WEDNESDAY, NOVEMBER 17, 2021 11:00 - 11:30 AM

ENERGY STORAGE USING AN ADVANCED CAES APPROACH

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- **1 CAES**
  State of the Art

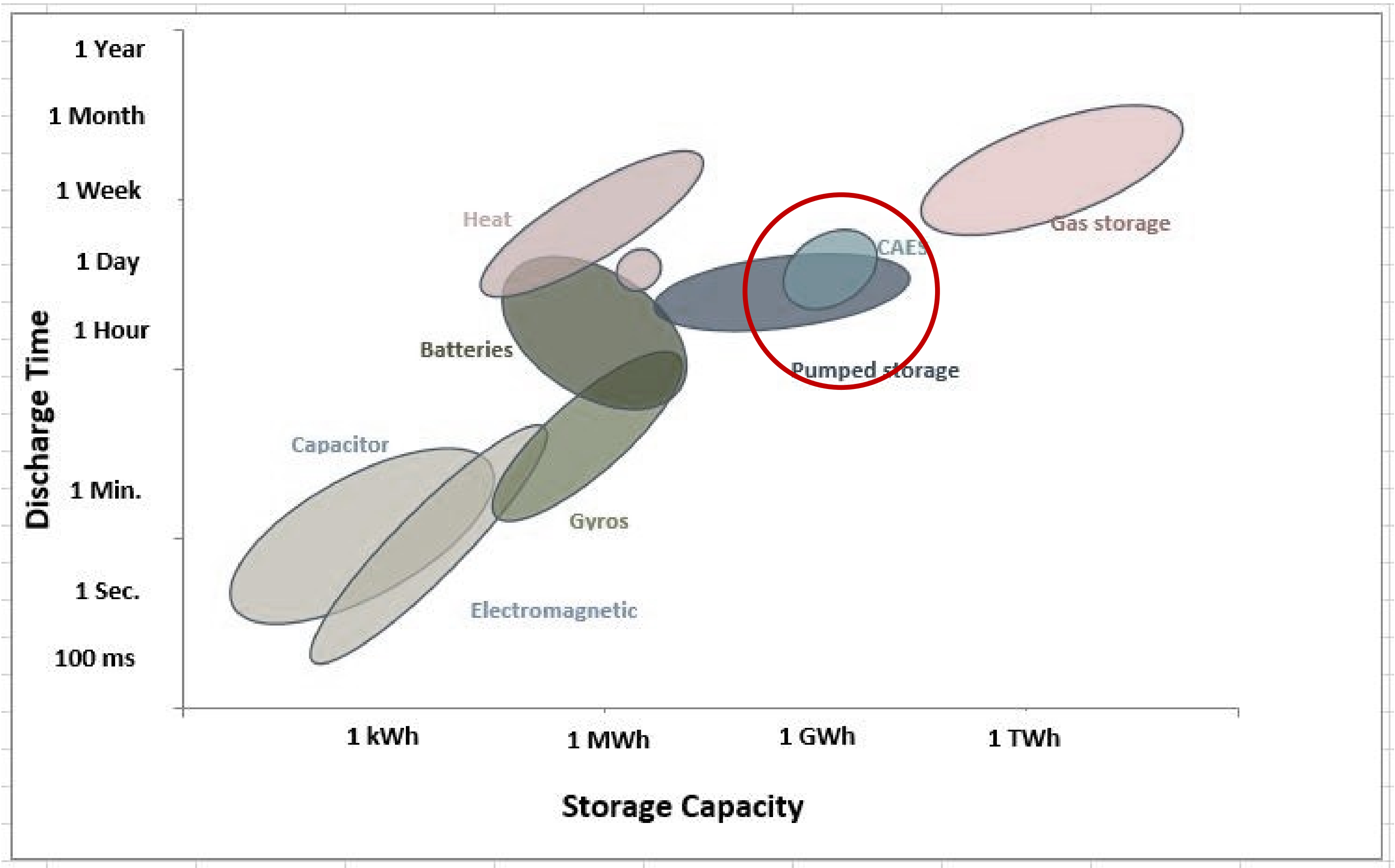
Energy Storage by Compression of Gases

- Compressed air energy storage (CAES) is a way to store massive amounts of renewable excess energy by compressing air or any other gas at very high pressures and storing the air or gas in huge underground caverns for later use, producing electricity by expansion.

CAES - Compressed Air Energy Storage

- **CAES** seems to be simple but is dominated by severe physical and technical constraints.

Energy Storage Options

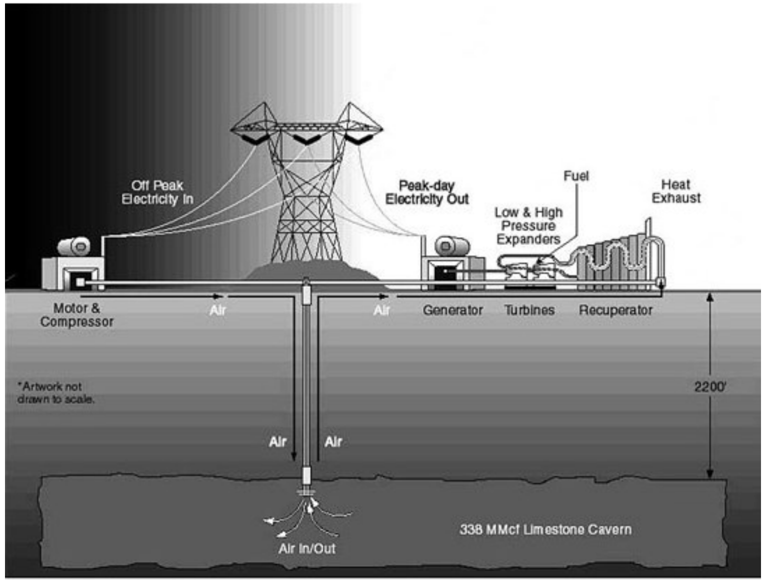


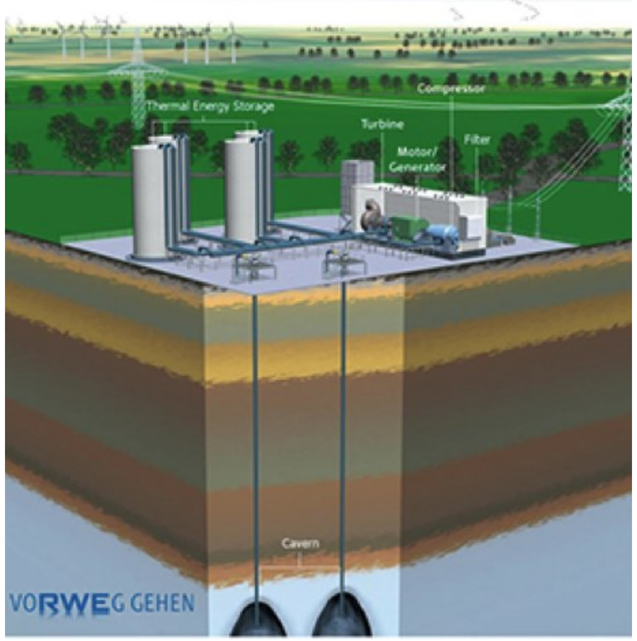
Compressed **A**ir **E**nergy **S**torage has a similar capacity as **P**umped **H**ydro **S**torage.

