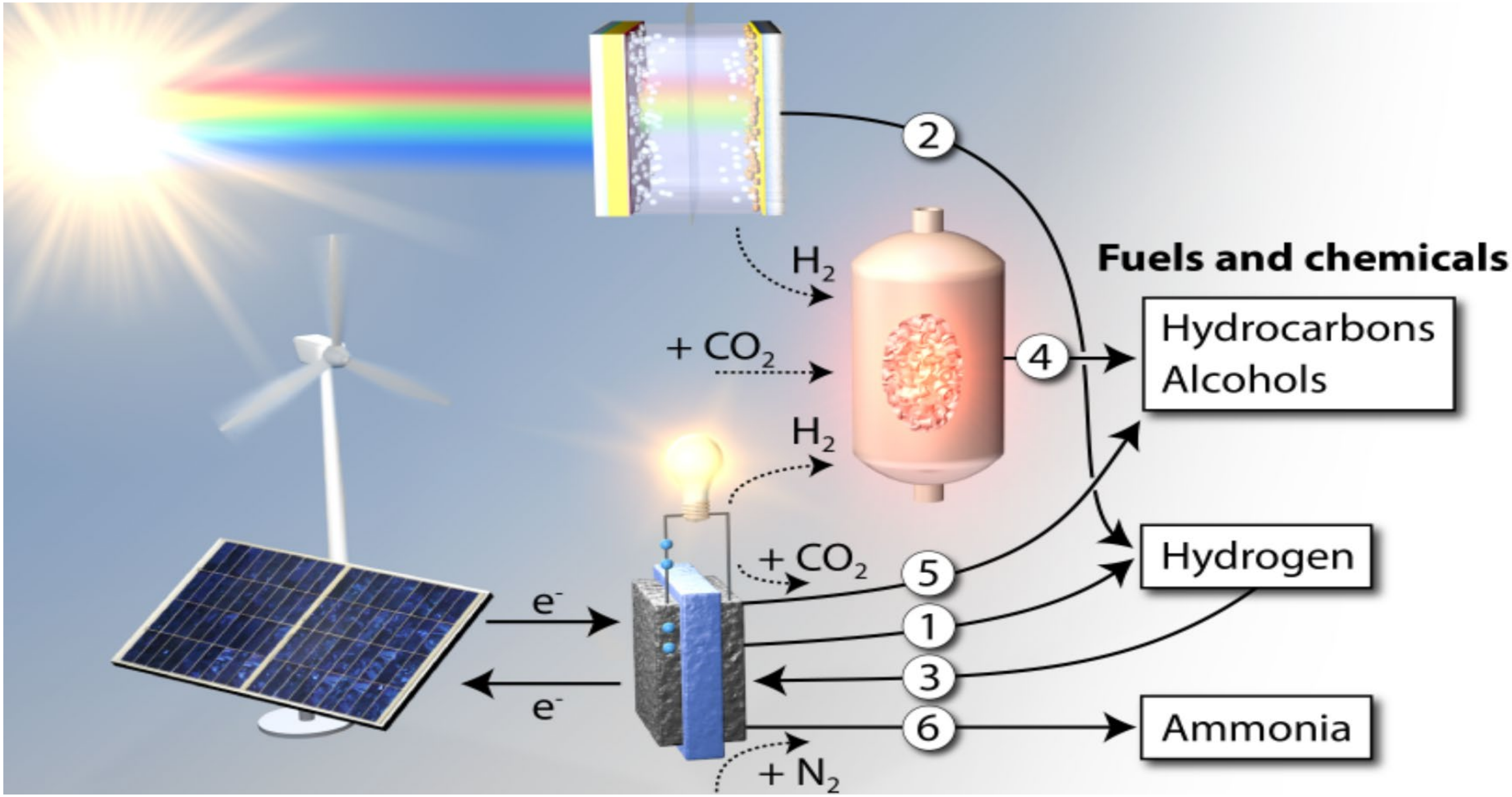
Bosch installed a Hybrid Energy Storage System in Northern Germany in conjunction to wind farm

