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Isothermal Compressed Air Energy Storage for Decentralised Energy Grid

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Partners and Funders

- EP/Y017471/1 Micro-scale Co-generation Near-isothermal-Adiabatic Compressed Air Energy Storage
- 4-year project funded by EPSRC
- 05/2024 – 05/2028

EPSRC

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ARUP

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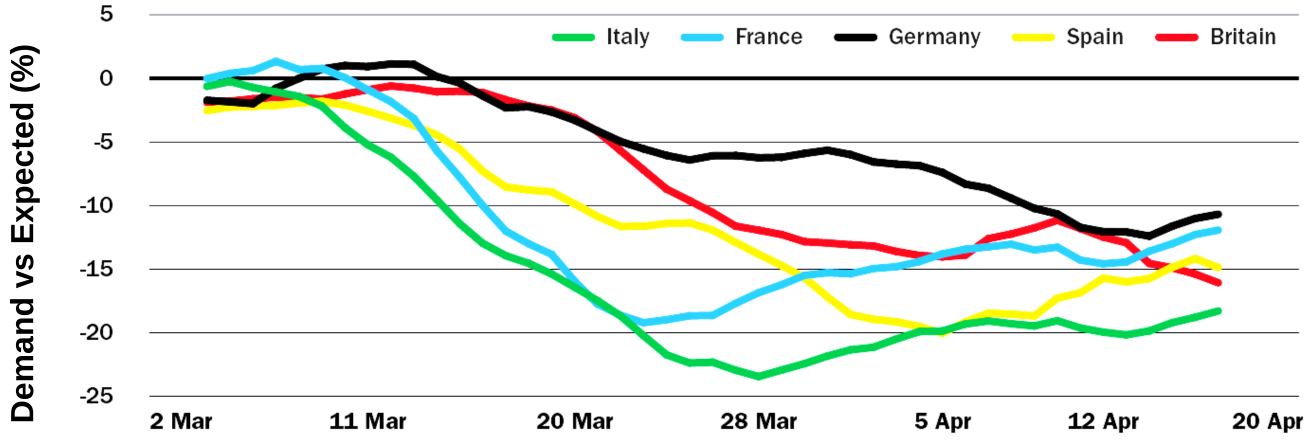
tnei

ADDED SCIENTIFIC

BL
Refrigeration and Air Conditioning Ltd

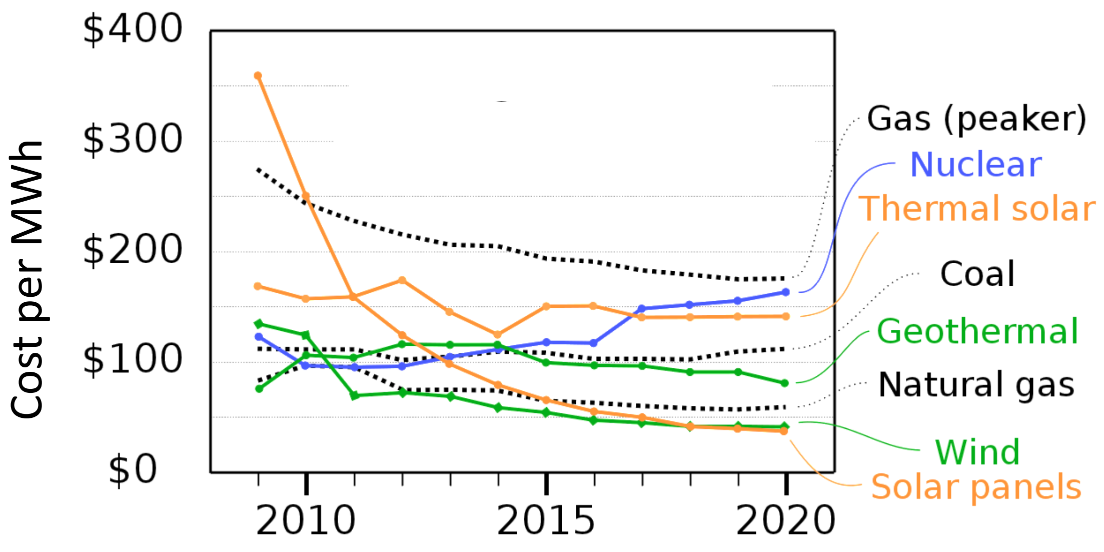
Need for Storage

- Net-zero by 2050
- The intermittent nature of solar and wind sources.
- Store energy for periods when demand is low (lockdown)



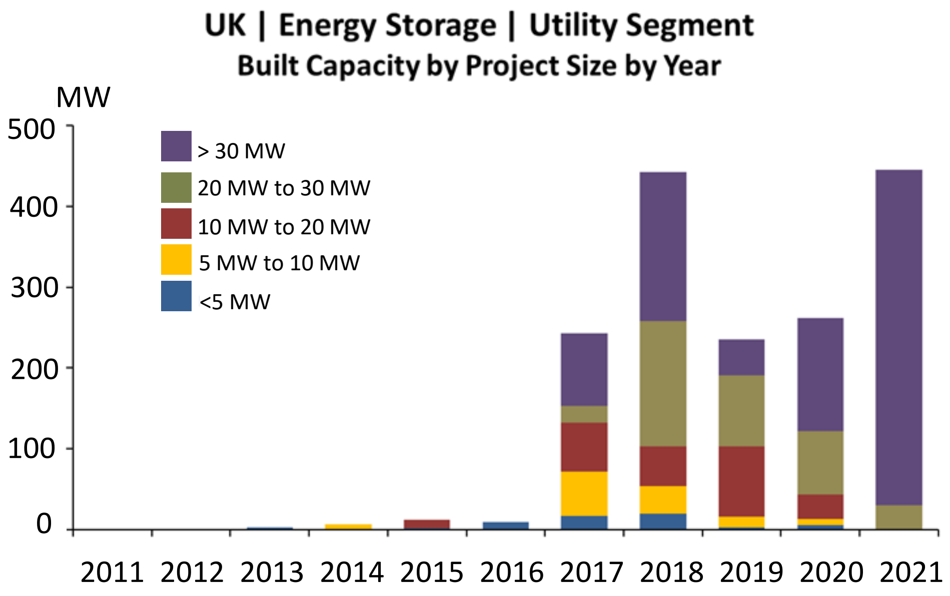
European electricity demand during coronavirus lockdowns

(source ICIC: Independent Chemical & Energy Market Intelligence)



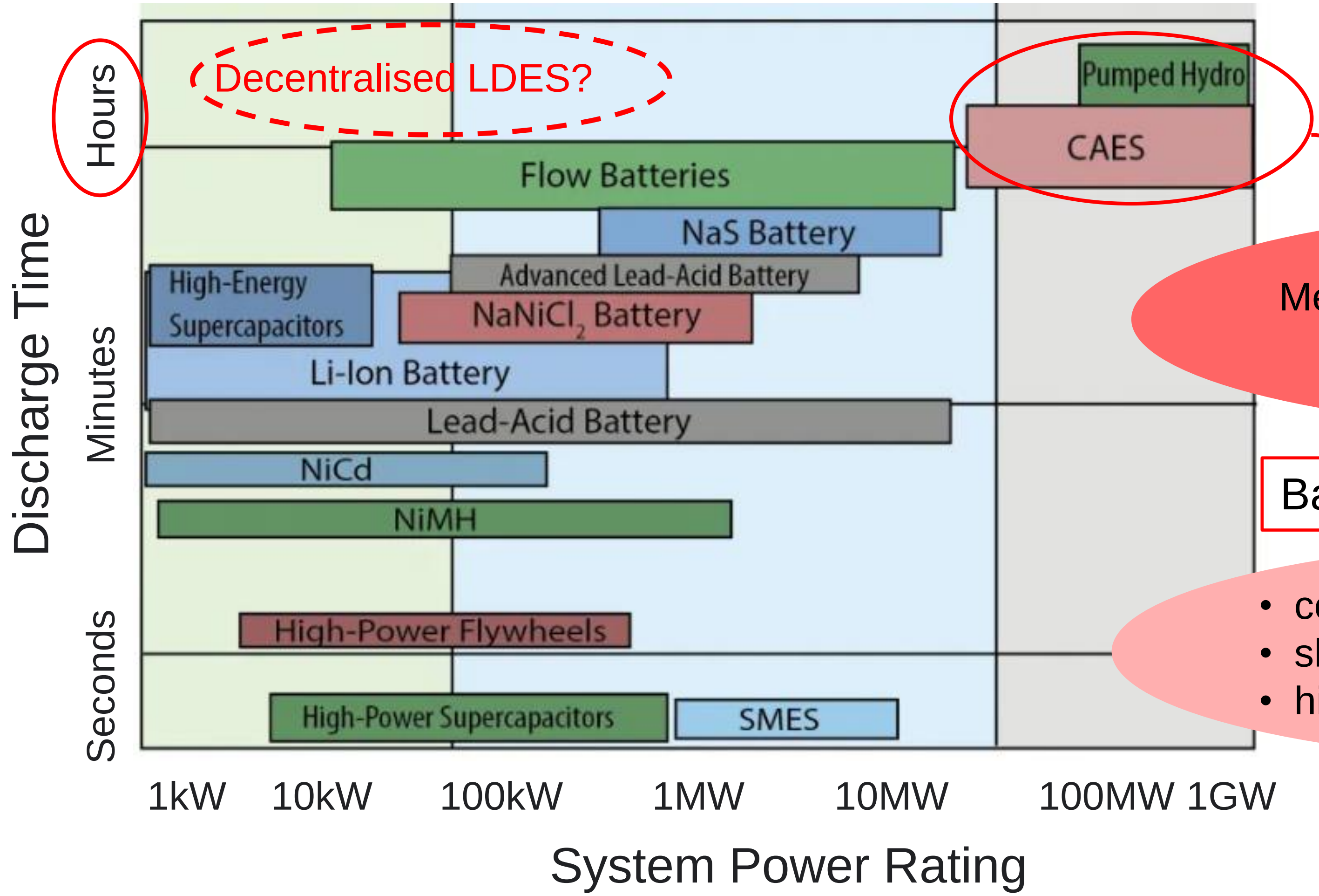
Levelized Cost of Energy

(Source: Lazard's Levelized Cost of Energy Version 14.0 . Lazard.com. Lazard)



(Source: UK storage project database report, March 2022)

Different Technologies for Energy Storage



Medium/Long Duration Energy Storage (LDES) (>4 hours)

Battery Storage is not enough/suitable

- cost per unit power density is still high
- short lifetimes (~5–10 years)
- high degradation (~60–70%)

CAES: Compressed Air Energy Storage
NiMH: Nickel-Metal Hydride battery
NiCd: Nickel Cadmium battery
SMES: Superconducting Magnetic Energy Storage