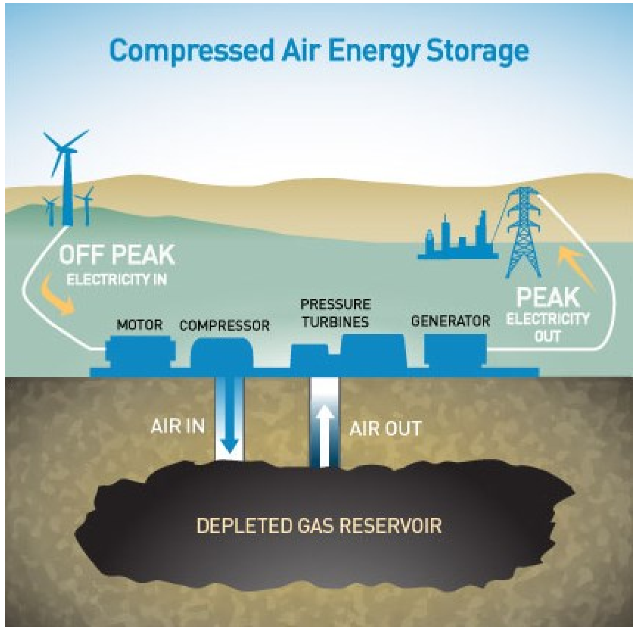
Only **U**nderground **G**as **S**torage has a higher Storage Capacity. UGS however is not directly applicable for electricity storage.

Compressed Air Energy Storage - CAES

Searching the Internet for CAES gives results like these:



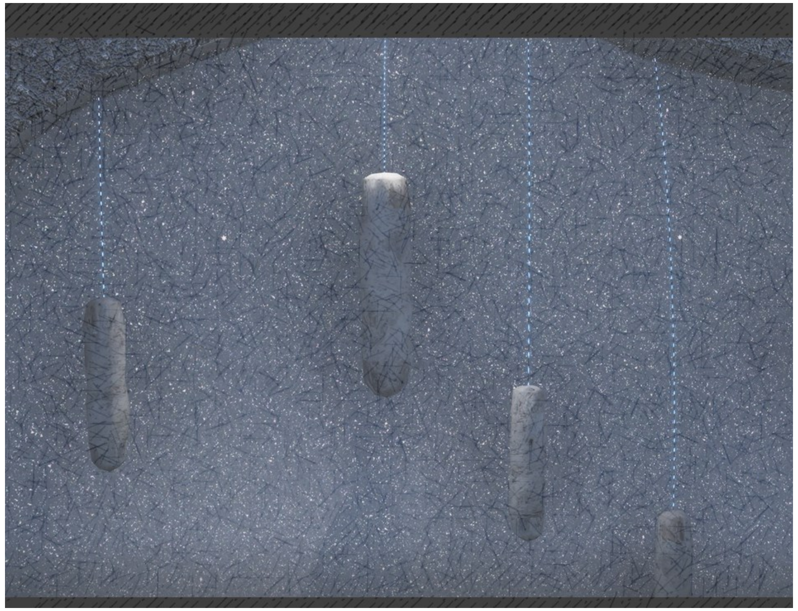




CAES is possible in Rock Caverns, Salt Caverns or depleted Gas Reservoirs.
In a smaller scale in buried pipes on the surface.

CAES in Salt Caverns

Small surface footprint.



Huge storage capacity.

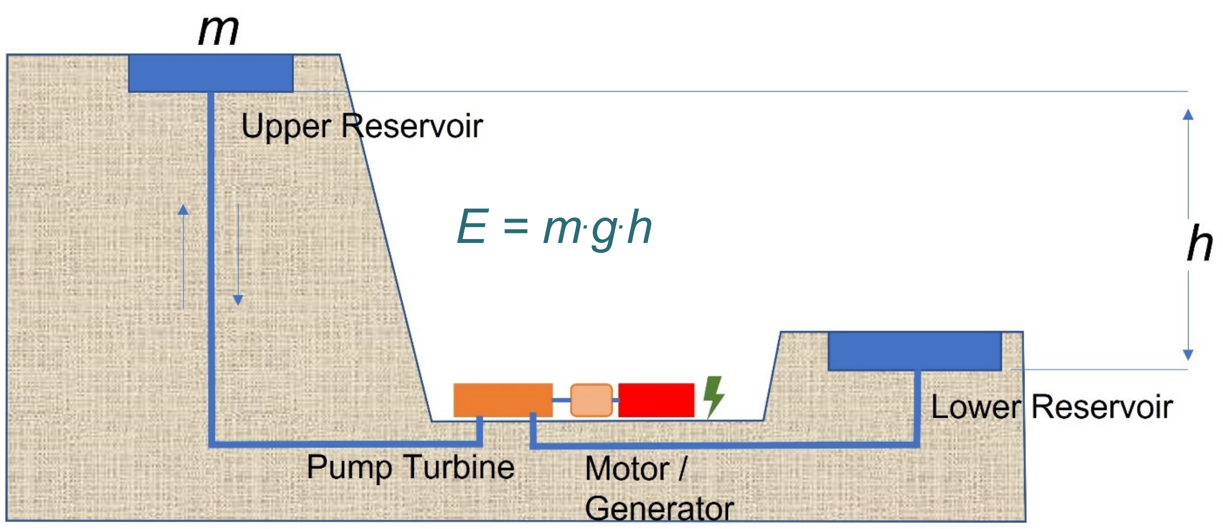
Summary State of the Art

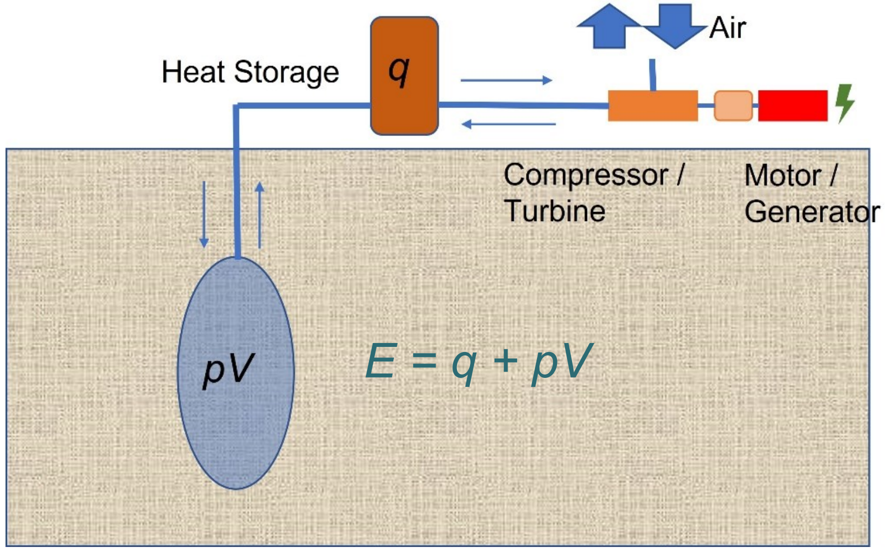
- Pumped Hydro Storage is a proven technology to store large amounts of energy, however it has a large surface consumption and needs height differences in mountainous areas.

