Introduction to Long Duration Energy Storage, Part 2. Non electrochemical Technologies

Ramesh Koripella, Ph.D.

CEC webinar, Sept 20, 2024.

Sandia National Laboratories

This material is based upon work supported by the U.S. Department of Energy, Office of Electricity (OE), Energy Storage Division.

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

SAND2024-123260

Outline

Session 1:

I. Introduction
- LDES need, classifications, use cases, challenges, current state of electric power generation and energy storage in CA

II. Technology Options for LDES
1. Electrochemical
   - Few battery fundamental concepts
   - Different types: Li- ion, Na- ion, flow batteries, metal-air batteries, others.

Q & A, break

Session 2:

2. Mechanical Storage — **Slides 4-16**
   - PHS, variations of PHS, Gravity, Compressed air, flywheels
3. Thermal Storage — **Slides 17-23**
   - Molten salt, solid particle media, heater brick, molten metal, liquid air.
   - Enhanced Geo thermal
4. Chemical Energy Storage — **Slides 24-31**
   - Hydrogen generation, storage, transport, ammonia, hydrocarbon fuels, conversion into electric power (fuel cells and gas turbines).

III. Summary

Q & A

Few Technology Options for LDES

Electrochemical Storage (Batteries - short, medium, long duration storage)

- **Lithium-Ion Batteries,**
- Sodium-Ion Batteries, Molten Sodium Batteries
- Zn-Based Batteries, Ni-H_2 batteries
- Metal-Air Batteries
- Flow Batteries

Mechanical Storage (short, medium, long duration storage)

- **PHS (Pumped Hydro Storage)**
- Variations of PHS (Quidnet Energy, RCAM)
- Gravity (ARES, Energy Vault)
- Compressed air (CAES)
- Flywheels (short duration storage)

Thermal Storage (medium, long duration storage)

- Molten salt thermal storage, ceramic particle storage media, Fixed bed thermal storage
- Heated brick (Antora, Rondo)
- Molten metal, liquid metal battery
- Liquid air energy storage

Chemical and Hydrogen Storage (long duration and seasonal storage)

- H_2 generation (Electrolysis, SMR), H_2 storage, Electric Power generation (H_2 combustion, Fuel cells)
- Hydrocarbon or ammonia conversion

Desired ES Characteristics:

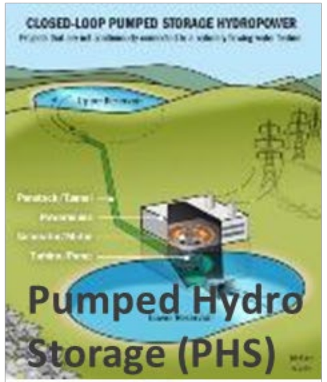
- **Ability to respond quickly for load demand**
- **High round trip efficiency**
- **Low self discharge**
- **High energy density**
- **Cost competitive**
- **Environment friendly**
- **Availability with good supply chain**
- **Safe**

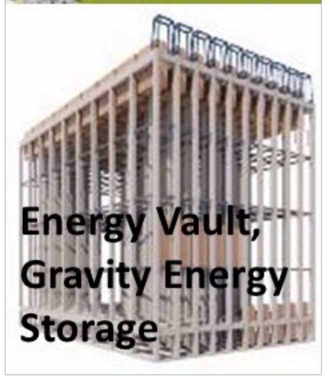
2. Mechanical Storage

Mechanical Storage (some of these can meet short, medium and long duration energy storage needs)

- **PHS** (Pumped Hydro Storage)
  - Variations of PHS (Quidnet Energy, Sage, RCAM)
- **Gravity** based energy storage
  - Concrete blocks on cranes (Energy Vault), on Railcars (ARES)
- **Compressed air** energy storage (CAES)
  - Adiabatic compressed air (A-CAES) - high RTE, the heat of compression captured
  - Diabatic compressed air (D-CAES) – simpler system
  - Variations – liquefied air, compressed CO_2 (Energy Dome)
- **Flywheels** (mostly suitable for short duration storage)

Mechanical Energy Storage





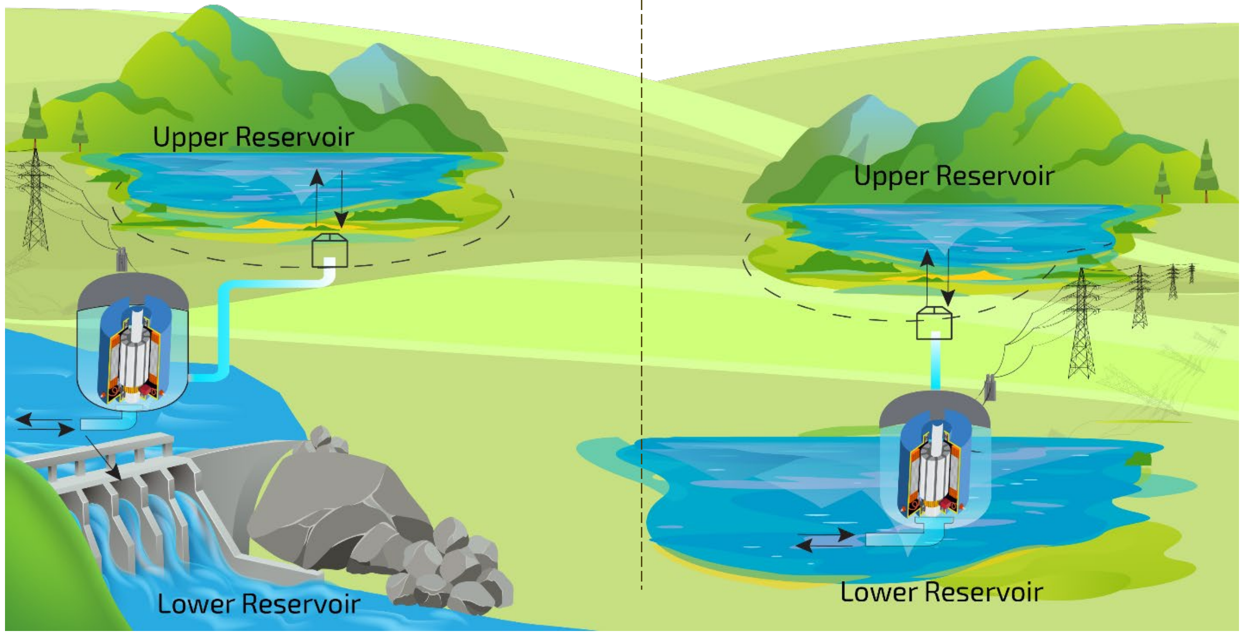
2.1 Pumped Hydro Storage (PHS)

- **Consists of pumping water between two reservoirs at different heights**
- **Converts electrical energy into potential energy (during charge and storage). Convert Kinetic energy into electrical energy (during discharge)**

Open loop:
- Integrates PHS directly into a naturally flowing water source, such as a river.
- Disadvantages include blockage of natural waterways, disruption of local aquatic ecosystem, flooding, displacement of terrestrial wildlife, etc.