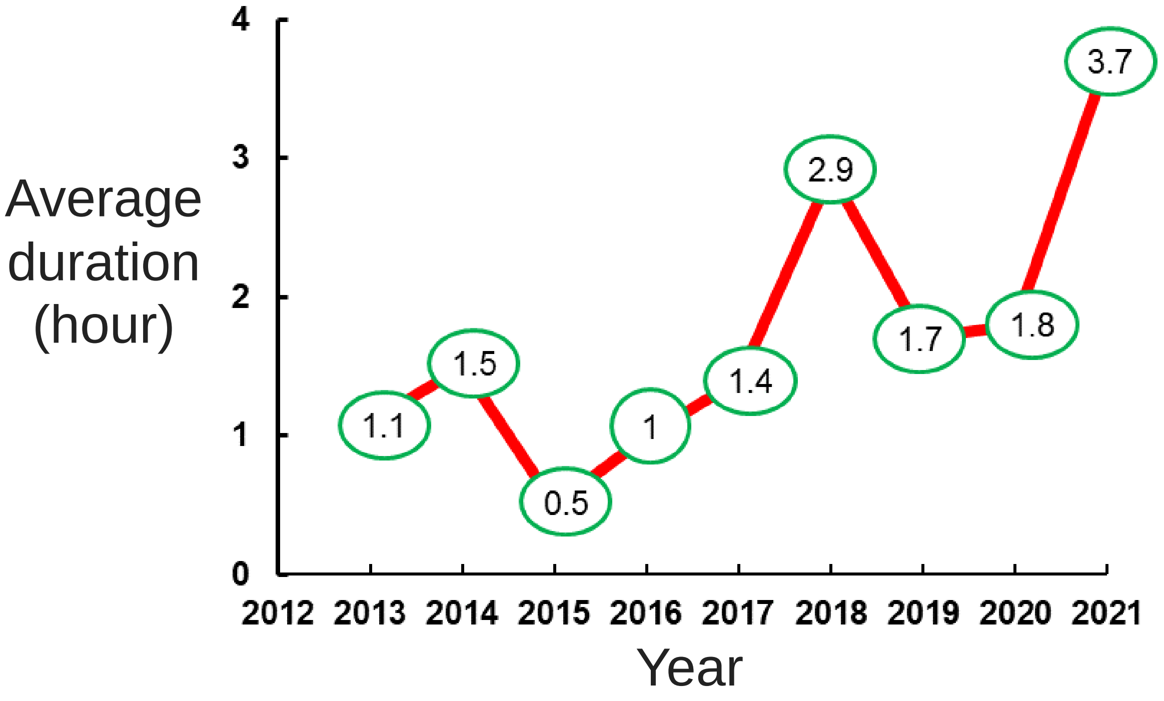
Source: SNL (2015) DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA.

How Long is LDES?

- Type 1: manages daily cycles and provides 10h up to 20 h of storage
- Type 2: manages seasonal cycles and provides storage measured in days or weeks

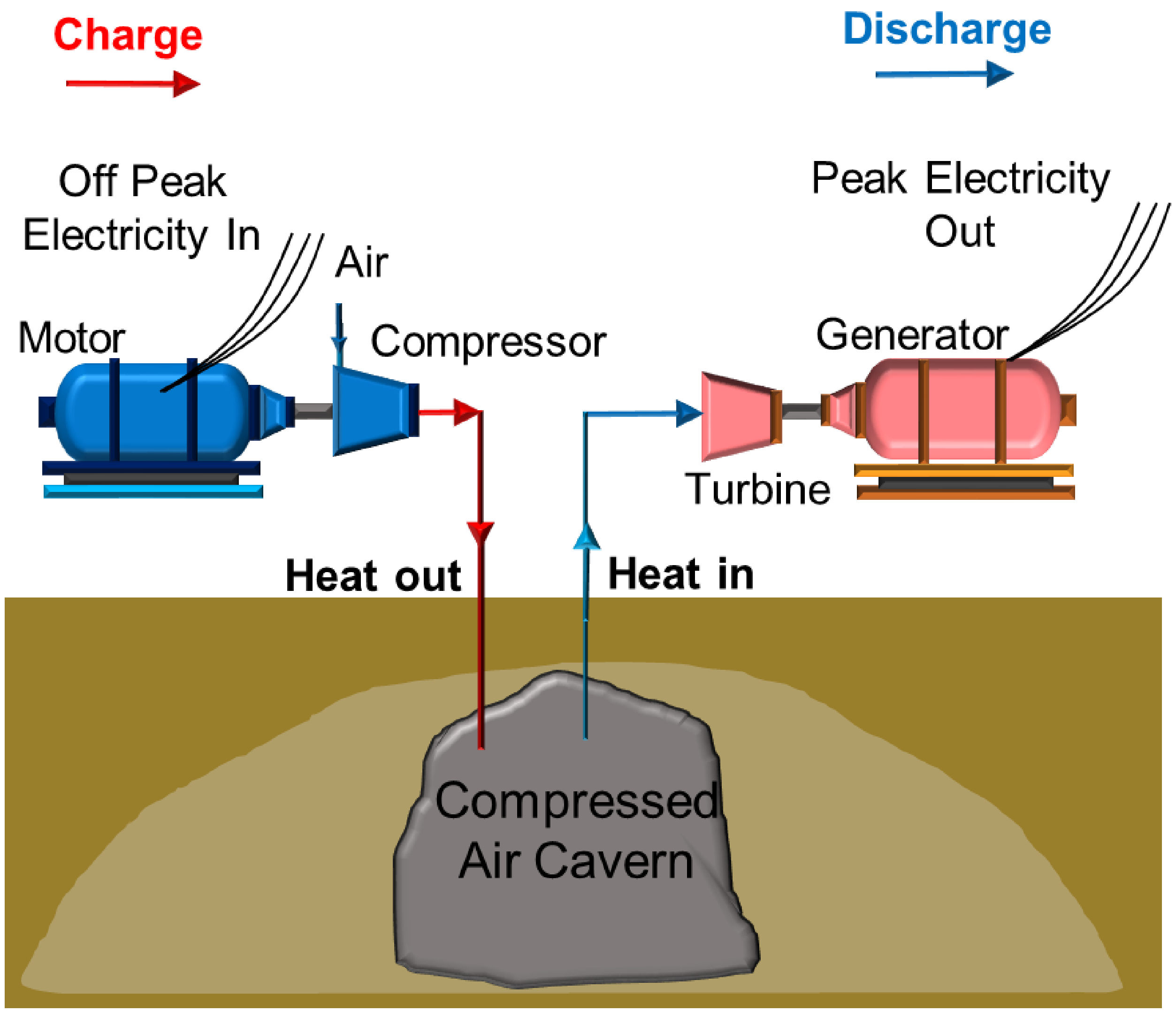
- Department of Energy (DOE) Storage Shot: seeks to deliver 10+ hours of storage within the next 10 years.
- Funding to support 10+ hours of storage is at $1.16 billion
- We lagged behind US!

Average duration of new utility-scale energy storage systems deployed in the U.S.,2013–2021 (hours).



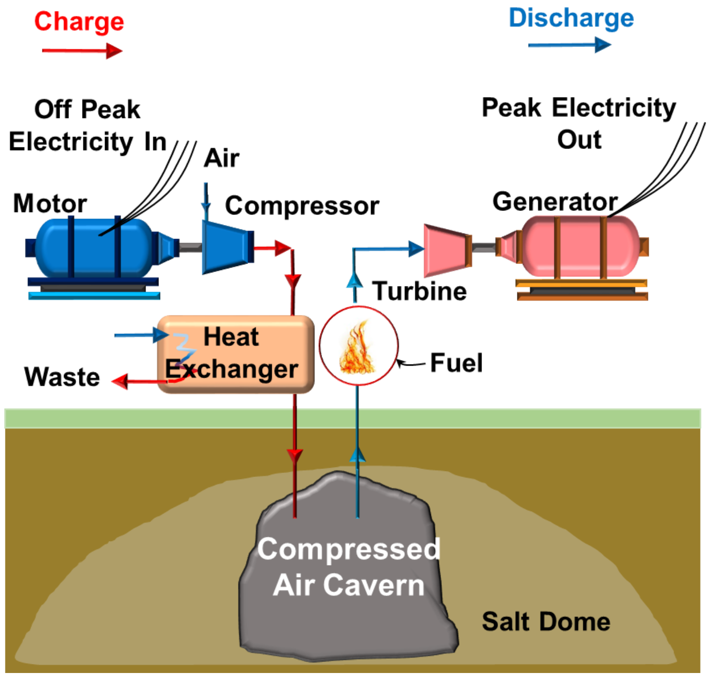
[ref] Twitchell, J., DeSomber, K. and Bhatnagar, D., 2023. Defining long duration energy storage. *Journal of Energy Storage*, *60*, p.105787.

What is Compressed Air Energy Storage (CAES)?



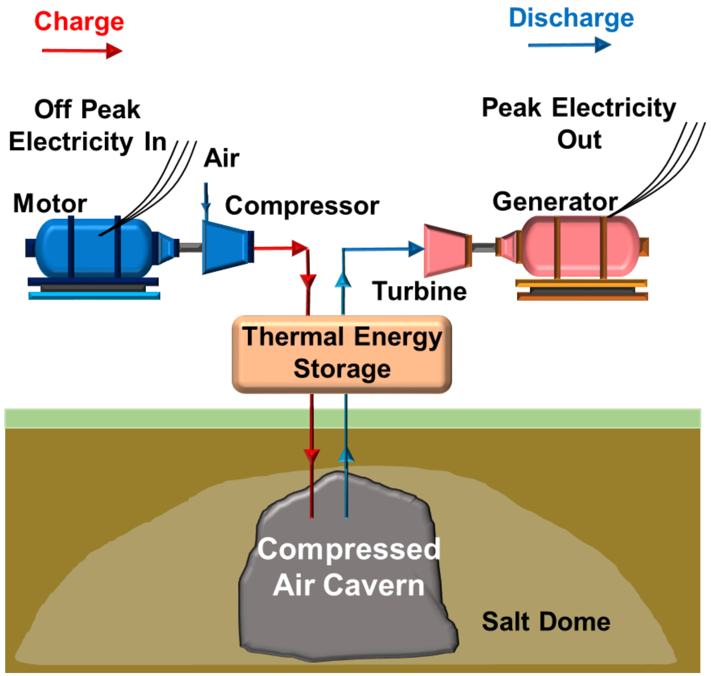
Manage Compression Heat

Diabatic CAES (DCAES)