- CAES can store the similar amount of energy but shows some unsolved deficiencies:
  - Heat is produced during compression and temperatures of more than 500 °C are reached.
  - This heat should be stored and added during expansion, however this is not possible in storage volumes like underground caverns.
  - The heat can be added at the surface but then expansion is limited in the caverns by geomechanical constraints. The gas in the caverns will cool down which may cause stability issues.
  - This reduces the efficiency of CAES.

- **2 Ideas and technical concepts to enhance CAES**

Stored Energy





Stored Energy

$$m \cdot g \cdot h \quad = \quad V \cdot \rho \cdot g \cdot h \quad = \quad p \cdot V$$

m: mass, *g*: gravity acceleration, *h*: height difference, *V*: volume, *ρ*: density, *V*: volume, *p*: pressure

Compression of a Gas

The 1st law of thermodynamics describes the conservation of energy and the equivalence of work and heat. The internal energy of a gas is the sum of work and heat.

$$\Delta U = \Delta w + \Delta q$$

The Equation of State for a perfect gas is:

$$pV = nRT$$

work *heat*

If *pV* is changed and no heat is transferred (adiabatic conditions) also the temperature must change.

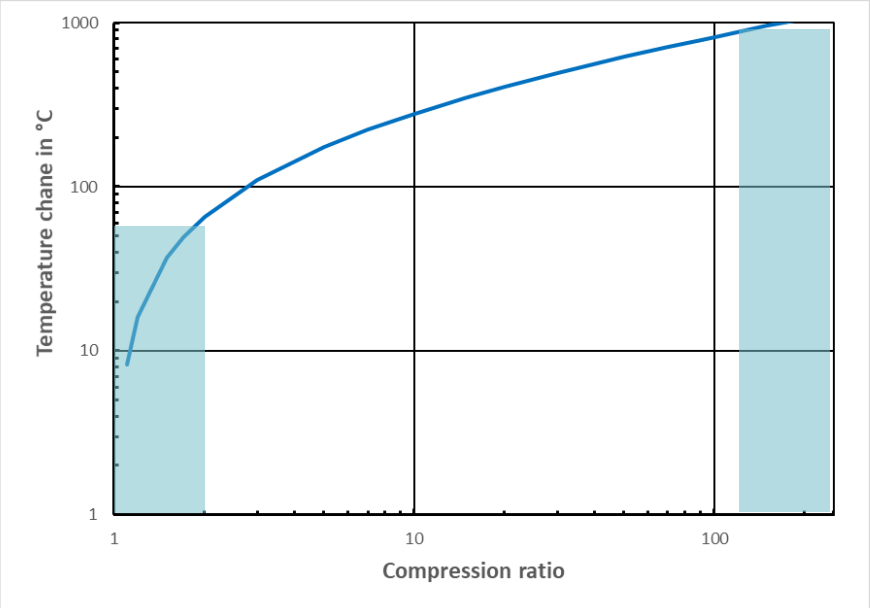
$$T_2 = T_1 \left[\frac{p_2}{p_1}\right]^{\frac{(\kappa-1)}{\kappa}}$$

The temperature change depends on the compression ratio.

p: pressure, *V*: volume, *T*: absolute temperature, *n*: moles, *R*: the gas constant, κ: c_p/c_v, c_p, c_v: heat capacities at constant pressure and constant volume

Heat production due to compression - a major handicap of CAES

- When compressing a gas heat is produced according to the 1st Law of Thermodynamics and the temperature rises respectively.
- This influences the efficiency of CAES!
- Temperature change is directly dependent on the compression ratio.
- At compression ratios of below 2 temperature changes remain in the range of between 10 to 20 °C .
- In conventional CAES the compression ratio is in excess of 100 and the temperatures are in excess of 500 °C (e.g. ADELE) which cause massive heat control issues .



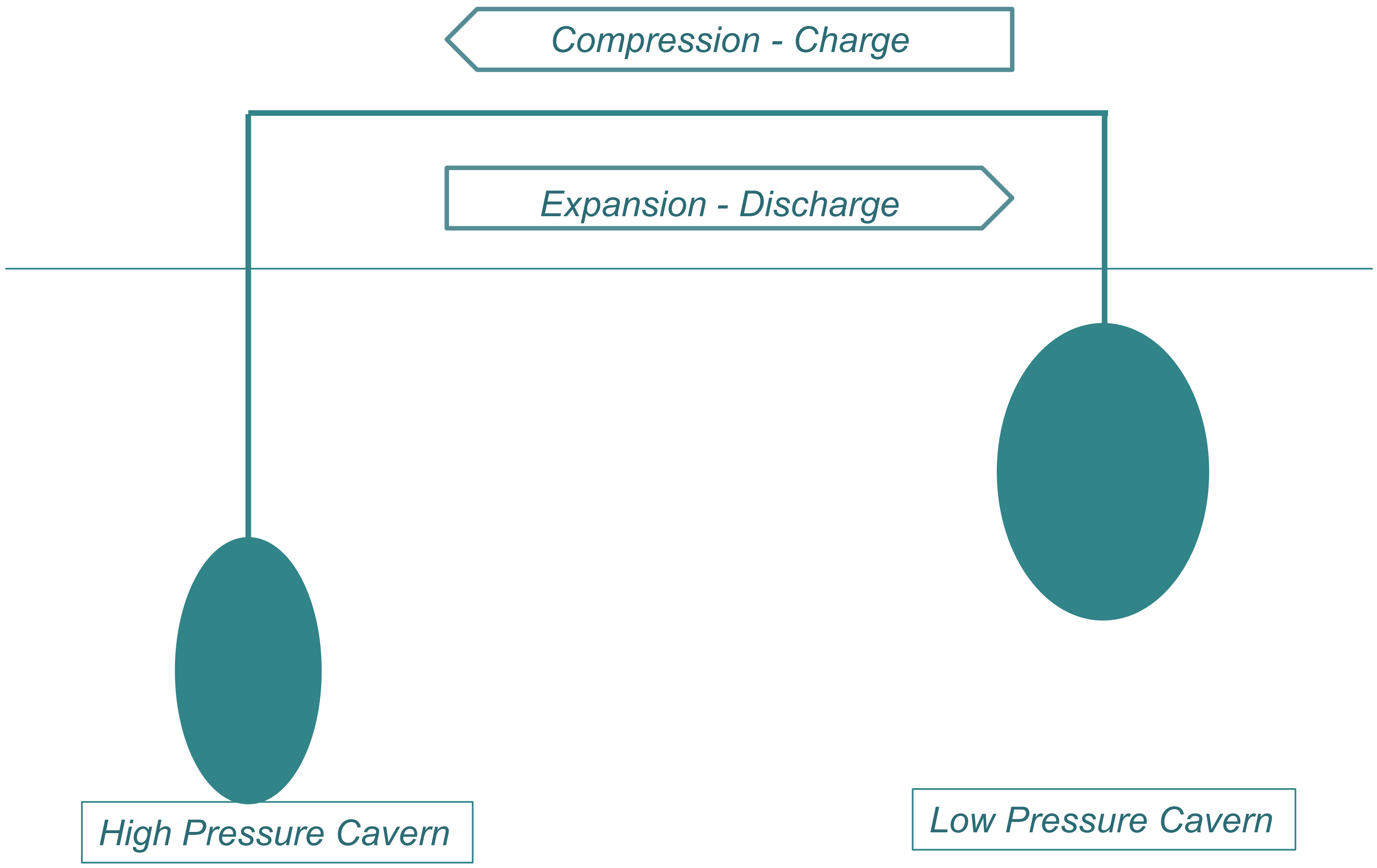
The efficiency of a compression / expansion process is given by the temperature ratio:
$\eta = T_1/T_2$