Open Loop

Closed Loop



Closed loop:
- Comprises two reservoirs that are interconnected but otherwise separated from a natural water source.
- Have the advantage of limiting impact on the natural aquatic environment.

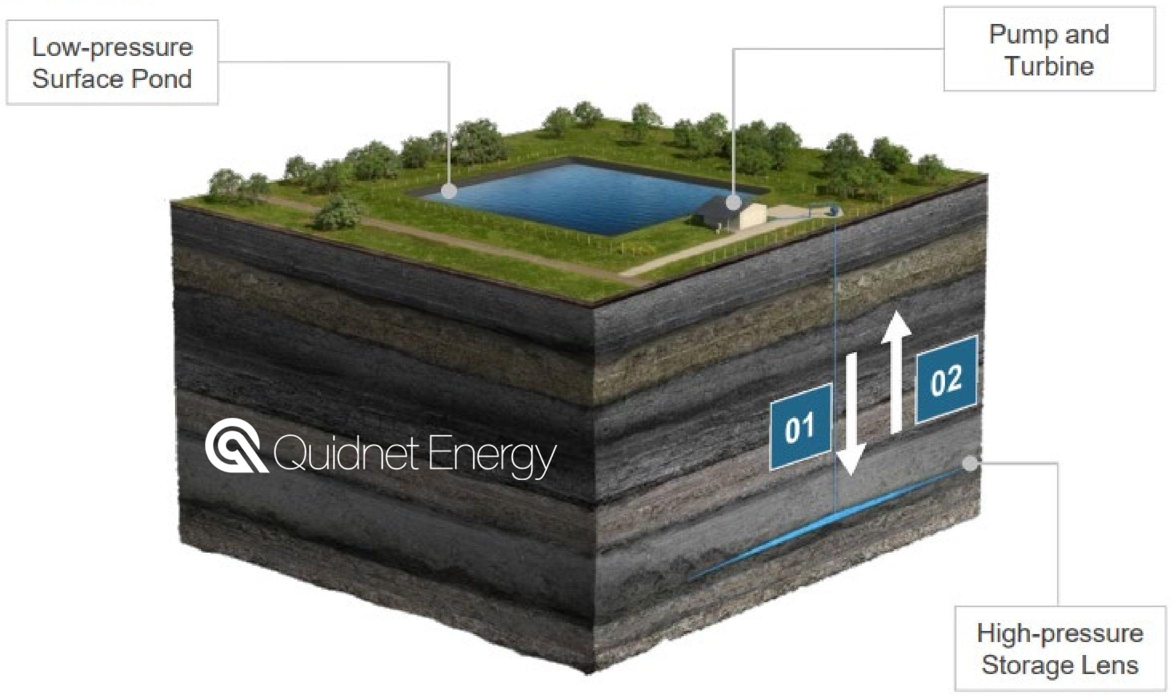
Other differences:

Fixed speed motor/generator – Can not perform frequency regulation.
Adjustable speed – These can provide frequency response services.
Reversible pump/generators – allows storage also

2.1 Variations of PHS- Quidnet Energy

Geomechanical Pumped Storge – Subsurface Pumped Hydro

How it Works



01	**Charge.** Water pumped down the well into high-pressure storage lens
02	**Discharge.** High-pressure water flows up the well to drive a turbine

Storage Process

- Pump water from a pond down a well and into a body of rock.
- The well is closed, keeping the energy stored under pressure between rock layers for as long as needed.
- When electricity is needed, the well is opened to let the pressurized water pass through a turbine to generate electricity, and return to the pond ready for the next cycle.