- 2.4 MWh Lithium-Ion battery (SAFT Batteries)
- 1 MWh Vanadium Redox-Flow battery (Vanadis Power)
- Total capacity 3.4 MWh and 2.25 MW
- Corresponds to consumption by 40 single-family houses for one week
- Precondition to allow more wind power in the neighborhood

Photo: Ingeniøren.dk

Power2X (hydrogen, SNG, ammonia…)

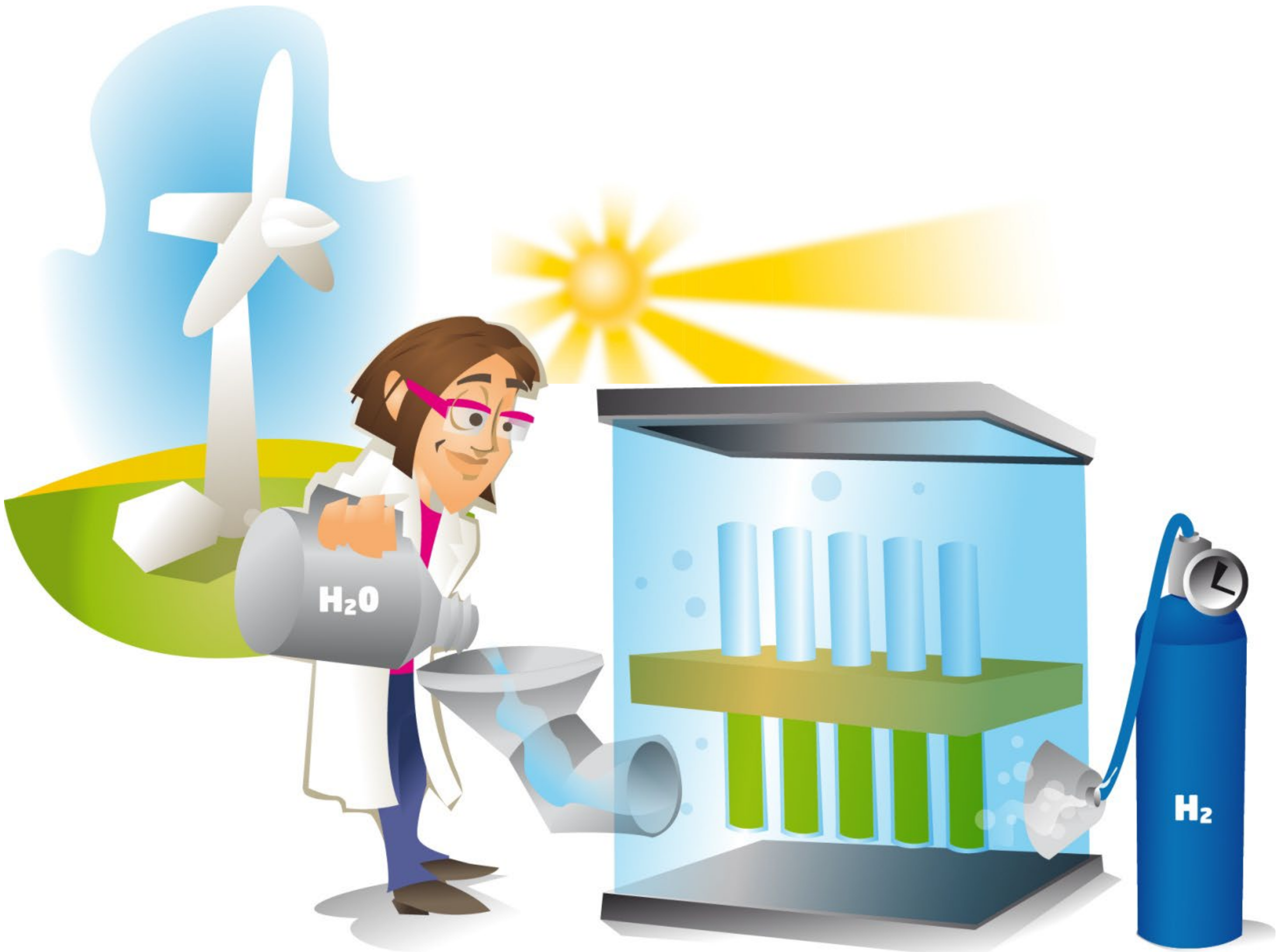
- Fuels and chemicals directly from solar/wind energy