Conventional CAES	$\eta = 300/750 = 0.4$
erneo	$\eta = 300/320 = 0.94$

Approach erneo

- The production of heat has to be minimized.
- The energy stored in compressed gas (*pV*) should be maximized.
- To achieve this a small compression ratio and a large *pV* is necessary.
- If the process is run e.g. between 100 and 250 bar, a compression ratio of 2.5 achieved and the stored work is the same as if the gas was compressed from atmospheric pressure to 150 bar.
- This requires a second storage volume.

Approach erneo



Approach erneo

What is new?

- In conventional CAES gas expands from 150 bar to atmospheric pressure. This requires heat storage at temperatures of ~ 500 °C and above.

- In the erneo process the storage of energy is in a closed system of 2 storage volumes. Compression and expansion is then e.g. between 100 and 250 bar.

erneo’s Advantage

- „Moderate“ wear of caverns and wells
  - Temperature changes in caverns app. 10 – 20 °C
  - Pressure changes, depending on operation mode between 20 – 40 bar / d.
- No restriction e.g. in depth for the layout of caverns.
- Can be realized in existing caverns or natural gas storage facilities.
- Heat storage at low temperatures between 30 – 90 °C. Operation without heat storage is possible.
- Efficiency between 70 and 90 % depending on the mode of operation.