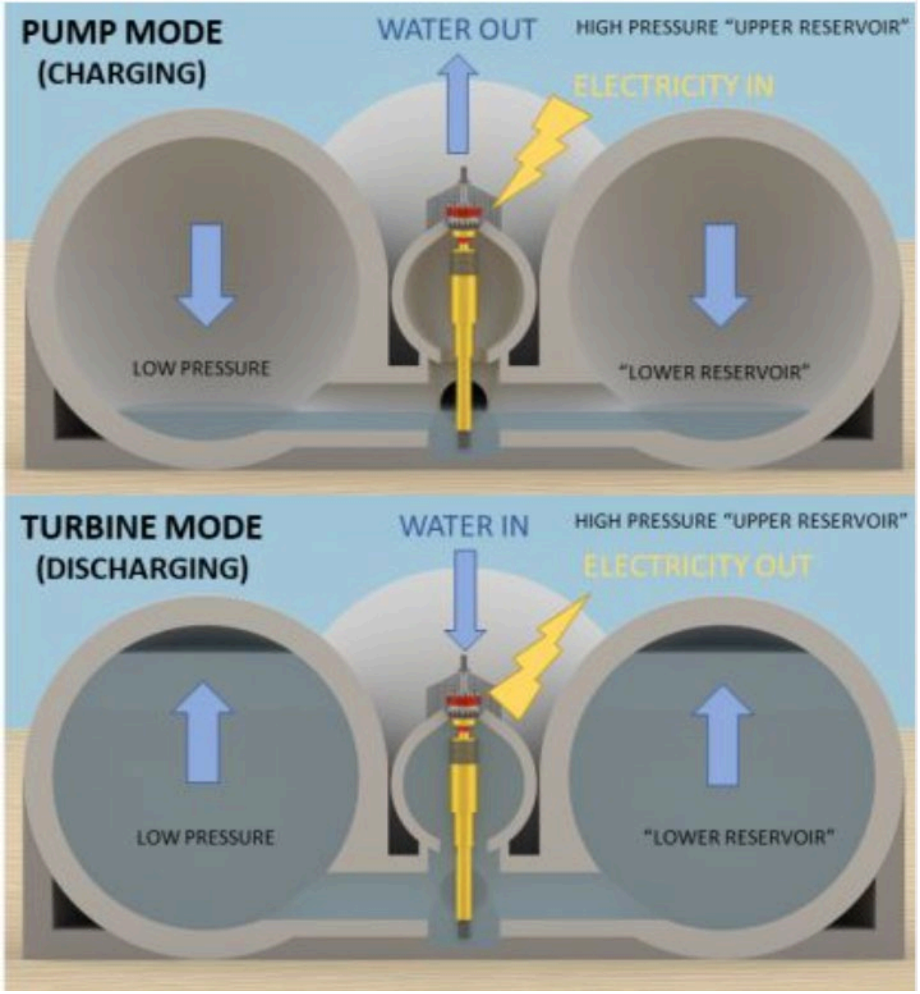
1-10 MW systems,
10+ hour modules

Partnering with Sage Geosystems – proof of concept demonstrated

2.1 Underwater Pumped Hydro (e.g., RCAM)

Subsea storage solution integrates with offshore wind to provide firm, steady power

100-2000m



Nominally, three 30-m diameter spheres installed in 700-m water and a 5-MW pump/turbine module has a storage capacity of 60 MWh (12 hours). Increasing the spheres to 8 per pump/turbine provides 32 hours or 160 MWh of energy storage.

Proof of concept stage

2.1 Pumped Hydro Storage (PHS)

- Mature technology. Good for 4-20 hr duration. RTE: 75-85%.
- Power capacities range from 100’s of MW to several GW
- It can serve a wide range of grid storage applications
- Life time: 50-60 years, some are still running after 100 yrs.
- Capital investment is high, storage cost is low. Operation and maintenance costs are also low.
- According to EIA data, in 2023, PHS ~0.59 TWh, which is very small (0.2%) relative to the total Hydroelectric power generated (239 TWh).
- 2023 EIA data shows the total capacity of PHS: 23.2 GW, and Batteries: 11.2 GW.

Disadvantages:

- Geographic constraints.
- Long permitting process.
- Higher capital investment.

2.1 Future prospects of PHS on the US grid

- PHS is a proven, reliable technology. They last for several years.
- IRA (inflation reduction act) gives 30% investment tax credit for standalone grid storage. Projects can gain an additional 10% credit by meeting domestic materials requirements.
- There are few plans to build new PHS in the US, but small activity compared to other countries. rPLUS, TVA are planning to add new PHS.
- In addition to the stand alone PHS possibilities, we need to **look into the possibility of adding reversible pumps and storage at some existing hydroelectric generators**.
- Despite the challenges (long permitting and installation process, huge capital cost, environmental concerns) a more detailed **techno economic analysis is needed for PHS storage**.

2.2. Flywheels, 2.3. Gravity Based Energy Storage

- **Flywheels** store energy in the form of angular momentum of a spinning mass called rotor. Kinetic energy is converted into electrical energy with a power conversion system.
  - They are contained in a rigid container, operated under vacuum or inert gas. Sizes range from few kW to MW range. RTE: 70-80%.
  - Several commercial deployments were made.
  - Flywheels can respond fast. They are good for frequency regulation applications.
  - Expensive. There are safety and scale up (to GW scale) concerns.
  - Not many new grid scale installations. Li ion batteries pretty much taken over this market.

- **Gravity Based Energy Storage Systems:** Move a large mass up with a crane or move it on an inclined rail road with a motor for charging. Store it at a higher elevation as potential energy, and bring it down under gravity for discharge. Covert kinetic energy into electrical energy with a generator.

Amber Kinetics Flywheel

Energy Vault Gravity Energy Storage

ARES Rail car gravity storage

2.3 Gravity Storage: Stacked Blocks

Convert electrical energy to potential energy (moving the blocks up and store) for charging. Convert kinetic energy into electrical energy for discharge

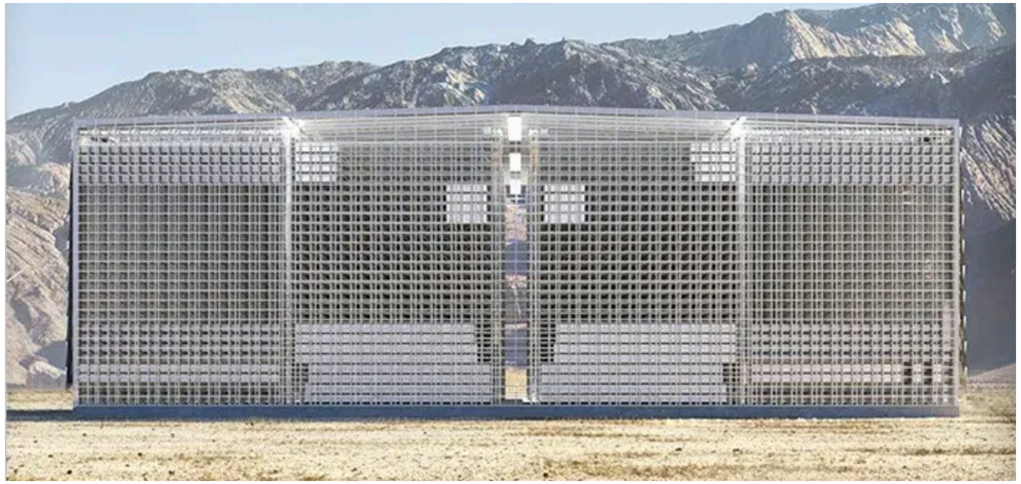
Prototype completed in July 2021 in Ticino, Switzerland

- Scalable in 10MWh increments
- 2-4 hour and 4-12+ hour duration
- Emphasizes local, sustainable sourcing of materials

Issues:

- Low energy density. Expensive. Difficult to stack heavy blocks accurately. Safety issues. Discharge rate is limited.
- They changed the design for next iteration.

2.3 Gravity Storage: Stacked Blocks



- Energy Vault® EVx™ system raises/lowers 30 ton bricks
- Scalable in 10MWh modules
- China Tianying Group (CNTY) installed a 25 MW/100MWh system in Rudong, China (near Shanghai). 4hr duration. Charge from a near by wind farm and discharge to the grid.

ENERGY VAULT
Enabling a Renewable World

Proof of concept stage. Safer design, but other concerns are same as earlier.