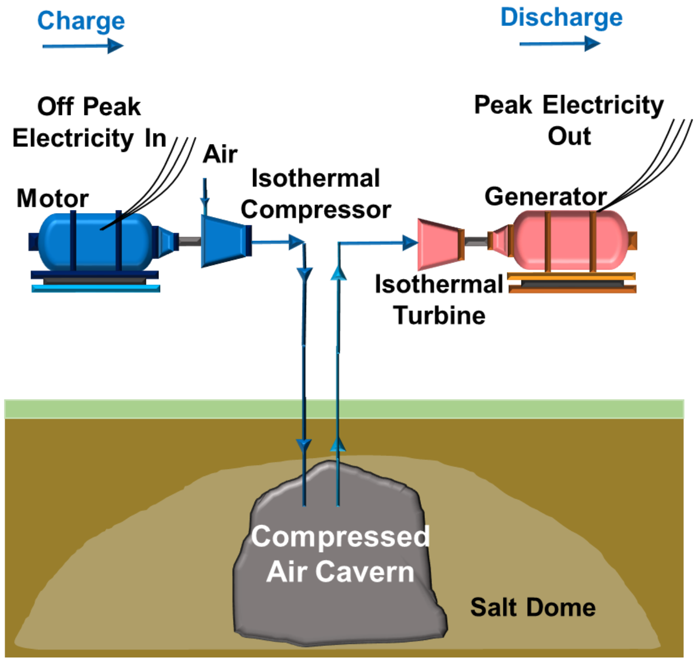
TRL 8: Two Commercial Products (next Slide)

Adiabatic CAES (ACAES)



TRL 3-4: No Commercial Product (several projects failed)

Isothermal CAES (ICAES)



TRL 2-3: No Commercial Product (few trails failed)

TRL: Technology readiness Level

DCAES: the only Commercial Plants

Huntorf Germany (1978).
20-43 bar; 290 MW, 42% efficiency;
Invest: $480/kW

McIntosh USA (1991);
45-74 bar; 110 MW, 54% efficiency;
Invest: $492/kW

Recent CAES projects (failed/on-going)

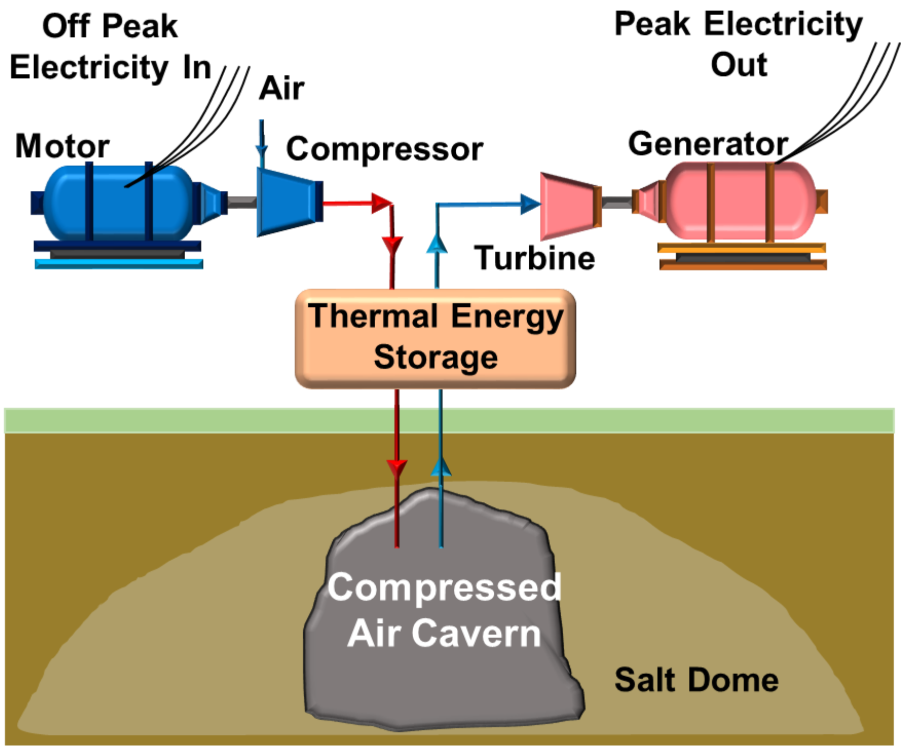
Plant	Performance	Comment	Year
ADELE (Germany)	Claimed 70% efficiency	• ACAES (200 MW) • € 10 million • Design details were not published • No plant built	2010-2018
ALACAES (Switzerland)	Claimed 63-74% efficiency	• ACAES • $5 million • Plant do not have a turbine (compression only)	2015-2018
Lightsail (USA)	Claimed 90% efficiency	• Isothermal CAES • $70 million • No technical data published • No plant built	2008-2018
SustainX (USA)	Claimed 54% efficiency	• Isothermal CAES (1.5 MW) • Cool water spray • $30 million • Failed to produce any pilot plants	2008-2016
TICC 500 (CAS-China)	Proved 23% efficiency	• ACAES (500 kW) • Plant built. Poor performance • Strong foundation for future full-system prototypes	2015
Hydrostor (Canada)	Claimed 50% theoretical efficiency	• ACAES (750 kW) • Commercial plant in 2015, off the coast of Aruba paused • Continues in 2021 to work on isobaric ACAES systems • Very low pressure of 8 bar	2014 - present

[ref] Barbour, E.R., et al. Why is adiabatic compressed air energy storage yet to become a viable energy storage option?. *IScience*, *24*(5), 2021.

Constraints for CAES Development

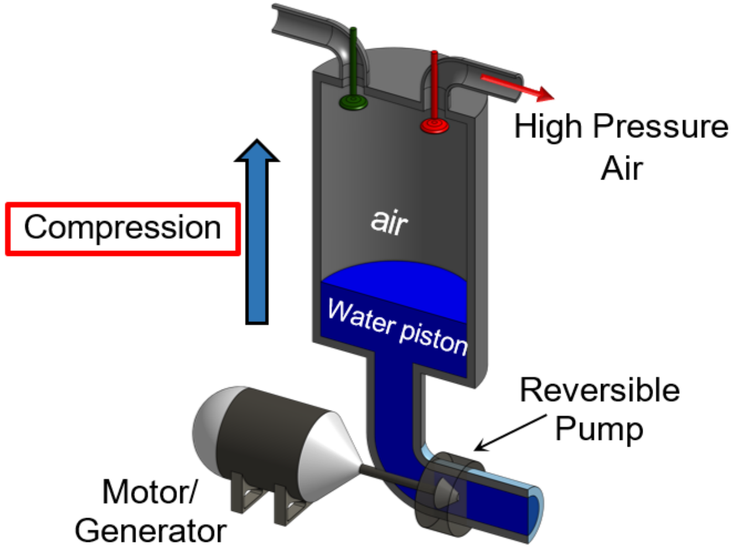
- Geological constraints
  - Salt cavern at depth of ~500 m with volume 230,000 m^3
- High temperature after compression (600 ^oC)
  - Metallurgical constraint on the TES unit
- Low operating pressures and Low Efficiency
  - McIntosh: 46bar; Hydrator: 8bar
- Low efficiency of compressors/turbines

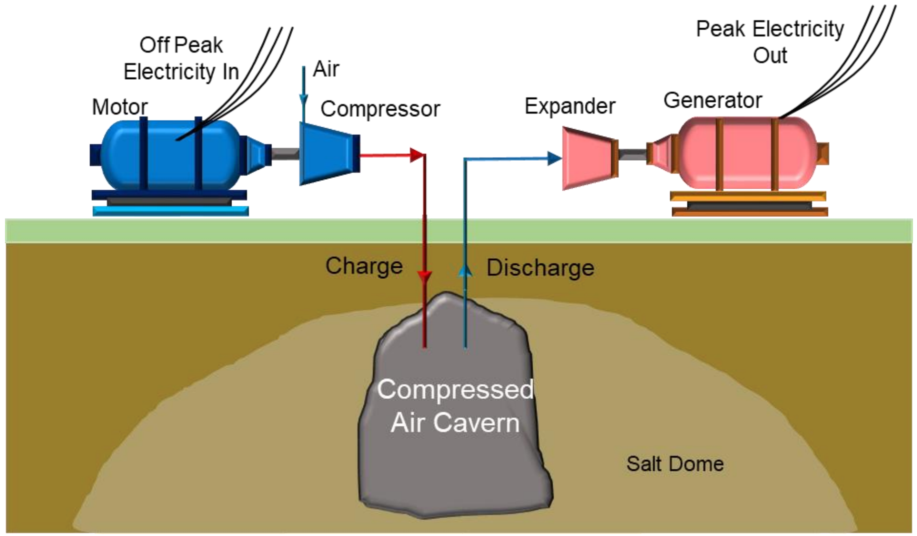
We aim to solve this long-standing problem through developing an over-ground Near-isothermal CAES system with high efficiency compressor/expander.



Water Piston Air Compressor/Expander (WPAC/E)

- Compression/Expansion occurs in one unit. While in conventional system is occurs in two separate devices





Conventional CAES system

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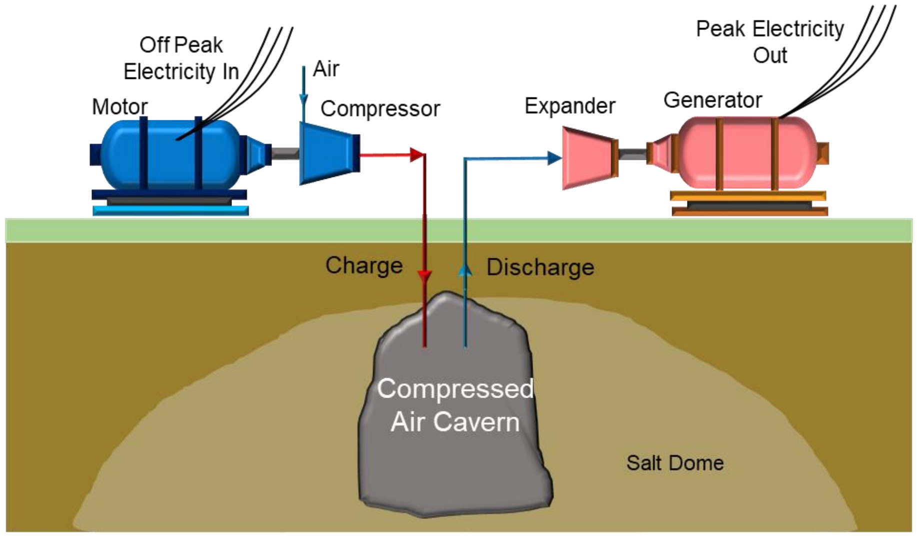
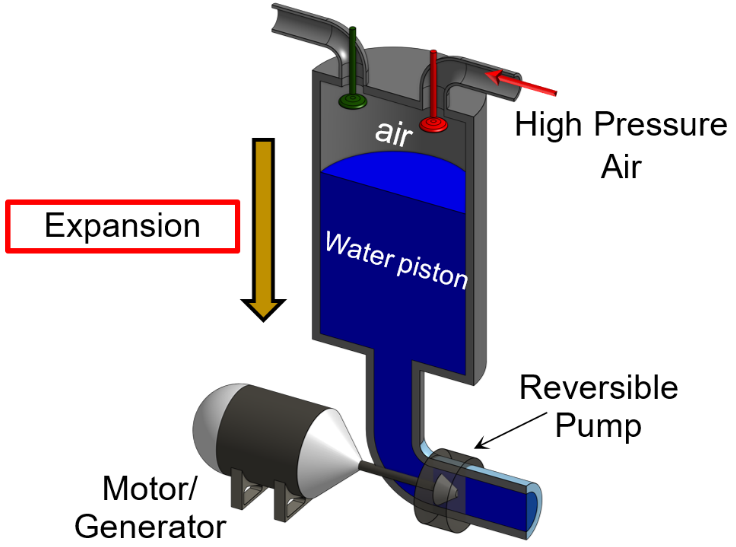
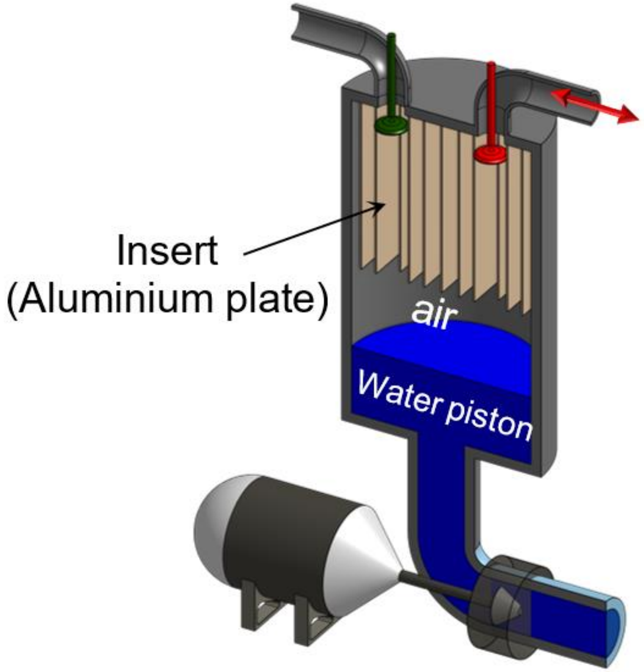