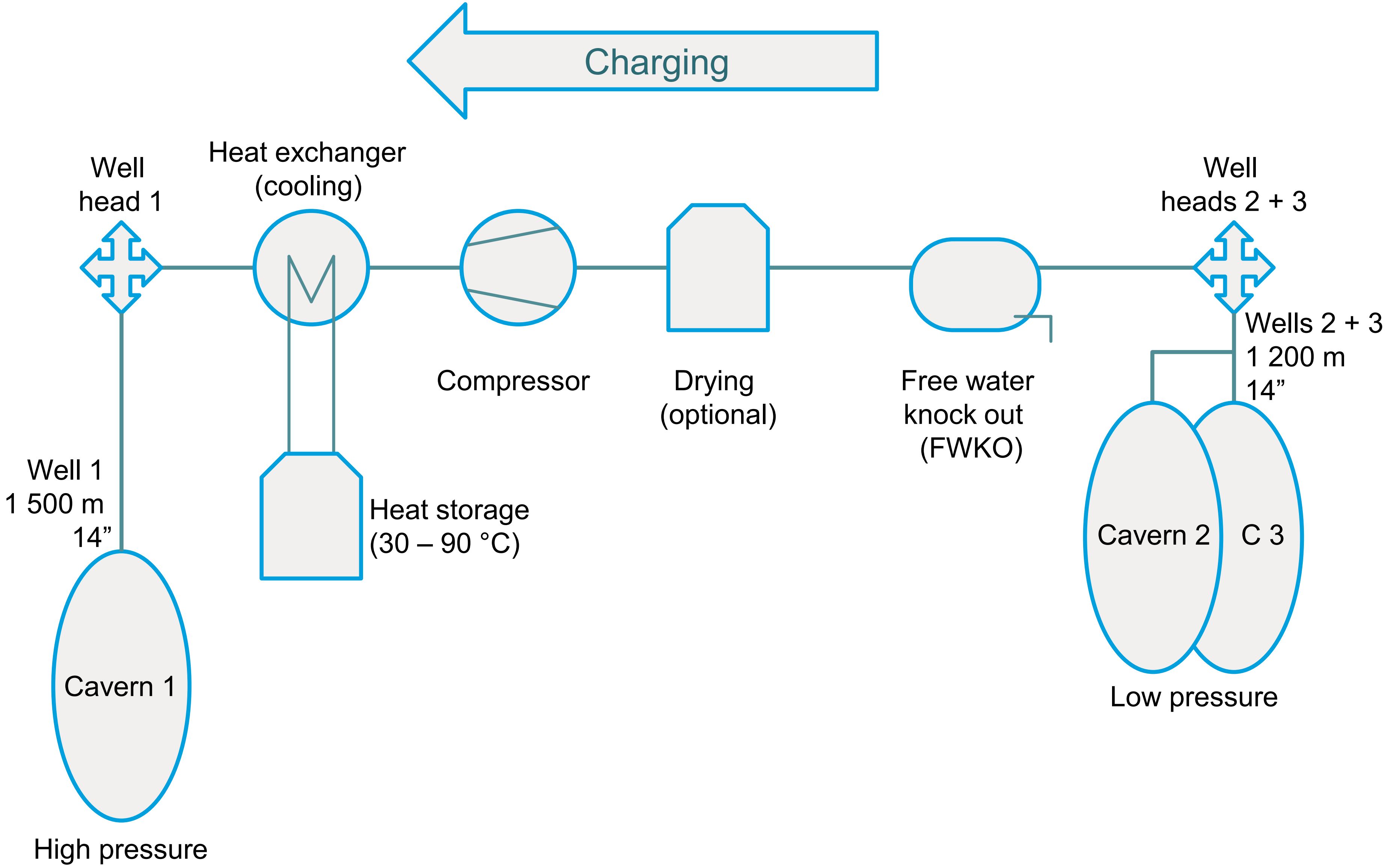
- **3 Examples**

Options

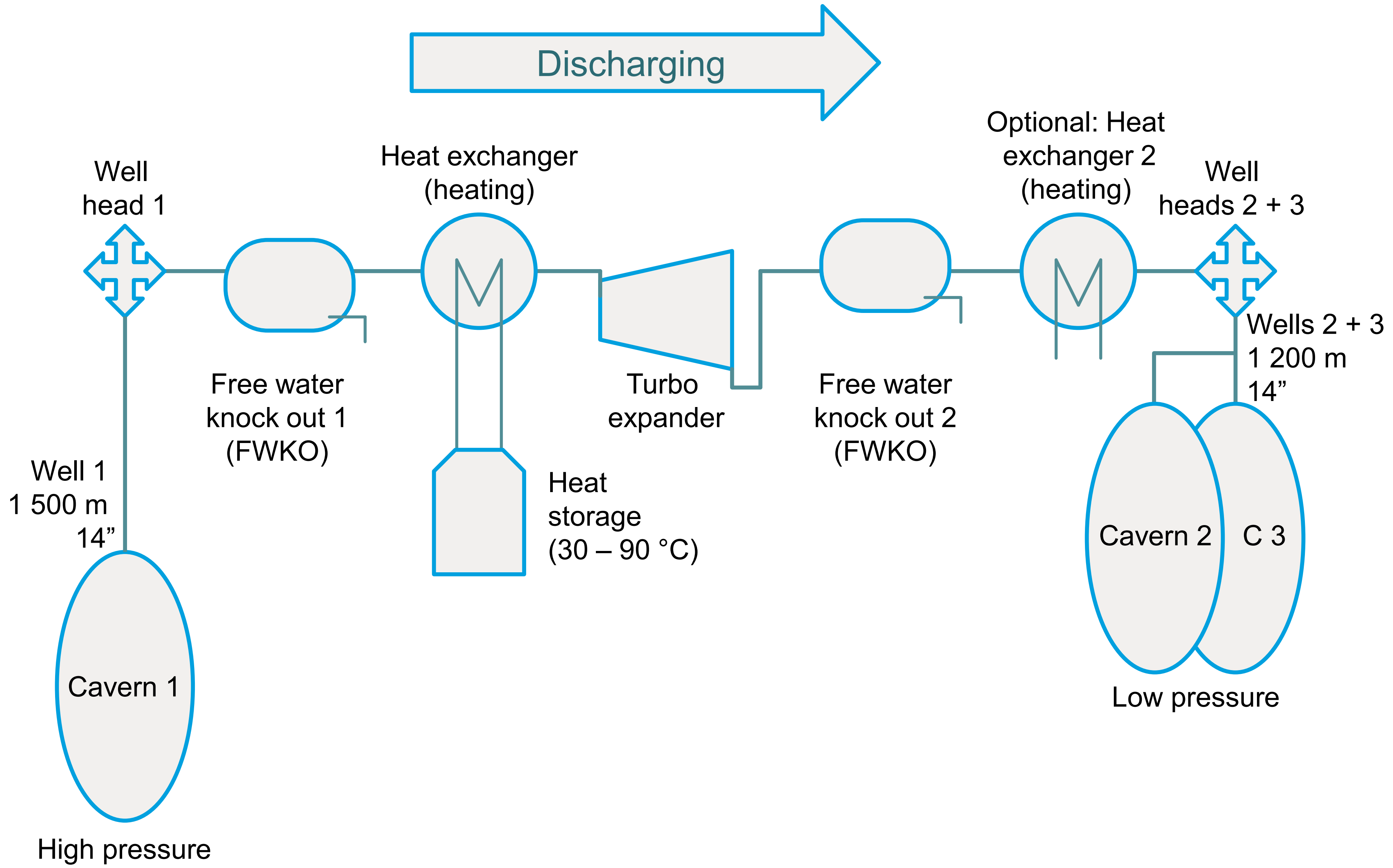
Options	Selection of caverns	Storage medium
Option 1	Existing caverns, modified gas storage plant + heat storage	Natural gas
Option 2	New cavern(s) in optimized depths, new plant + heat storage	Compressed air or natural gas

➔ technically fast realisation is possible with option 1

Possible setup option 2
new cavern(s), plant with natural gas or air



Possible setup option 2
new cavern(s), plant with natural gas or air



Simulation results option 1
existing plant with heat storage

Discharge power	5 - 7	MW
Discharge capacity	50	MWh
Discharge duration (h)	8	h
Rate (Nm3/h)	250 000	Nm^3/h
Efficiency	78	%
Heat reservoir (water)	1 200	m^3

Option 1: Existing caverns, existing gas storage facility + expansion turbine + heat storage

Cavern design			
Number of caverns:	3 (1 high p, 2 low p)	Geom. Volume:	500 000 m³ (each)
p_{min} / p_{max}:	60 / 180 bar	Depth LCCS:	1 000 m (each)
Completion:	9 ⅝“ in 13 ⅜“ LCC	Storage medium:	Natural gas

Simulation results Option 2
New cavern(s) in optimized depths, new plant, Air

Discharge power	100 – 120	MW
Discharge capacity	440 / 530	MWh
Discharge duration (h)	5	h
Rate (Nm3/h)	2 600 000	Nm^3/h
Efficiency	76 / 95	%
Heat reservoir (water)	8 000	m^3

Cavern design			
Number of caverns:	3 (1 high p, 2 low p)	Geom. Volume:	800 000 m³ (each)
p_{min} / p_{max}:	60 / 260 bar	Depth LCCS:	1 500 / 1 200 m
Completion:	14”	Storage medium:	Air
2 scenarios with 2 wells and 4 wells per cavern			

Summary

- In an existing natural gas storage facility an electricity storage can be integrated.
- The storage capacity is ~ 50 MWh and power of 5 MW over 8 hours.
- The discharge is limited by the possible gas rates, which are determined by the well tubing diameter.
- Improvements are achieved when heat storage is applied and when optimized cavern depth / tubing diameter can be realized.
- These improvements will also allow for higher efficiency.

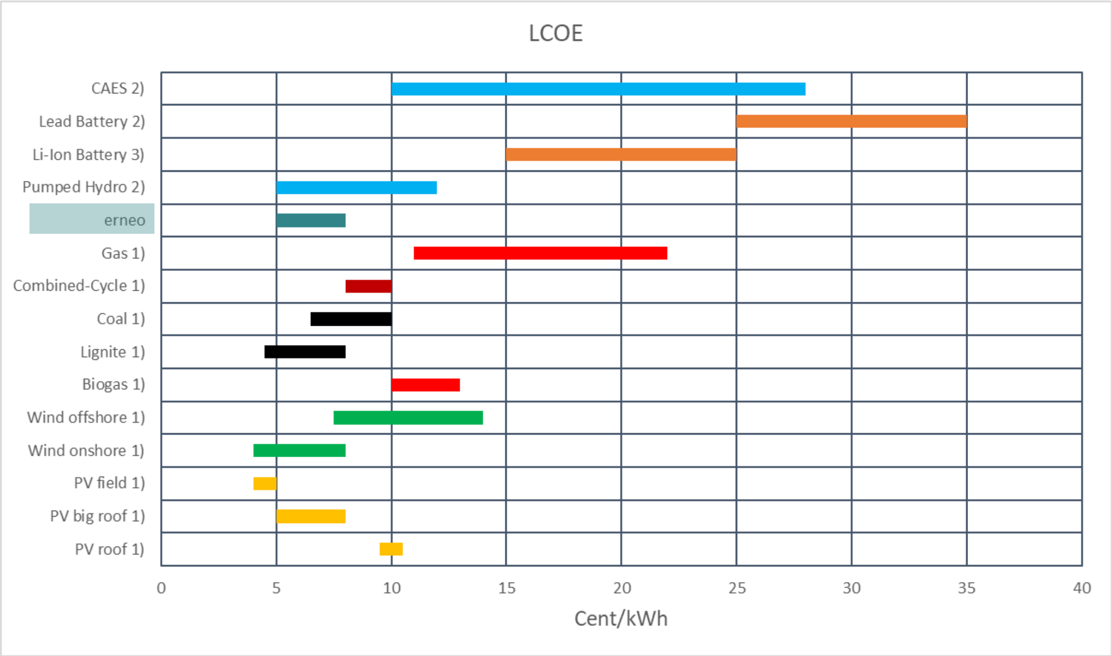
- **4 Economics**

Cost for Energy Storage Technologies

Technology	Energy related Cost €/kWh	Power related Cost €/kW	Efficiency %	Replace-ment Cost €/kWh	Cycles or Lifetime	O&M €/kW/a
Lead Acid Battery	150	125	75	150	700	15
Lithium Battery	200	200	95	200	1 000	5
Tesla Powerwall	440	1 030	95	440	1 000	5
Pumped Hydro	40 - 180	550 - 2 040	80	0	> 50 a	2.5
CAES	40 - 80	600 - 800	40	0	> 50 a	3
erneo	85	950	70 - 90	0	> 50 a	3

Cycles for Batteries are full charge and discharge. Lifetime or number of cycles is significantly higher, if only half the capacity is used, however then the double price per kWh and per kW should be considered.