2.3 Gravity Storage: Rail Cars

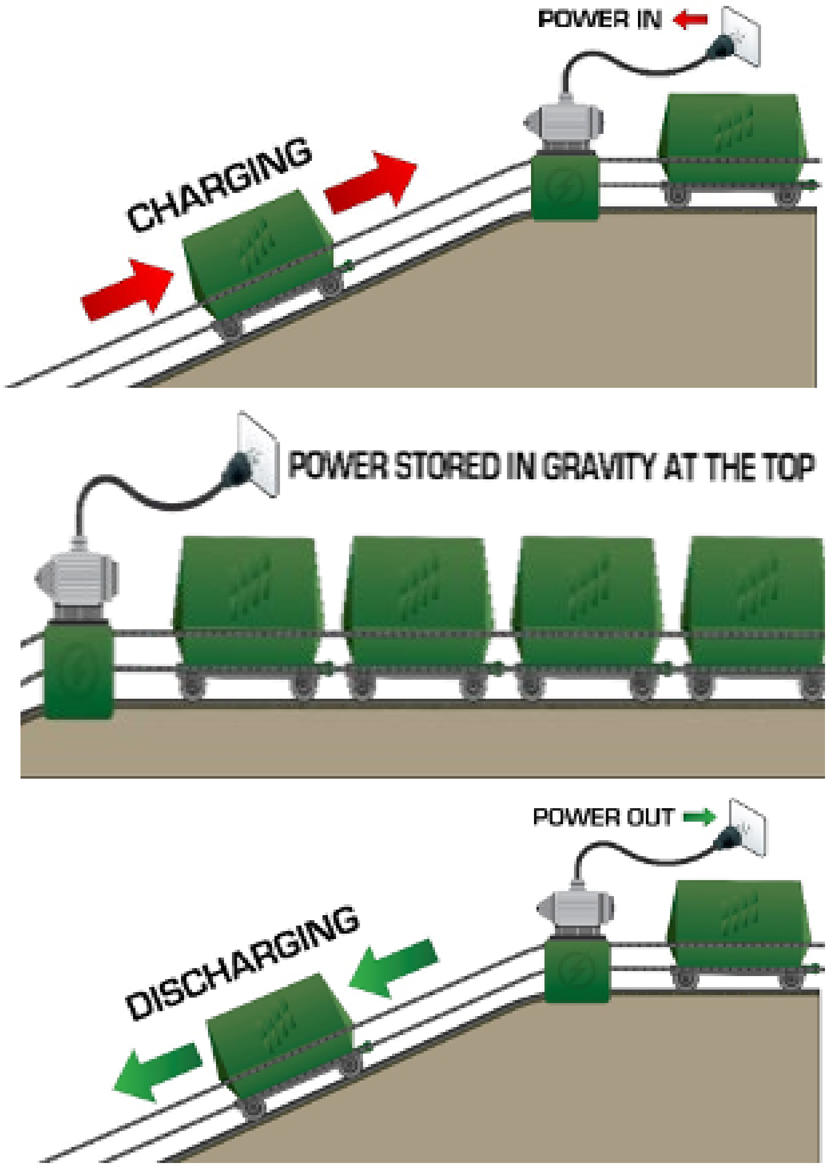
Advanced Rail Energy Storage (ARES)

Scalability :	5MW – 1GW
Storage Duration:	15 mins–10 hours
Time to Max Output Discharge (optimal) :	3 seconds
Time to Max Output Consumption (optimal):	3 seconds
Round-Trip Efficiency :	90%+
System Life:	40+ years

*50MW GravityLine™ system in Pahrump Valley, NV is under construction

- Rail cars are less friction compared to cranes.
- Issues are similar: low energy density, cost, safety, controlling the rate of charge/discharge.

Proof of concept stage.



ares

2.4 Compressed Air Energy Storage (CAES)

- **Compressed air (CAES)**
  - Use electricity to compress air, store it and then re-expand to generate electricity. Compression of air generates heat.
  - Two types of CAES: diabatic, adiabatic. In adiabatic the heat of compression is captured for higher efficiency. In diabetic the heat is not captured. Typical RTE: 55-65%.
  - Compressed air can be stored above or under ground.
  - A-CAES system consists of an air compressor, a storage chamber that holds pressurized air, a thermal energy storage facility and turbine.
  - Two old CAES systems in operation, recent proposals are in development stage.
  - CAES cannot respond fast and they are not suitable for power quality voltage and frequency regulation applications.
- **Variations of CAES:** Liquid air energy storage (LAES), CO_2 dome, Storing compressed air or gas in gas pipelines, a combination of compressed air and water head.

Energydome - Compressed CO_2

- Working fluid is CO_2.
- Easier to deal with than air. Clean CO_2 is used. CO_2 has higher molar mass than air, so smaller turbo machinery is needed. Critical temperature is 31C.
- Proof of concept demonstration project done is Italy.
- Uses existing technology. Sacrifices some efficiency for system simplification and reliability.
- Limiting the phase change and not capturing all the heat in the thermodynamic cycle

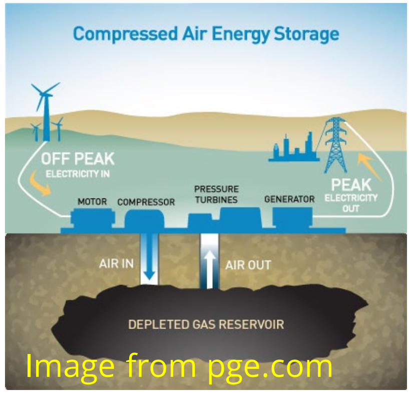
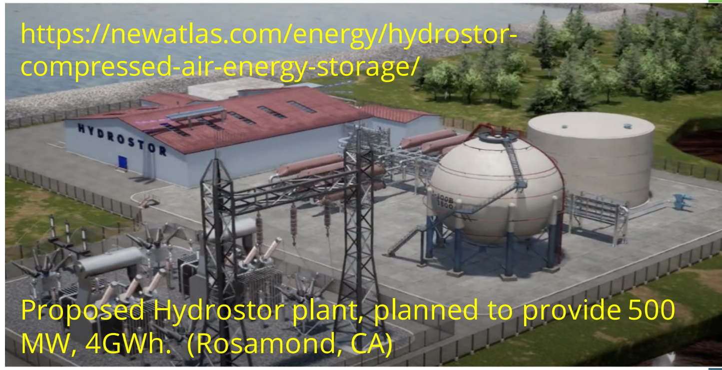