Conventional CAES system

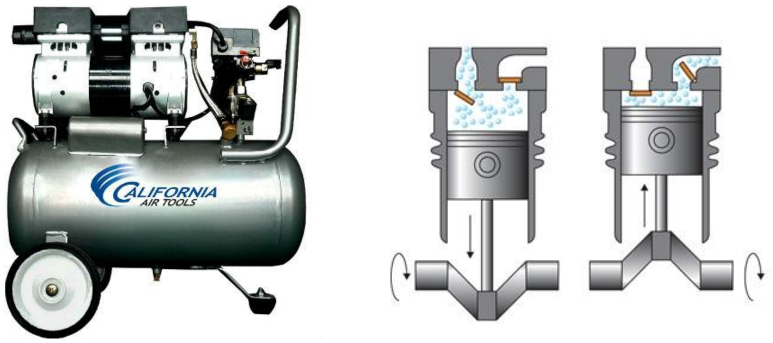


Water Piston Air Compressor/Expander (WPAC/E)

- Compression/Expansion occurs in one unit
- Metal inserts inside cylinder increase heat transfer from/to air
- Near-Isothermal compression/expansion processes
- High efficiency (up to 90%)



Liquid piston compression with plate inserts

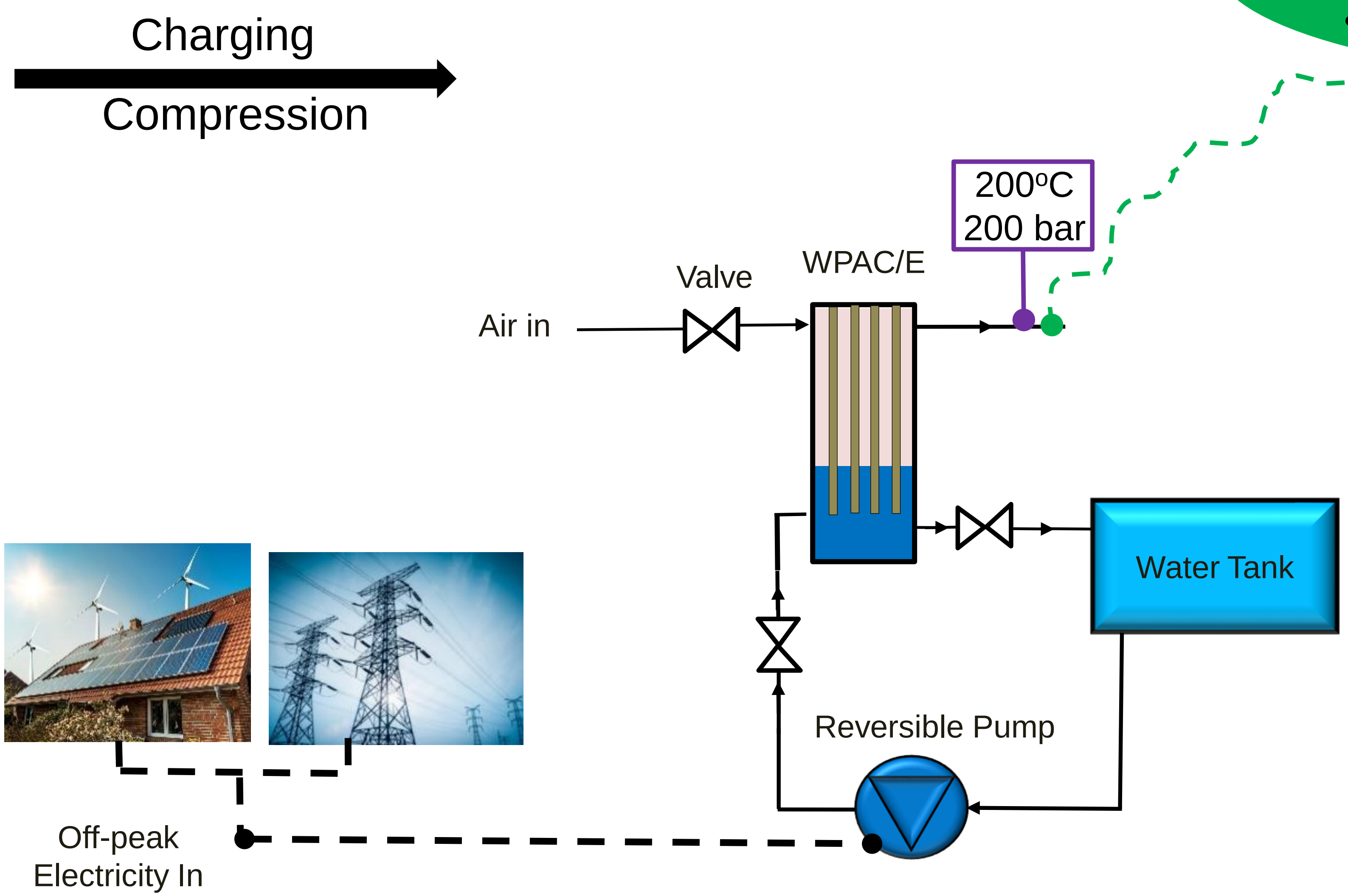


Conventional solid piston compressor

www.rateaircompressors.com

Near-isothermal CAES with WPAC/E (1 bar to 200 bar)

- 475ºC without aluminium plates in the WPAC/E
- Structural challenge for the TES