Levelized Cost of Energy



1) Frauenhofer ISE "Stromgestehungskosten erneuerbare Energien" (2018)
2) IRENA International Renewable Energy Agency (2012)
3) div. Internet (2019)

LCOE measures lifetime costs divided by energy production and allows the comparison of different technologies (e.g., wind, solar, natural gas) of unequal life spans, project size, different capital cost, risk, return, and capacities.

- **5 Process Simulation**

Process Simulation

- A simulation program was developed where all relevant modules could be connected and the total flow be simulated with respect to rate, pressure, temperature, water, and condensate content.
- Thermodynamic properties were calculated using GERG 2008, AGA/GRI, etc.
- Equation of state using Soave-Redlich-Kwong, Peng-Robinson.

- Modules can be simulated like
  - Caverns
  - Wells
  - Pipes
  - Compressors / Turbines
  - Separators
  - etc.

Option 1: Process Simulation - Discharge

Module	Cavern1	Well1	Freiw01	Heater1	Turbine1	AirCool1	Spl01_a
In.Rate	0.0	-250000.0	250000.0	250000.0	250000.0	250000.0	250000.0
Out.Rate	-250000.0	250000.0	250000.0	250000.0	250000.0	250000.0	125000.0
In.Pressure	180.0	173.4	150.1	150.1	150.1	59.0	59.0
Out.Pressure	173.4	150.1	150.1	150.1	59.0	59.0	59.0
In.Temp.	50.0	47.8	27.2	27.2	50.2	-15.6	20.0
Out.Temp.	47.8	27.2	27.2	50.2	-15.6	20.0	20.0
In.Water							
Bound	0.0	1365.3	764.6	764.6	2052.5	41.8	465.6
Free	0.0	-585.1	15.6	0.8	-1287.1	723.6	299.8
Total	0.0	780.2	780.2	765.4	765.4	765.4	765.4
Out.Water							
Bound	1365.3	764.6	764.6	2052.5	41.8	465.6	232.8
Free	-585.1	15.6	0.8	-1287.1	723.6	299.8	266.3
Total	780.2	780.2	765.4	765.4	765.4	765.4	249.5

Module	Well2	Cavern2	Spl01_b	Well3	Cavern3
In.Rate	125000.0	125000.0	250000.0	125000.0	125000.0
Out.Rate	125000.0	0.0	125000.0	125000.0	0.0
In.Pressure	59.0	63.5	59.0	59.0	63.5
Out.Pressure	63.5	62.6	59.0	63.5	62.6
In.Temp.	20.0	25.4	20.0	20.0	25.4
Out.Temp.	25.4	32.8	20.0	25.4	32.8
In.Water					
Bound	232.8	624.7	465.6	232.8	624.7
Free	266.3	-125.6	299.8	266.3	-125.6
Total	249.5	499.1	765.4	-249.5	499.1
Out.Water					
Bound	624.7	0.0	232.8	624.7	0.0
Free	-125.6	0.0	266.3	-125.6	0.0
Total	499.1	0.0	-249.5	499.1	0.0

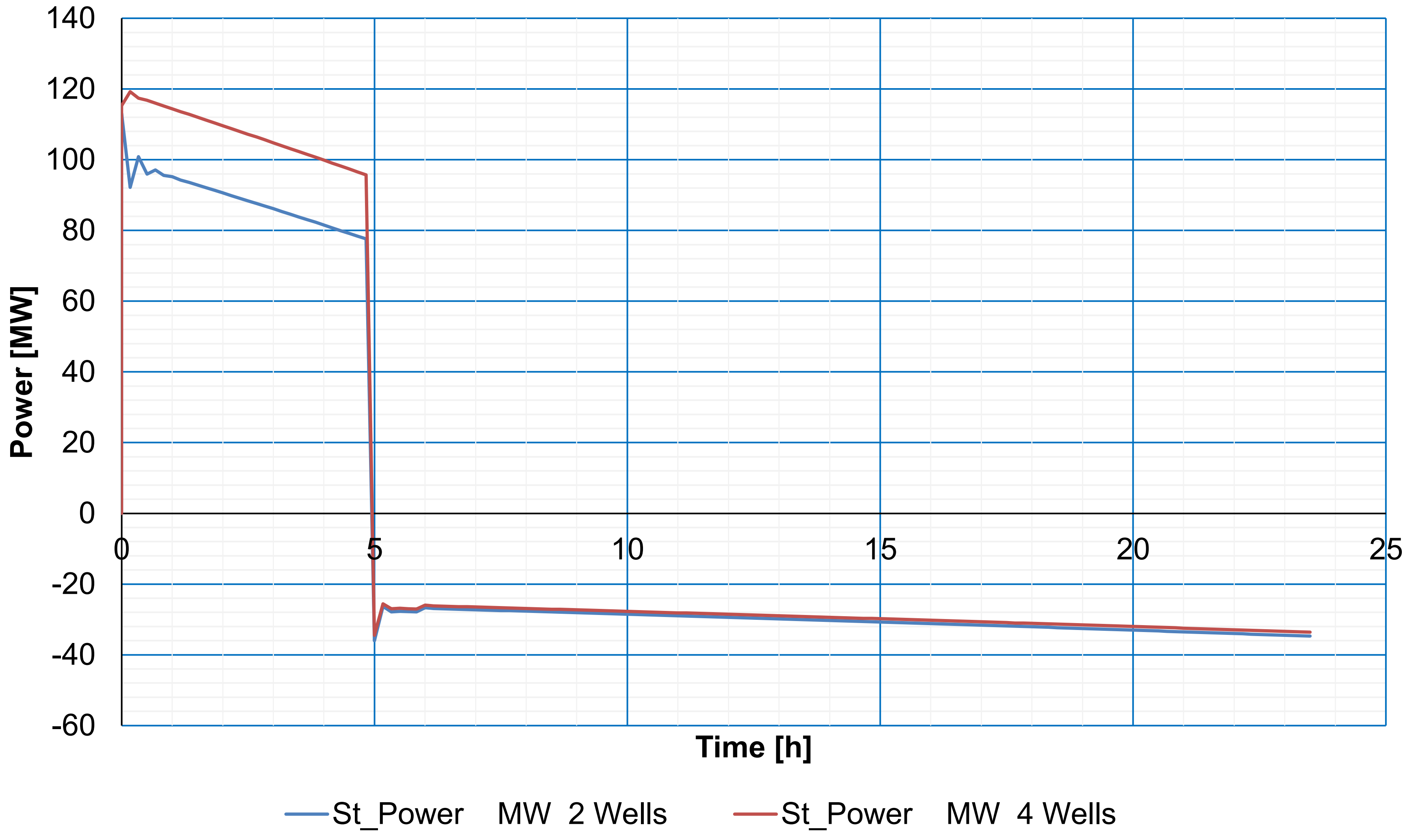
Free water, low temperature and high pressure may cause formation of gas hydrates.