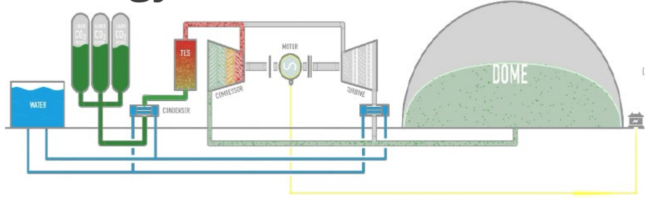
Image from pge.com



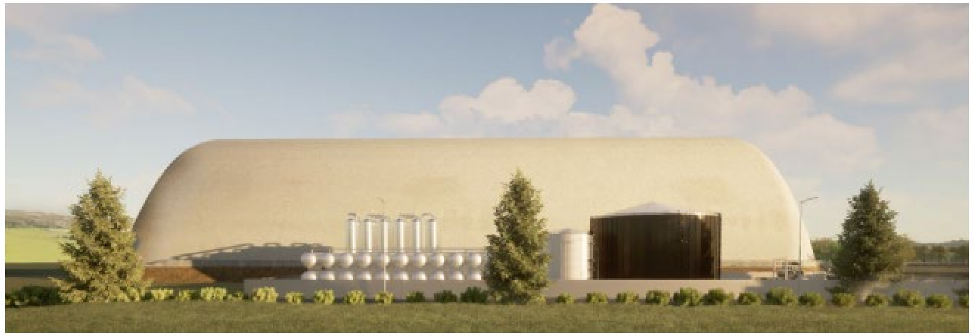
https://newatlas.com/energy/hydrostor-compressed-air-energy-storage/

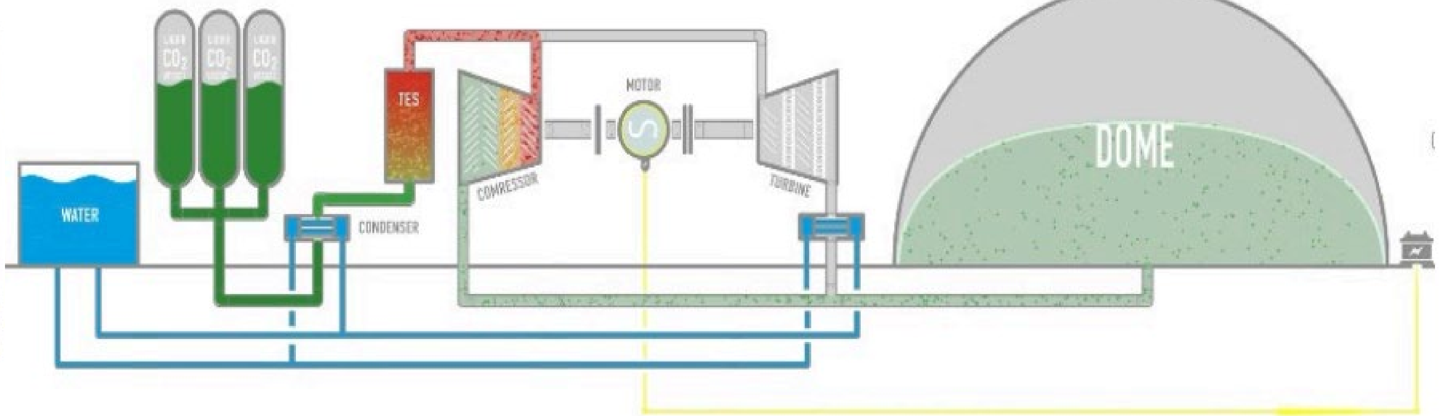
Proposed Hydrostor plant, planned to provide 500 MW, 4GWh. (Rosamond, CA)

Energydome, https://energydome.com/



2.4 Energy Dome – Compressed CO_2 storage





- 20 MW x 10h Commercial Module - Needs 10 to 12 acres of land (mostly for dome) - Dome height is 45 m (@ 150 ft). Outside rigid dome, inside bladder moves up and down with gas.
- Used all commercially available equipment for a quick demo.
- Working fluid CO_2. It can be stored as a liquid at ambient temp in carbon-steel pressure vessel, no cryogenics or chillers needed, Cleaner fluid, less contaminants, higher molar mass relative to air, so smaller turbo machinery. Not corrosive.
- Not going to supercritical CO_2 and eliminated the cold storage for simplicity.
- Development started on CO2B Version 3.0, unit with larger turbine/compressor and higher efficiency (Pilot plant V1.0, Commercial Plant V2.0).
- Capex: $225-250/kWh, RT 75%, 30+ yr life time

Proof of concept demonstrated. Low energy density. Need to understand the scale up issues, operating costs, self discharge losses and RTE.

3 main states

1 **Charging**
- CO2 withdrawn from atmospheric gasholder (Dome), and compressed by inter-refrigerated compressor
- Heat generated from compression stored into Thermal Energy Storage System (TES)
- CO2 is condensed into liquid state

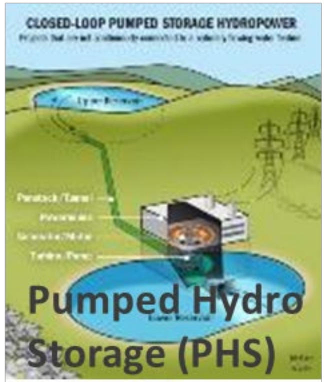
2 **Idle**
- Liquid CO2 stored at ambient temperature in CO2 vessels

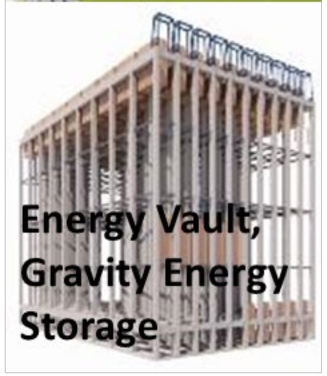
3 **Discharging**
- Liquid CO2 is evaporated and heated by recovering heat from TES
- Reheated CO2 expands in turbine, returning power to the grid
- Gaseous CO2 is stored in Dome at ambient temperature and pressure without emissions to atmosphere

2 Mechanical Storage Summary

- **PHS** (Pumped Hydro Storage)
  - Known proven technology.
  - Despite potential hurdles (geographic constraints, permit process and capital) need to be considered carefully.
  - Evaluate the feasibility of adding PHS with hydroelectric generation.
  - Perform economic analysis of running hydroelectric versus PHS.
- **Gravity** based energy storage
  - Proof of concept stage. Low energy density, not cost competitive, rate of charge/discharge limitations, safety issues.
- **Compressed air** energy storage (CAES)
  - Low energy density, not cost competitive, low RTE, self discharge issues, permitting process. Several new ideas are in the proof of concept stage.
- **Flywheels**
  - Good for short duration frequency response type applications. Scaling issue for long duration storage. Not cost competitive with Li ion batteries.