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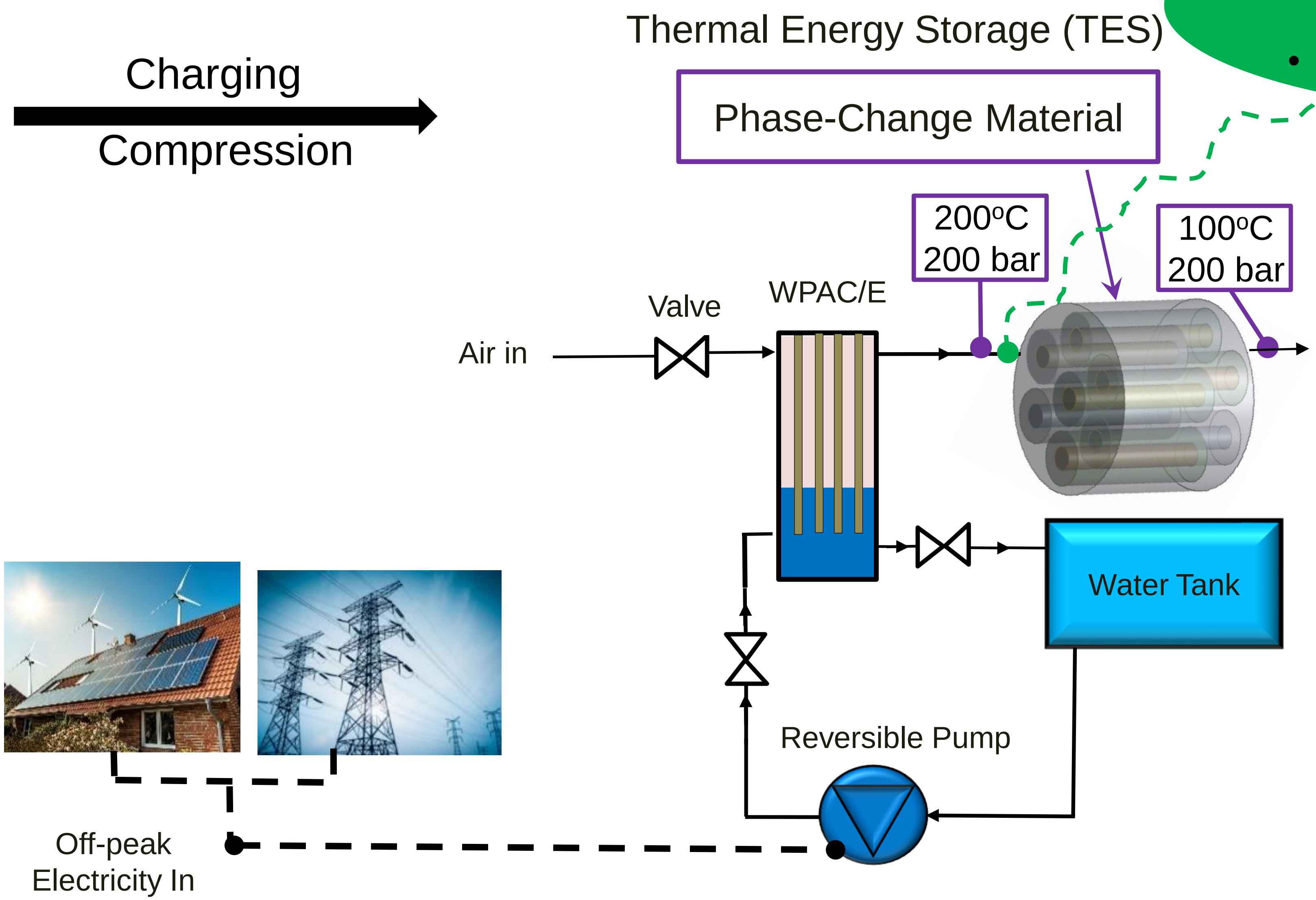
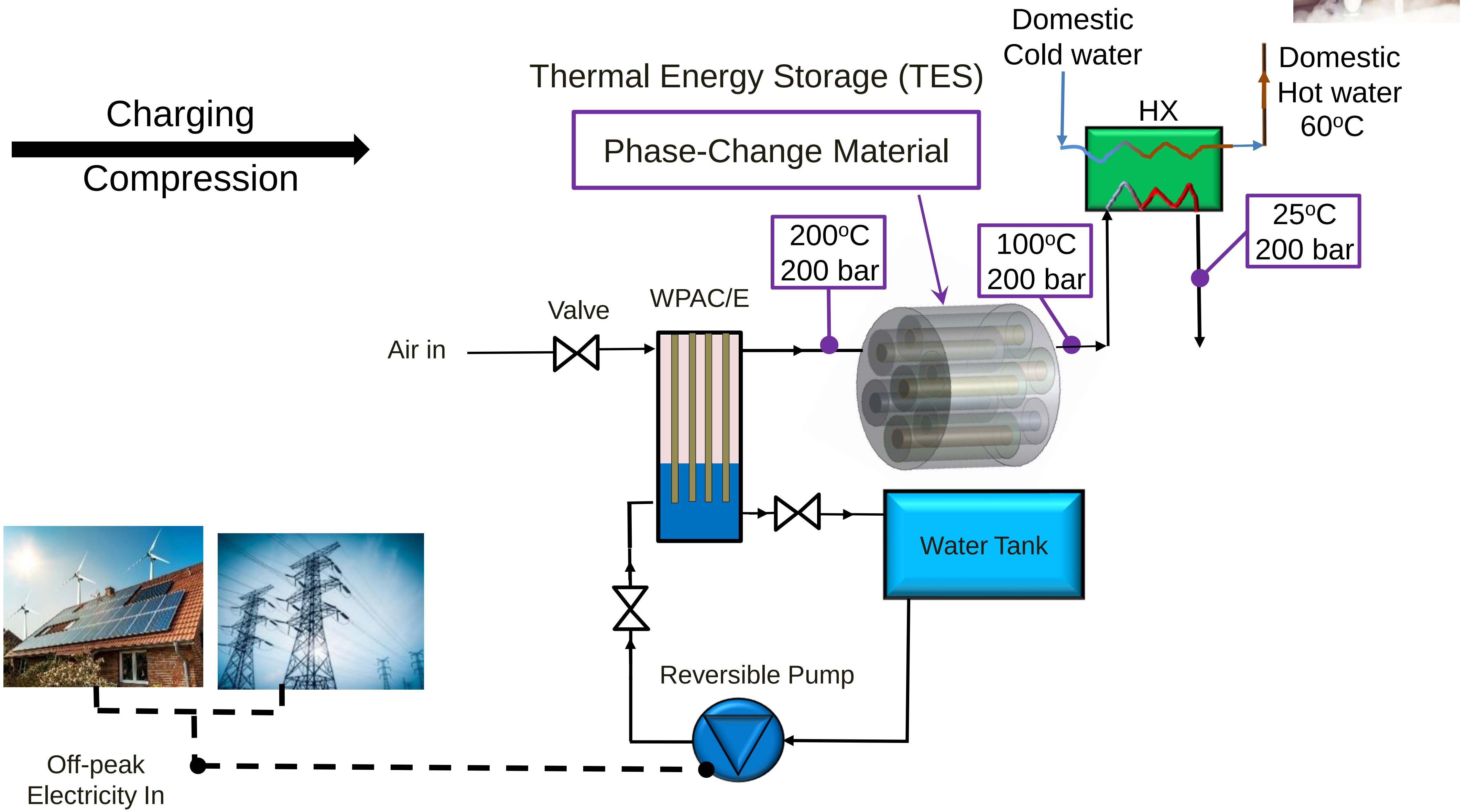
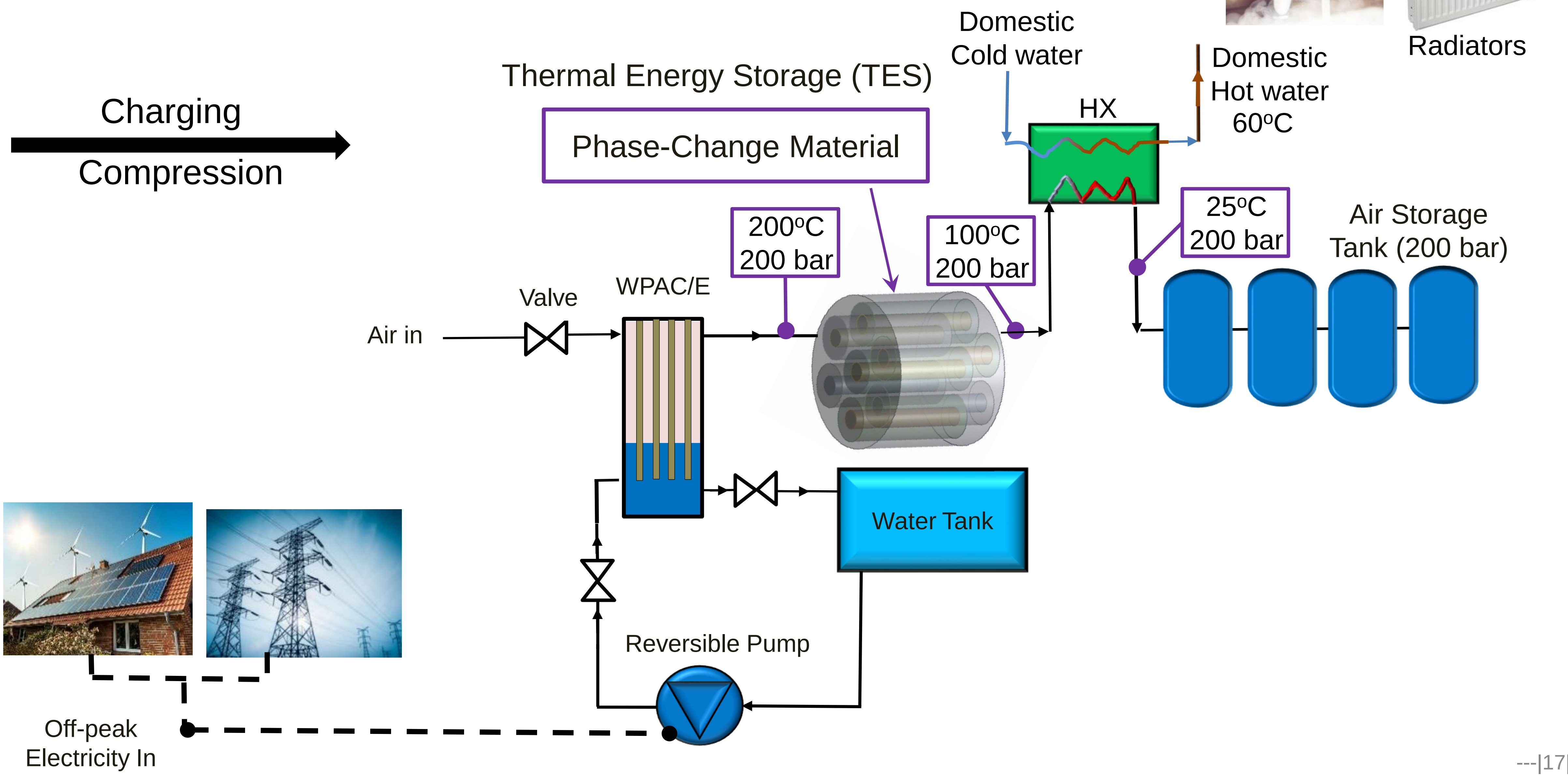


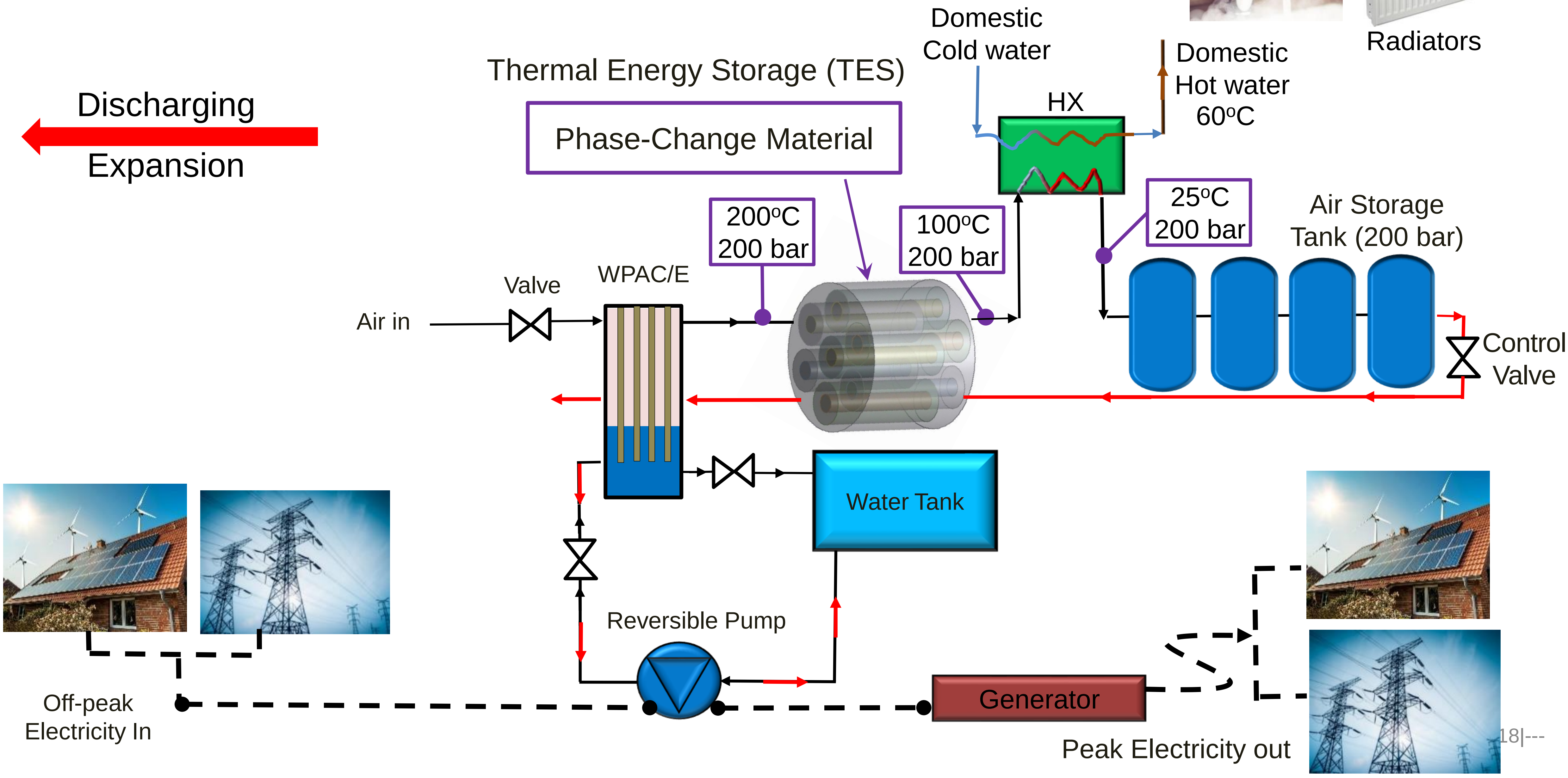
Near-isothermal CAES with WPAC/E (1 bar to 200 bar)