The Villum Center for the Science of Sustainable Fuels and Chemicals

Sustainable chemical fuels

- $2H_2O \rightarrow O_2 + 4H^+ + 4e^- \rightarrow O_2 + 2H_2$



Hydrogen Storage can be a challenge

Storage and distribution

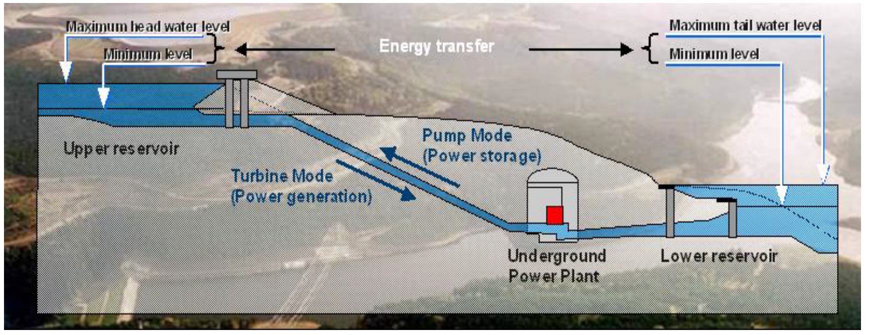
- Synthetic fuels can be stored in huge quantities in surface containments or underground
- High energy density – about 10-30 times that of batteries
- Existing (and depreciated) fine-meshed gas transmission and distribution grid covering major parts of Europe
- Consumers are conversant with chemical fuels and conversion equipment

SUMMARY

- Energy Storage is an essential component of any future energy system
- LCOS is falling fast for many storage solutions
- Mechanical energy storage:
  - Pumped hydro storage (PHS), Compressed Air Energy Storage (CAES), Flywheels
- Thermal energy storage
  - Sensible heat, latent heat and thermochemical energy storage (TES)
- *Electrical and electrochemical*
  - *Super capacitors, batteries and electro fuels (see specific lectures)*
- Energy density, charging time, LCOS, CAPEX and WACC are critical parameters when choosing energy storage solutions

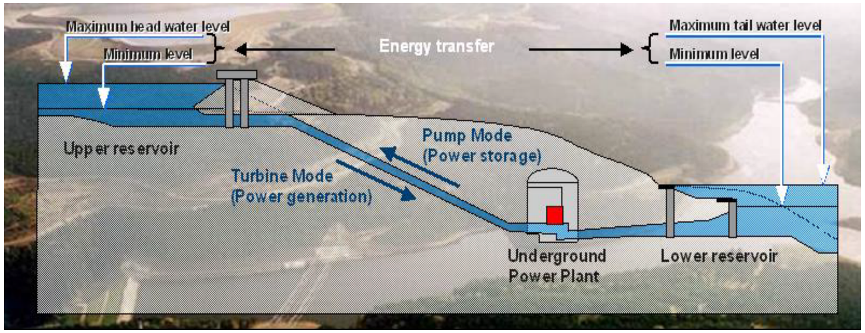
EXERCISE I: Mechanical

- CASE: You have to store 100 kWh (360 MJ)
- What is the weight of the 'body of storage' is required:
  - 1) Pumped Hydro Storage (PHS) @ 500 m
  - 2) Flywheel @ 20 Wh/kg
  - 3) Li-ion batteries (find your own type)
  - 4) Chemical storage in hydrogen
- Which of the storage technologies has the highest efficiencies?
- Compare LCOS for the four technologies in 2015 and 2030?
- Estimate (i.e., high, moderate, low) and compare CAPEX and OPEX