Mechanical Energy Storage





3. Thermal Storage

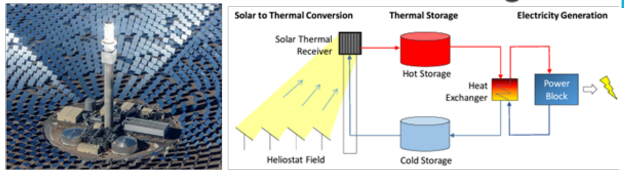
Thermal Storage

- Convert electrical energy into heat – store heat – convert heat into electrical energy.
- Thermal storage is more suitable for long duration storage.
- More economical in larger scale. Surface area/volume ratio works better to minimize heat losses.
- It is economical if thermal storage is placed near a facility that can use thermal energy (example: industrial heat or process heat).
- Thermal energy can be stored in three forms: Sensible heat, latent heat (phase change) and chemical reaction.

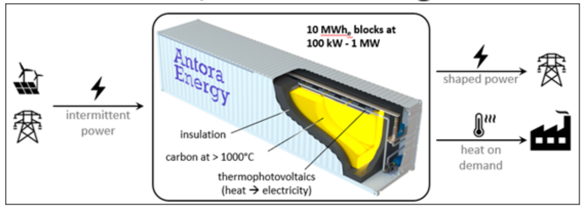
- **Different variations:**
  - Molten salt thermal storage. *– more mature*
  - Ceramic particle storage media. *– early R&D*
  - Fixed bed thermal storage. *– early R&D*
  - Heated brick or carbon blocks *– proof of concept stage*
  - Molten metal. *– early R&D*
  - Liquid metal battery. *– proof of concept stage*
  - Liquid air energy storage. *– early R&D*
  - Thermochemical *– proof of concept stage*

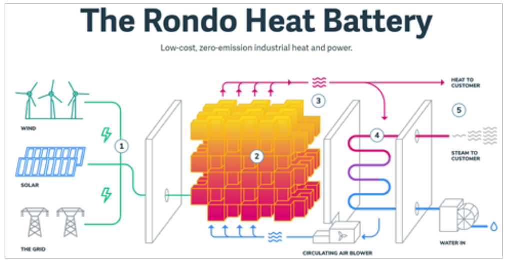
Thermal Energy Storage

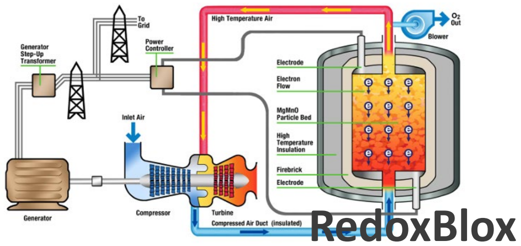
Concentrated Solar Thermal Storage



Antora, Thermal Storage







Thermal Storage Variations

Electrical energy in

Convert into Heat
Different methods

Compress a working fluid: air, N_2, Ar, CO_2 (Malta, CO_2 dome)

Resistive heating with different types of heating elements
- Graphite (Antora)
- Metal/ceramic (Rondo)

Resistive heating plus Chemical reaction (oxidation, reduction reactions to increase energy density) (RedoxBlox

Capture and Store Heat

Capture heat through a heat exchanger (HEX) and transfer heat to a storage medium

Store heat
-molten salt (Malta)
-Packed bed (Siemens Gamesa, CO_2 dome)

HEX

Convert into Electricity
Similar to traditional power plants

Transfer heat to a working fluid: gas, air or steam

Use heat in industrial processes

Run a turbine to generate electric power

Cold storage

Another method

TPV
Thermo Photo Voltaic (Antora)

Direct conversion of heat to electricity

Electrical energy out

3. Molten Salt Thermal Storage

- More developed technology with concentrated solar power.
- Technology is similar for grid scale application also using renewable electrical energy to thermal energy and storage.
- Molten salts (e.g., nitrate salts) are the primary storage medium. Salts are heated to high temperatures (e.g., 385 °C to 565 °C)
- Stored energy in salt is then used to heat a medium, such as water to generate steam.
- Nitrate salts are inexpensive (~$1/kg), but need to be maintained at ~200-300 °C to keep from freezing.
- Other issues are corrosion. Handling of hot fluids

Solana Parabolic Trough Solar Project
1.5 GWh_e storage in 6 pairs of hot and cold tanks.

CSP/Storage Examples

Solana Parabolic Trough Solar Project (Arizona)
280MWh_e with 6 hour storage (~1.5GWh_e)

Crescent Dunes Central Receiver Solar Project (Nevada)
125 MWh_e with 10 hours of storage (1.250GWh_e)

Noor I Parabolic Trough Solar Project (Morocco)
160MWh_e with 3 hours of storage (480MWh_e)

Noor III Central Receiver Solar Project (Morocco)
150MWh_e with 7 hours of storage (1GWh_e)

3. Thermal Storage Examples

MALTA

Proof of concept stage

Molten salt storage

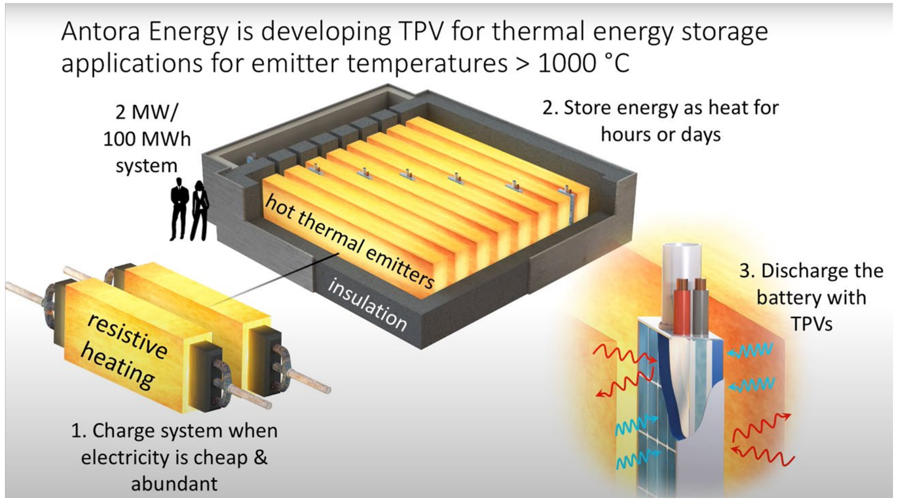
SNL: National Solar Thermal Test Facility (NSTTF)
Research on **molten salt, solid particle bed**, fixed bed thermal storage

Siemens-Gamesa, Hamburg, Germany
1000 tons of rock at 750ºC. Using steam turbine, generator to produce 24 hour storage at 1.5MW.