Near-isothermal CAES with WPAC/E (1 bar to 200 bar)

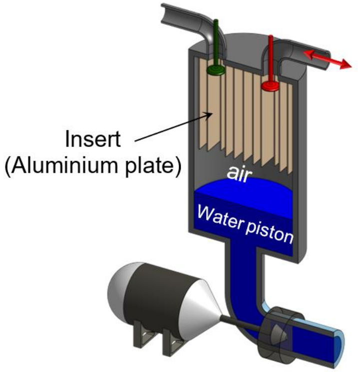


Near-isothermal CAES with WPAC/E (1 bar to 200 bar)

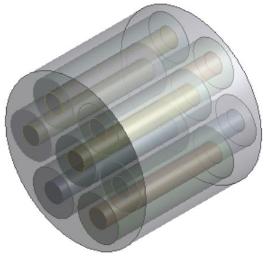


Analysis Procedure

- Design of WPAC/E

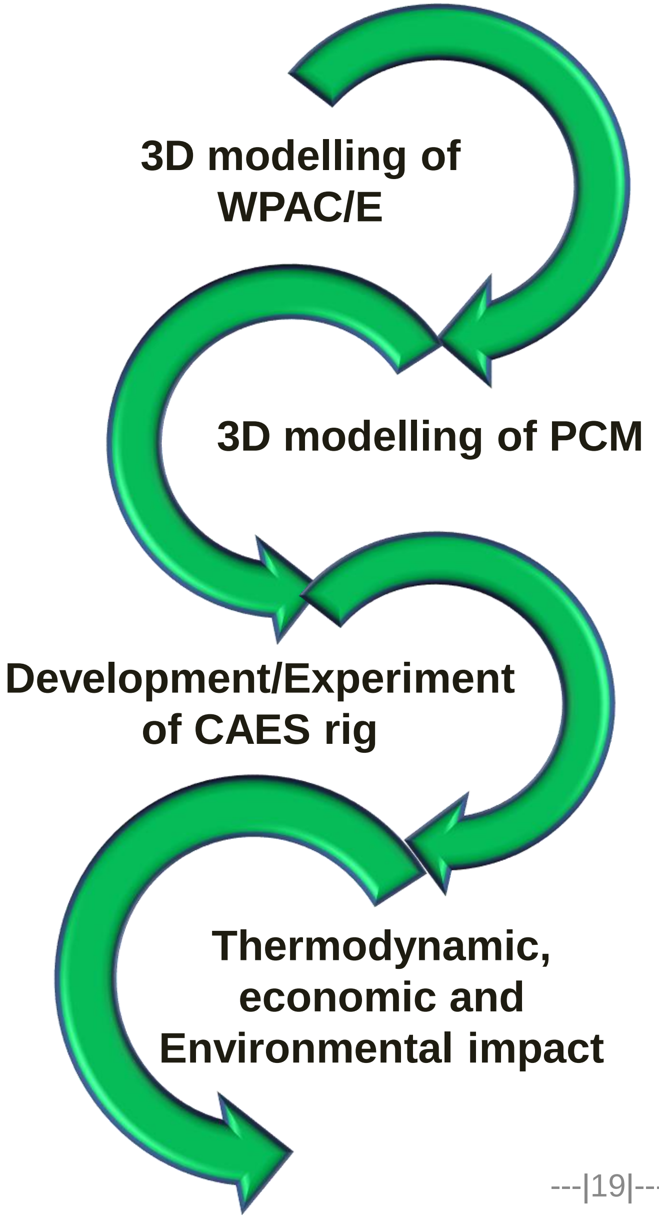


- Design of Thermal Energy Storage (TES) with Phase Change Material (PCM)



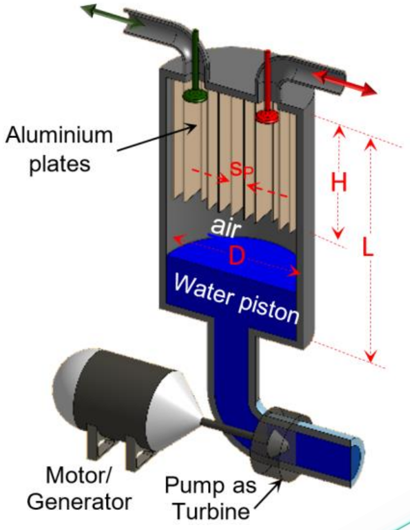
- Development/Experiment of base-case CAES rig

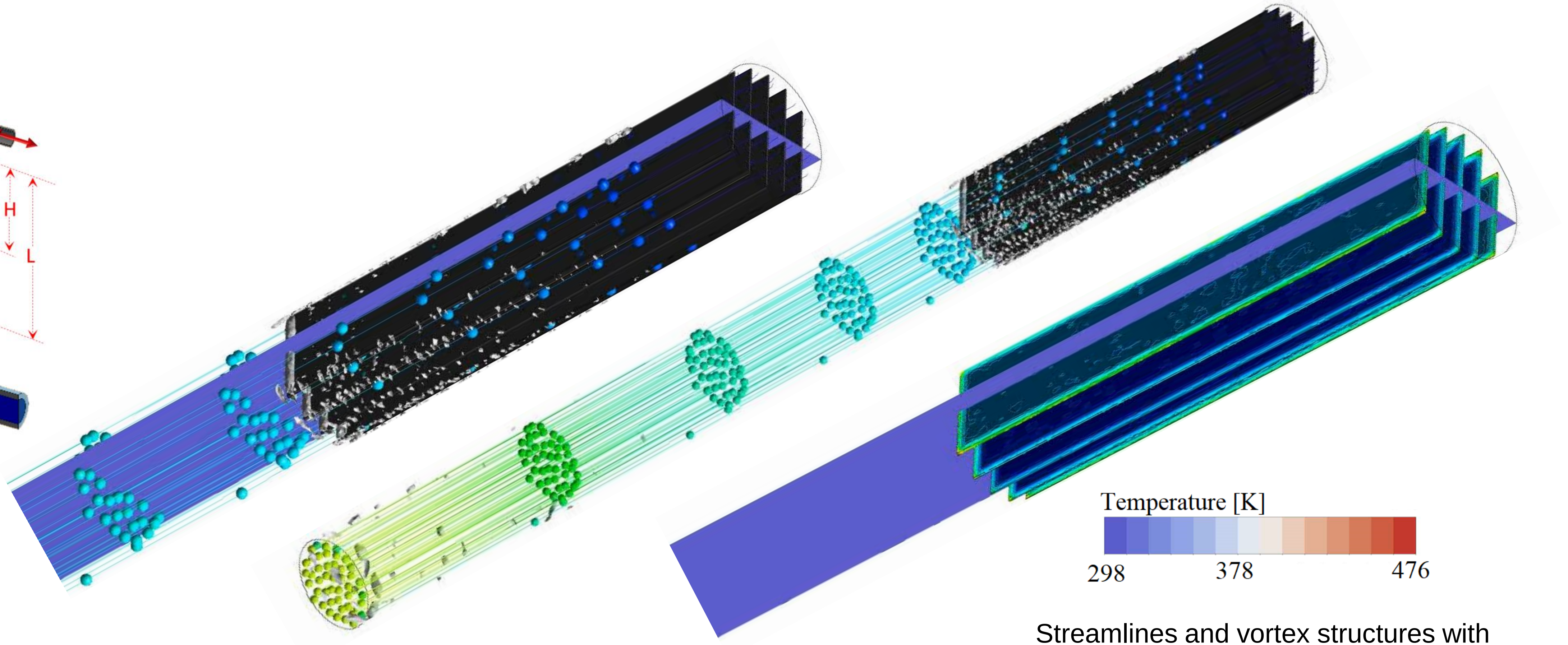
- Thermodynamic, Techno-economic and Environmental Impact



Analysis Procedure

- Design of WPAC/E
  - Modelling of multiphase compressible turbulent flow with conjugate heat transfer



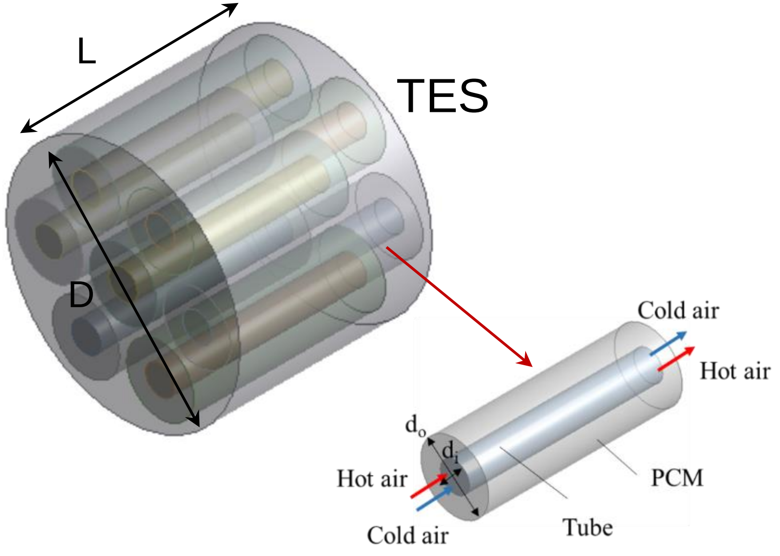


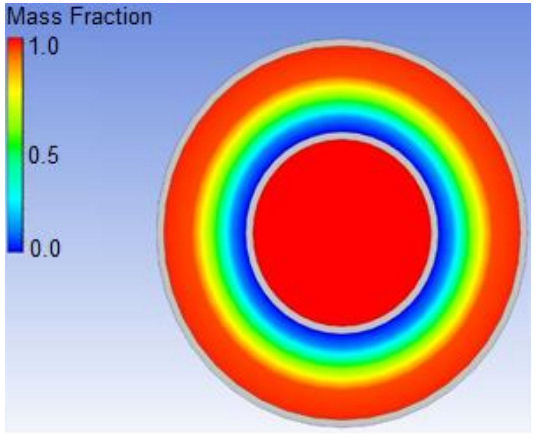
Streamlines and vortex structures with contour of temperature

[1] S. Khaljani, D. Surplus, A. Murphy, P. Sapin, C.N. Markides, Y. Mahmoudi, *Energy Conversion and Management*, 245, p.114536, (2021)