Option 1: Process Simulation - Charge

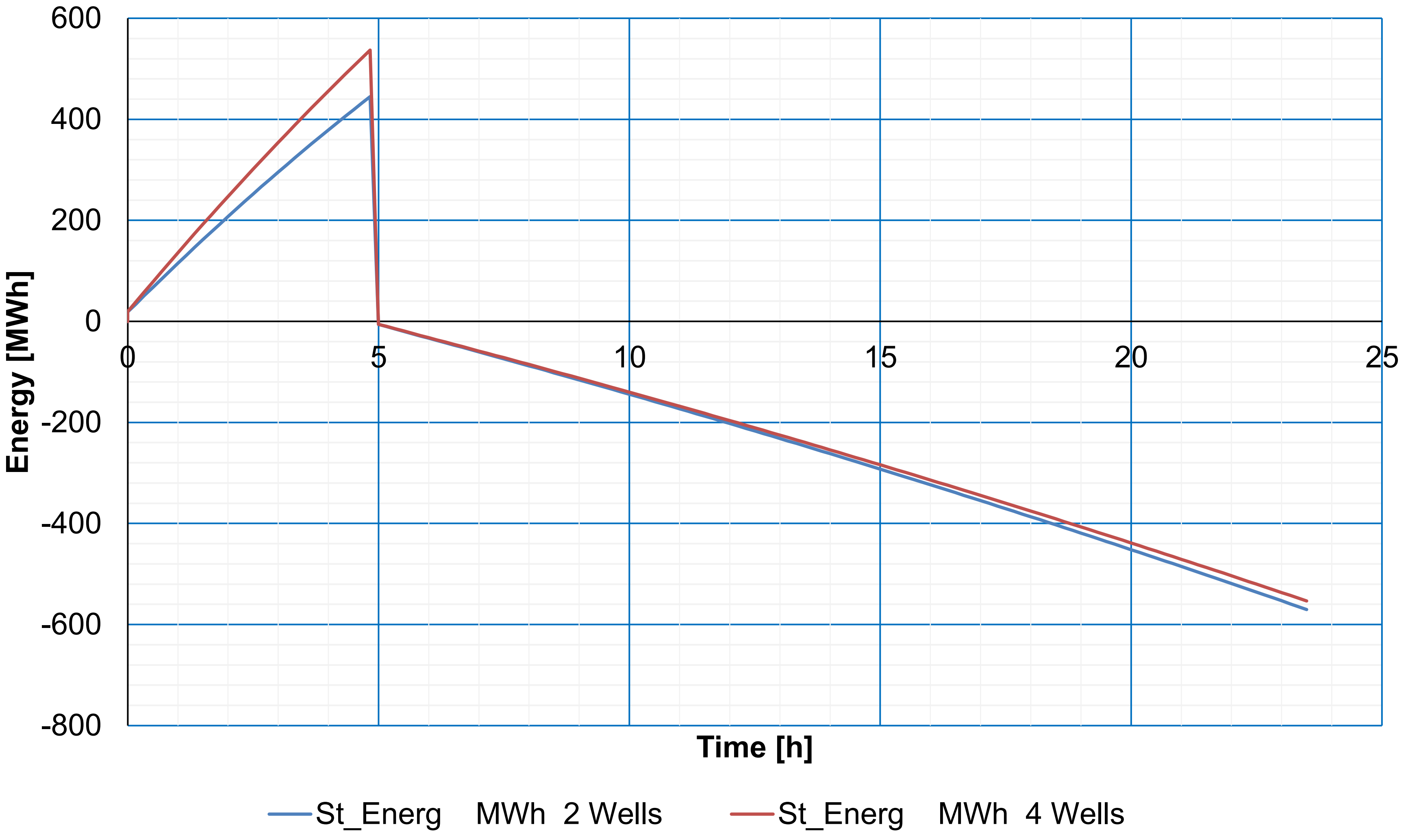
Module	Cavern3	Well3	Cavern2	Well2	Jnt01	Freiw01	AirCool2
In.Rate	0.0	-62500.0	0.0	-62500.0	62500.0	125000.0	125000.0
Out.Rate	-62500.0	62500.0	-62500.0	62500.0	125000.0	125000.0	125000.0
In.Pressure	63.5	60.0	63.5	60.0	53.8	53.8	53.8
Out.Pressure	60.0	53.8	60.0	53.8	53.8	53.8	53.8
In.Temp.	25.4	29.9	25.4	29.9	21.8	21.8	21.8
Out.Temp.	29.9	21.8	29.9	21.8	21.8	21.8	20.0
In.Water							
Bound	0.0	816.5	0.0	816.5	534.3	534.3	534.3
Free	0.0	0.0	0.0	0.0	282.3	1098.8	54.9
Total	0.0	816.5	0.0	816.5	816.5	1633.1	589.2
Out.Water							
Bound	816.5	534.3	816.5	534.3	534.3	534.3	478.9
Free	0.0	282.3	0.0	282.3	1098.8	54.9	110.2
Total	816.5	816.5	816.5	816.5	1633.1	589.2	589.2

Module	Comp01	Heater1	Well1	Cavern1
In.Rate	125000.0	125000.0	125000.0	125000.0
Out.Rate	125000.0	125000.0	125000.0	0.0
In.Pressure	53.8	164.6	164.6	181.4
Out.Pressure	164.6	164.6	181.4	180.6
In.Temp.	20.0	106.5	78.4	91.6
Out.Temp.	106.5	78.4	91.6	50.6
In.Water				
Bound	478.9	478.9	5915.3	9082.2
Free	110.2	110.2	-5326.2	-8493.0
Total	589.2	589.2	589.2	589.2
Out.Water				
Bound	478.9	5915.3	9082.2	0.0
Free	110.2	-5326.2	-8493.0	0.0
Total	589.2	589.2	589.2	0.0