Horizontal **rock bed storage** with air heat transfer fluid. RTE ~ 25 %. Estimates for a larger system consisting of blocks several hundreds of MW each can have an efficiency of ~ 42 %.

Proof of concept stage

3. Thermal Storage Examples



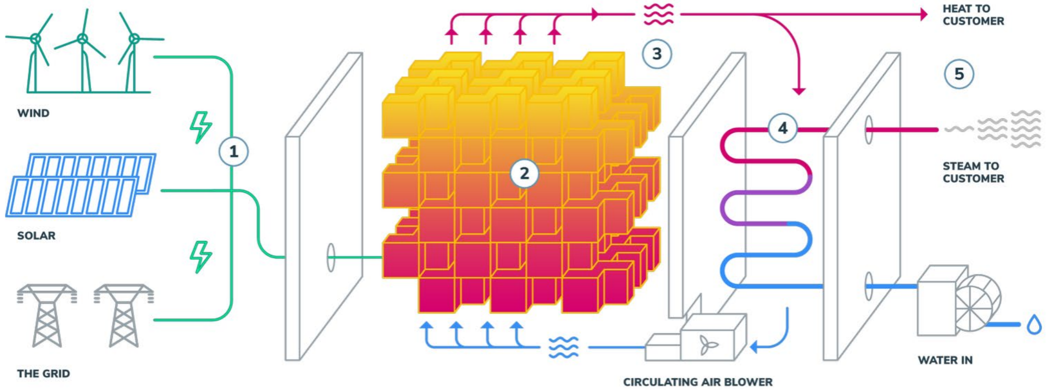
ANTORA

Use renewable power to heat graphite blocks. Store thermal energy. Use TPV to convert into electrical power.
Initially focused on supplying heat only.

Proof of concept stage

The Rondo Heat Battery

Low-cost, zero-emission industrial heat and power.



Use renewable power to heat ceramic bricks with heaters.
Store thermal energy. Air is the working fluid for heat transfer.
Initially targeting thermal storage only for industrial use.

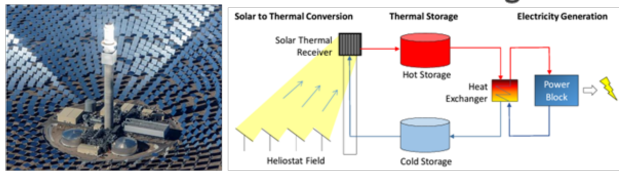
Proof of concept stage

3. Thermal Storage Summary

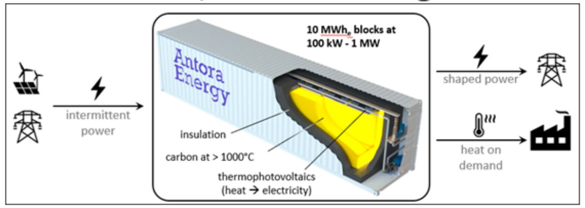
- **General issues:**
  - Suitable for long duration storage. Not ideal for short or medium duration (not competitive with batteries).
  - RTE: 55-65% range.
  - Ideal if co-located with a facility where heat can be used for process heat.
  - Compressors, heat exchangers are known technology.
  - Molten salt storage is more developed compared to other concepts.
  - Molten salts are corrosive, difficult to handle hot fluids.
  - With other concepts the issues are; need for good thermal insulation, heat transfer, electrical heating issues, high temperature electric contacts, oxidation, reliability.
  - With TPV: the band gap need to be tuned for thermal radiation. Need a method to remove waste heat from the back end.
  - **Most of these are in development stage, low TRL level.**