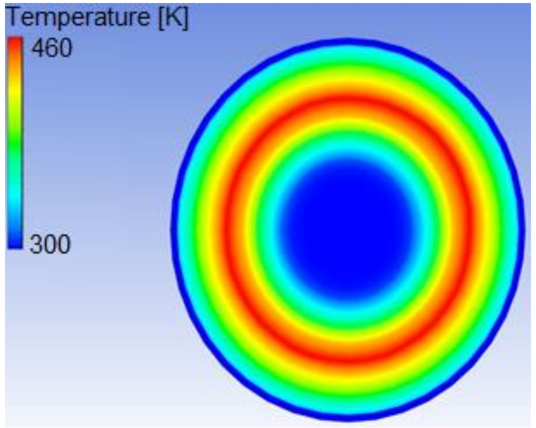
Analysis Procedure

- Design of Thermal Energy Storage
  - Model the Phase-Change Material (PCM)
  - Enthalpy-porosity method for melting/solidification
  - 3-dimentional modelling for turbulent air flow in the pipe





Mass fraction
(Discharge process)

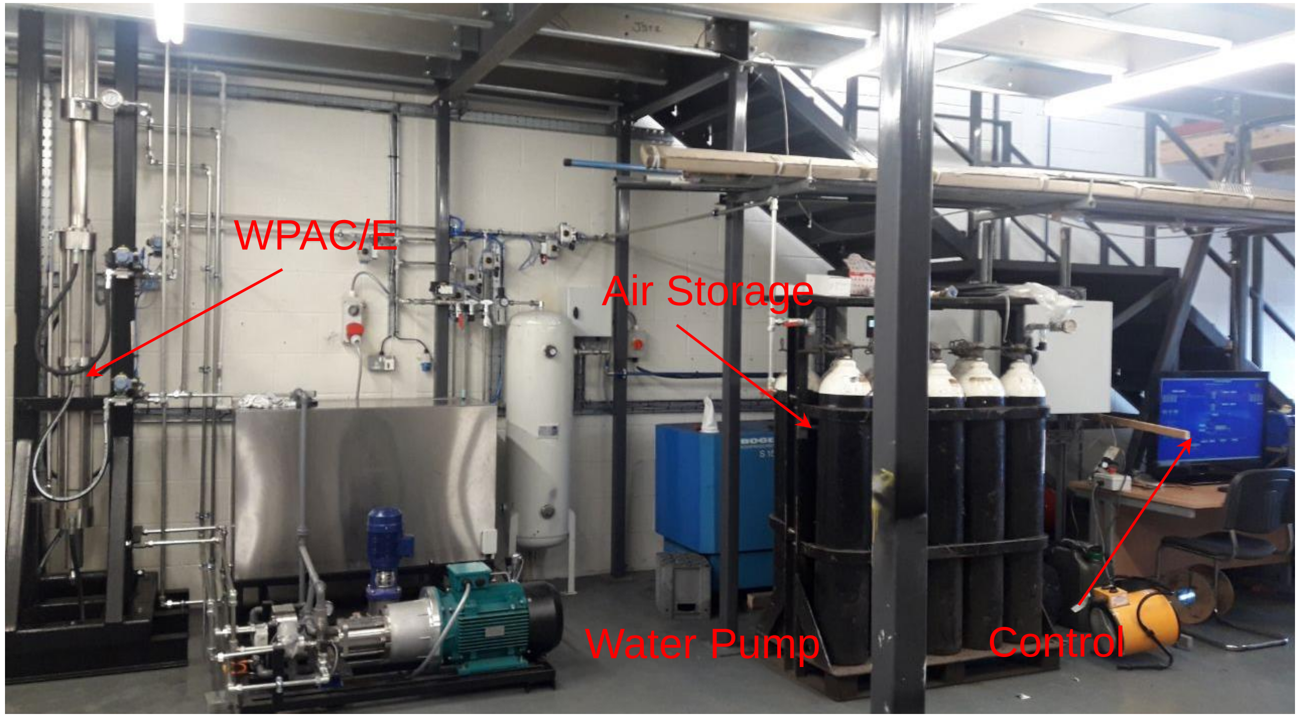


Temperature
(Discharge process)

Analysis Procedure

- Development/Experiment of the CAES system

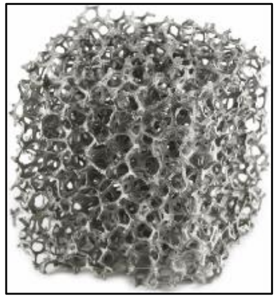
Tested for compression (1 bar to 40 bar) for model validation



parallel plate

Interrupted plate

open cell metal foam



Experimental results on WPAC/E (compression 1bar – 40bar)

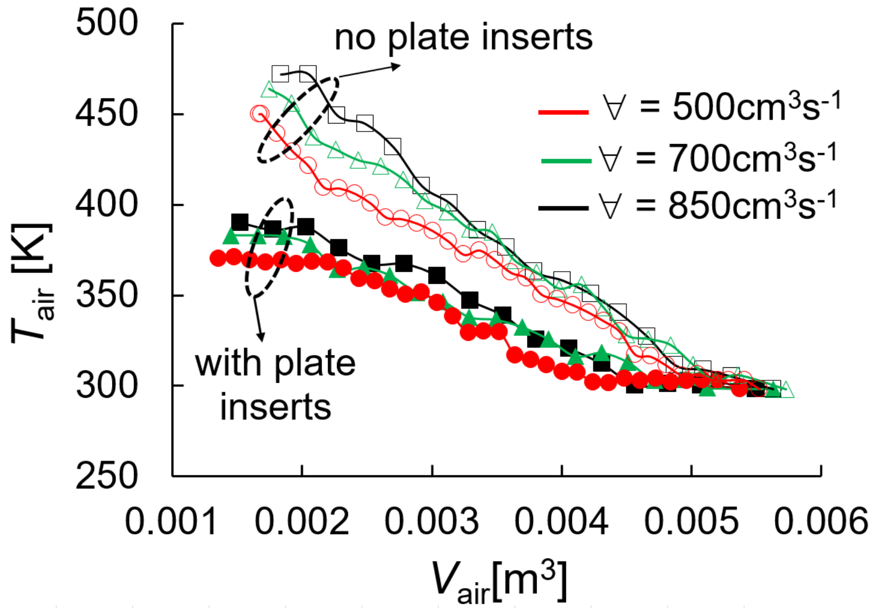
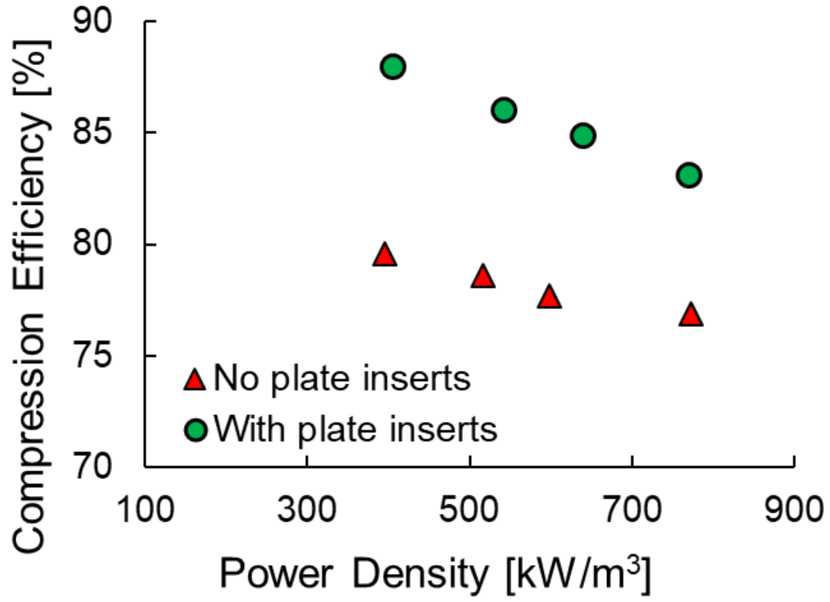
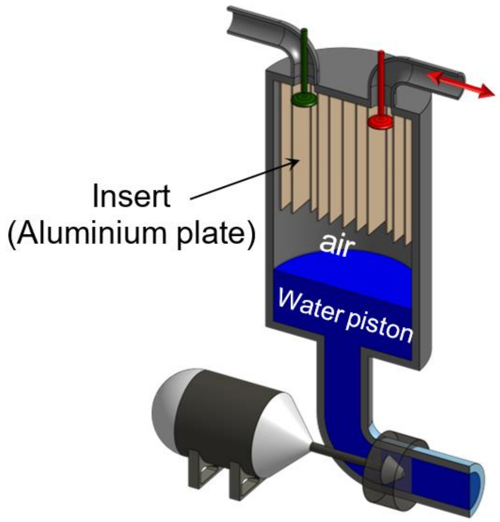


Plate inserts
with $h_P/H = 0.5$



$$\rho_c = \frac{E_{St}}{t_c V_0} \qquad \eta_c = \frac{E_{St}}{W_{in}}$$

E_{St}: Storage energy
W_{in}: Compression work
t_c: Compression time
V_0: Air volume



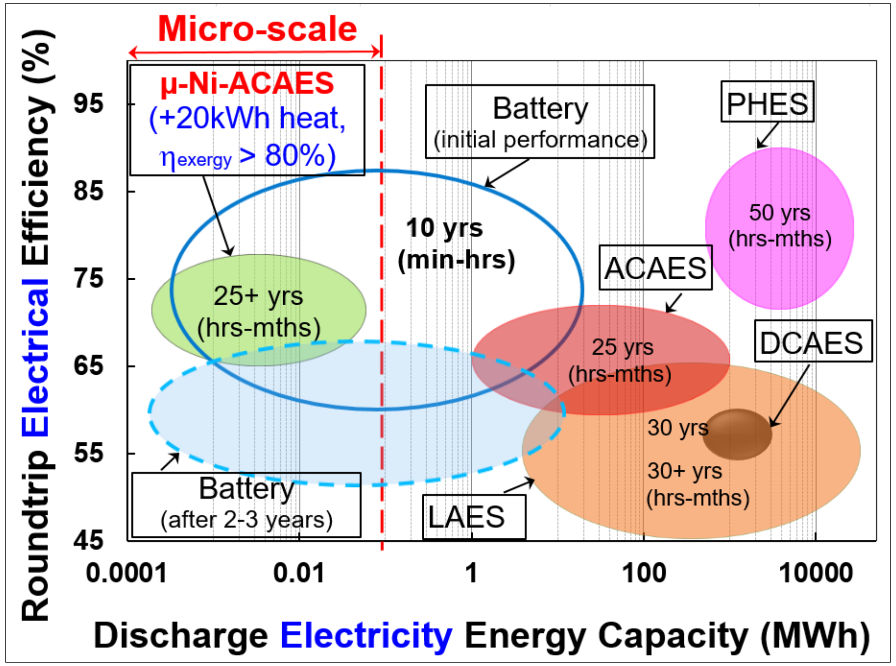
[1] S. Khaljani, A. Vennard, J. Harrison, D. Surplus, A. Murphy, Y. Mahmoudi, *Journal of Energy Storage*, 43, p.103240, (2021).