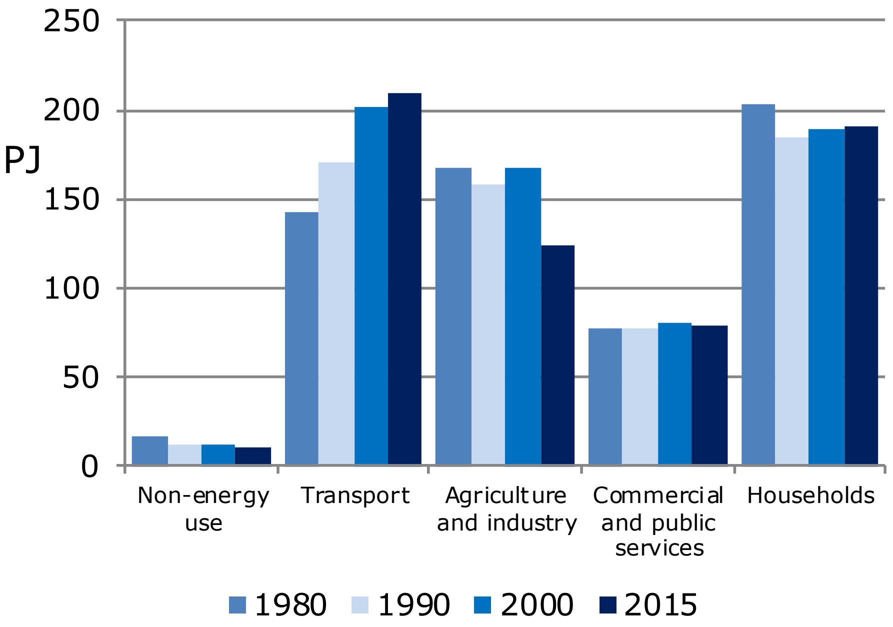
EXERCISE I: Mechanical

- CASE: You have to store 100 kWh (360 MJ)
- What is the weight of the 'body of storage' is required:
  - 1) Pumped Hydro Storage (PHS) @ 500 m: $9*10^4$ kg (~80% efficiency)
  - 2) Flywheel @ 20 Wh/kg: $5*10^3$ kg (~95% eff.)
  - 3) Li-ion batteries: $4*10^2$ kg (~250Wh/kg) (~95% eff.)
  - 4) Chemical storage in hydrogen: 5 kg (~50% eff.)
- Which of the storage technologies has the highest efficiencies?
- Compare LCOS for the four technologies in 2015 and 2030?
- Estimate (i.e. high, moderate, low) and compare CAPEX and OPEX



EXERCISE II: Thermal

- Assumption: the annual Danish energy household consumption (190 PJ) has to be stored using thermal storage
- What is the weight of the required body of storage using:
  - 1) water (ΔT=50 °C), 2) sensible heat (granite ΔT=500 °C), 3) latent heat: PCM (paraffines @80 kWh/m³) and 4) thermochemical ($MgCl_2*6H_2O$)
- Determine the energy densities and compare to values from Ex.1
- How long would it take to fill 1.5 m³ DTU 'Shoebox' (425 kWh)?
- Estimated how long it will take to store the same amount of energy in $MgCl_2*6H_2O$ or a flywheel (seconds/minutes/hours/days)?
- Compare LCOS for sensible heat, latent heat and thermo-chemical



EXERCISE II: Thermal

- Assumption: the annual Danish energy household consumption (190 PJ) has to be stored using thermal storage
- What is the weight of the required body of storage using:
  - 1) water (ΔT=50 °C): $9*10^{11}$ kg, 2) sensible heat (granite ΔT=500 °C): $5*10^{11}$ kg, 3) latent heat: PCM (paraffines @80 kWh/m^3): $6*10^{11}$ kg and 4) thermochemical ($MgCl_2*6H_2O$): @460 kWh/m^3: $2*10^{11}$ kg
- Determine the energy densities and compare to values from Ex.1 (~50-100 Wh/kg, expect $MgCl_2*6H_2O$ which compares to Li-ion ~250 Wh/kg)
- How long would it take to fill 1.5 m^3 DTU 'Shoebox' (425 kWh)? (>18 h)
- How long would it take to store the same amount of energy in $MgCl_2*6H_2O$ or a flywheel? (min.; sec.)
- Compare LCOS for sensible heat, latent heat and thermo-chemical