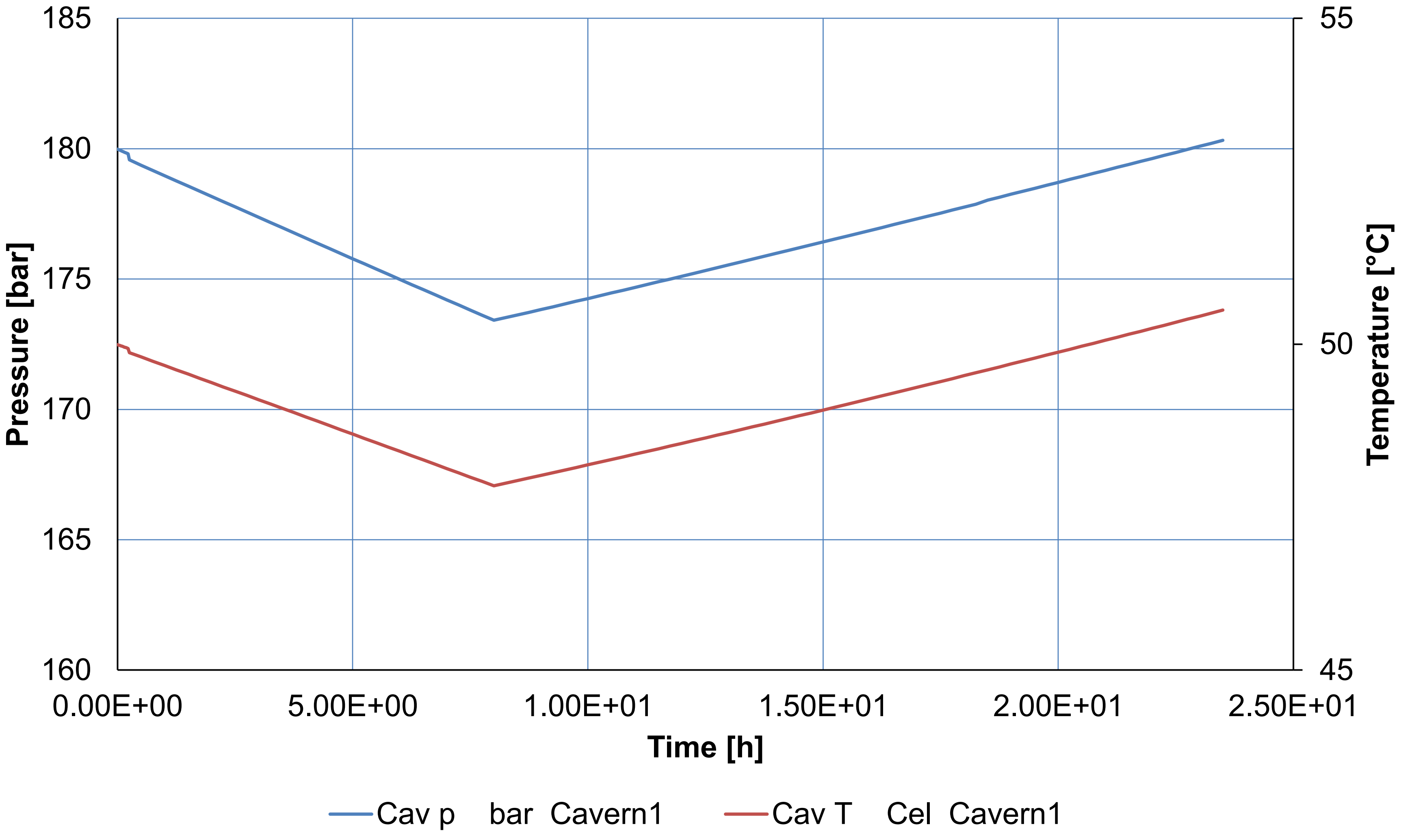
Option 2: Storage Power



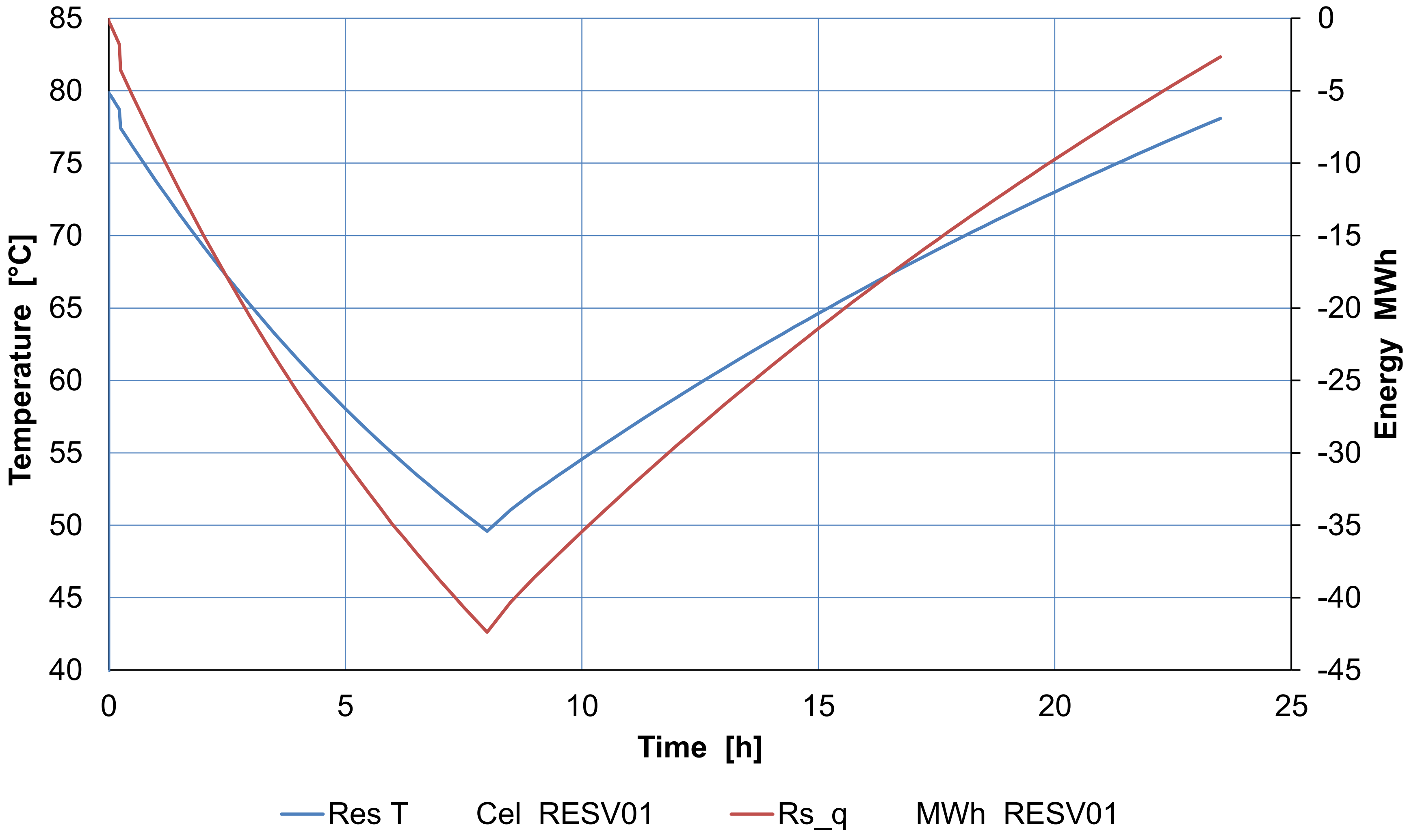
Option 2: Storage Energy



Option 2: Cavern Pressure and Temperature



Option 1: Temperature Heat Storage



Thank you for your attention.

Contact:

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The technology is patented and protected by US Law.

double click to start video of follow the link: https://youtu.be/AYE_toXHZqE