Thermodynamic model results (CAES full cycle - 1 bar to 200 bar)

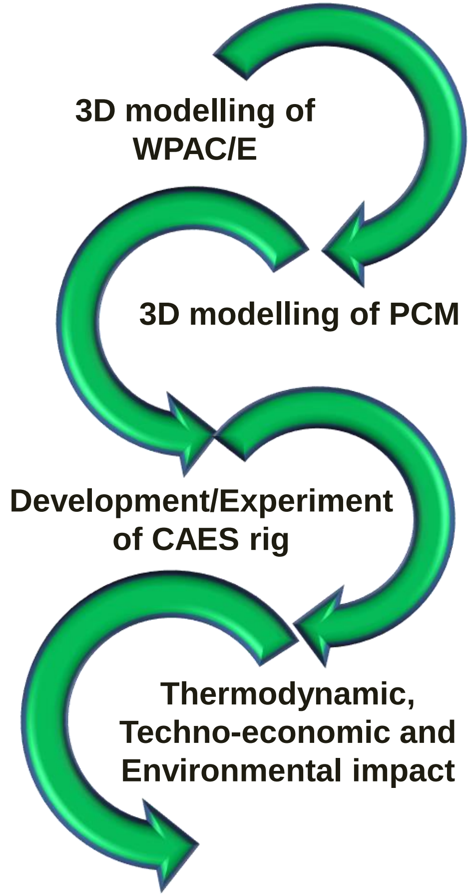
Performance indicators

Required Electricity	27 kWh
Generated Electricity	20 kWh
Electrical efficiency	75%
Generated Heat	18 kWh

Exergy efficiency	85%
Discharge Time	7 h
Charge Time	3.5 h



Discharge capacity and efficiency for different storage technologies



Economic/Environmental indicators

Investment cost	$15,000
Annual cost/maintenance	$700
Annual income	$2,650

Lifetime	25+ years
Dynamic payback period (with incentives)	7.5 years
Dynamic payback period (No incentives)	10 years
CO_2 saving c/gas	4 Tonnes/year

- Electricity Smart Export Guarantee (SEG): 5.5 p/kWh
- Renewable Heat Incentive (RHI): 21 p/kW incentives

[1] S. Khaljani, D. Surplus, A. Murphy, P. Sapin, C.N. Markides, Y. Mahmoudi, *Energy Conversion and Management*, 245, p.114536, (2021)

THANK YOU FOR LISTENING

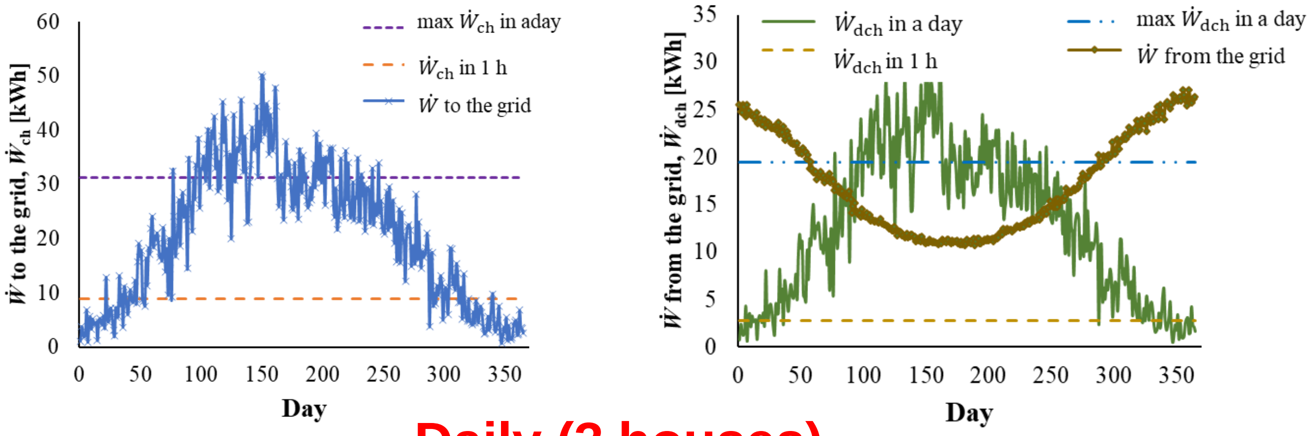
Solar PV integrated with CAES (1 cycle/day)

- 3-bed Semi detached house with 4 occupants
- 16 PV panels on the roof

Overall

Electricity	
Household Electricity Demand	3812 kWh
Electricity Sent to Grid	2509 kWh
Electricity Taken from the Grid	2097 kWh
CAES Charge Energy	9855 kWh
CAES Discharge Energy	7300 kWh
No. of Houses to Charge CAES	~4.0
No. of Houses CAES can Supply	~ 3.5
CO_2 Saving c/ to Gas (2×0.18 kg/kWh)	2560 kg

Hot Water	
Household Demand	2549 kWh
CAES Cycle Heat	18 kWh
CAES Annual Heat	6570 kWh
No. of Houses CAES Heat Supply	~2.5
CO_2 Saving c/gas Heating (0.18 kg/kWh)	1280 kg

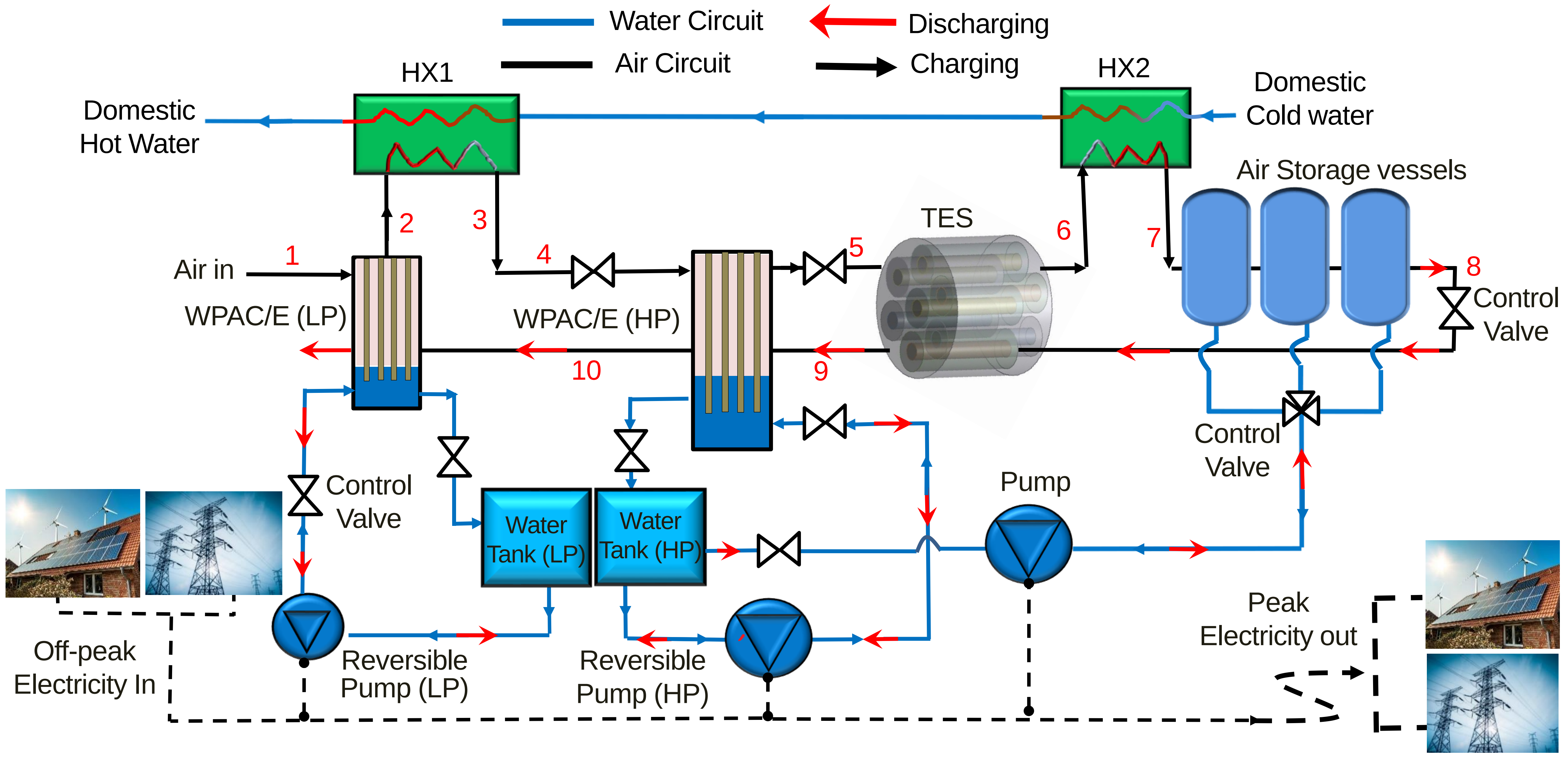


Daily (3 houses)

4.0 houses equipped with PV panels

- 3.5 houses supported for electricity demand
- 2.5 houses supported for hot water demand
- 3.8 tonnes/year of CO_2 saving by CAES only
- 6.6 tonnes/year of CO_2 saving by PV and CAES

Ref for emissions factors: BEIS: 2019 GOVERNMENT GREENHOUSE GAS CONVERSION FACTORS FOR COMPANY REPORTING, Methodology Paper for Emission Factors Final Report


Water Circuit
Air Circuit
Discharging
Charging
HX1
HX2
Domestic Hot Water
Domestic Cold water
Air Storage vessels
TES
1
2
3
4
5
6
7
8
9
10
Air in
WPAC/E (LP)
WPAC/E (HP)
Control Valve
Control Valve
Control Valve
Water Tank (LP)
Water Tank (HP)
Pump
Reversible Pump (LP)
Reversible Pump (HP)
Off-peak Electricity In
Peak Electricity out

CAES-WPAC/E vs. Battery

PowerVault 3: The only commercial 20 kWh Solar Battery (April 2018)

- Usable capacity: 19 kWh
- Lithium-polymer (Li-MNC)
- No data on lifetime but warranty of 10 years
- ~ £15,000
- ~ £30,000 battery cost for 20 years lifetime of Solar PVs
- Round trip Efficiency ~ 90%
- Efficiency and capacity drops (60%) over time and with temperature
- Payback period: longer than battery lifetime

- 2050mm×980mm×250mm
- 330 kg

CAES-WPAC/E system

- ~ £13,000 ($15,000)
- 25+ years lifetime
- Produce both electricity (20 kWh) and Heat (18 kWh)
- Round trip Electrical Efficiency ~ 75%
- Combined Heat and Electrical (Exergy efficiency): 85%
- Payback period: 7.5 years with incentives and 10 years without incentives

[1] https://www.solarguide.co.uk/solar-batteries/powervault-g200#/
[2] https://electriccarhome.co.uk/battery-storage/powervault/