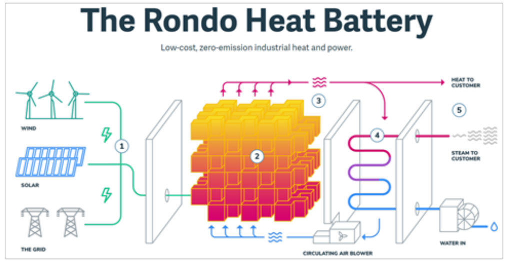
Thermal Energy Storage

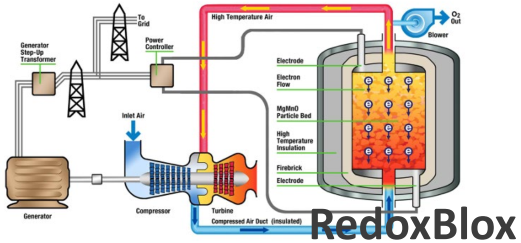
Concentrated Solar Thermal Storage



Antora, Thermal Storage



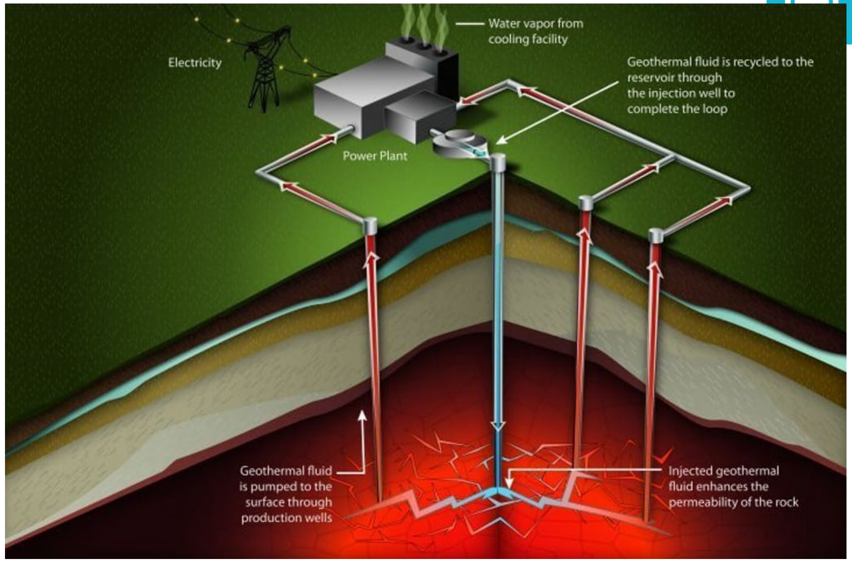




RedoxBlox

Enhanced Geothermal

- Geothermal system requires **three key elements** to generate electricity: **heat, fluid and permeability** (for water to move freely through the underground rock).
- In many areas, the underground rock is hot but not permeable or fluids present. In those cases, an enhanced geothermal system can be used to create a human made reservoir to tap that heat. Wells are drilled up to 8000 feet.
- In Utah, DOE is sponsoring an ongoing project(FORGE) to develop enhanced geothermal system. DOE goal is to drop the cost of Geo power by 90% by 2035 to $45/MW
- Fervo energy is using the **horizontal drilling technology** and **fiber optic sensing** tools from the oil and gas industry to develop low cost geothermal power.
- In Nov 2023, Fervo demonstrated a proof of concept (Project Red) supplying 3.5 MW power to the NV Energy (green power for Google data center). They drilled two wells to reach 7700 feet and then connected with horizontal conduits stretching some 3250 feet long.
- Fervo claims it can hit the DOE cost targets as it scales the technology.
- In a proof of concept experiment, Fervo also showed that it is possible to plug the well to let pressure build up and release it later to <u>**time shift production**</u>.



Fervo Energy's 3.5-megawatt enhanced geothermal plant in Nevada. (Google/Fervo)

4. Chemical Storage - Hydrogen

- **Pros:**
  - Clean fuel. No greenhouse gases. It can be stored, transported and good for seasonal storage.
- **Cons:**
  - Low RTE. Flammable gas. difficult to store and transport, leakage or self discharge.
- From electrolysis of water for H_2 generation and electricity conversion using fuel cell, the round trip efficiency estimate: 0.95x0.75x0.95x0.95x0.50x0.95 = ~31%

Process	Efficiency (%)
AC-DC for electrolyzer	95
Electrolysis	75
H_2 compression	95
H_2 storage (assume 5% leakage loss)	95
Fuel Cell	50
DC-AC	95
RTE	**31**
reasonable guess estimates	

- However, it is very attractive to produce H_2 from renewable resources such as PV or wind, especially when they are asked to curtail.
- Volumetric Energy Density (ED) of H_2 fuel is very low.
- Natural gas ED = 3x H_2 ED (at normal temp and pressure)
- Oil ED = 1000x Nat. gas = 3000x H_2.
- It means 1 tanker volume of oil = 1000 tankers of nat. gas and 3000 tankers of H_2.
- Compression and liquefaction helps little bit in ED, but both (compression and liquefication) requires energy.

4. Advanced Clean Energy Storage Hub in Utah

ADVANCED CLEAN ENERGY STORAGE HUB

TECHNOLOGY: core integrated hydrogen production equipment and electrolyzers

LOCATION: Delta, Utah, USA

Two salt domes, each the size of the Empire State Building, with a storage capacity of 150 GW hours of energy and the ability to house 100 caverns.

Will initially convert more than 220 MW of renewable energy to 100 metric tonnes per day of green hydrogen.

Significant amount of curtailments avoided with hydrogen, a more reliable grid with greater carbon reductions and at a lower system cost

Offtake secured by Intermountain Power Agency. Intermountain Power Plant is an 840 MW GTCC power plant that will use 30% of green hydrogen in 2025, and 100% by 2045.

$504.4 million loan guarantee from U.S. Department of Energy's (DOE) Loan Programs Office to develop the world's largest industrial green hydrogen facility.

MITSUBISHI POWER

4. Generation of Hydrogen - Shades of Hydrogen

- There are different colors of hydrogen **depending on how it is produced**.
- Two major categories: Blue and Green Hydrogen.
- **Green Hydrogen** is produced from renewable electricity, with **water electrolysis**. The most desirable way to produce H_2.
- Electrolyzers are commercially available. It takes approximately 50-60kWh of electricity to produce 1 kg of H_2. Cost is **~ $5/Kg**
- **Blue Hydrogen** is produced from **hydrocarbon fuels** by steam reforming and with **carbon capture**. It is **Grey Hydrogen** without carbon capture.
- Currently most of the hydrogen is produced this way. Cost is **~$2-3/kg.**
- Unless CO level is vey low, H_2 produced this way is not suitable for PEM fuel cells. It can work in solid oxide fuel cells and in combustion turbines to make electricity.
- DOE – "Hydrogen Shot" goal is to reduce the cost of Hydrogen production to $1/Kg in 1 decade.
- IRA (inflation reduction act) has a **tax credit worth up to $3/Kg of hydrogen produced** with near zero emissions. Firms that produce hydrogen using fossil fuels get less.
- The credit ranges from $0.60 to $3 per kg, depending on whole lifecycle emissions.

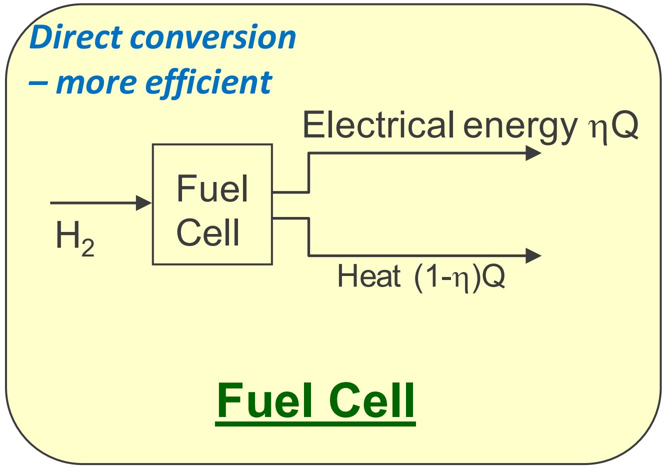
4. Chemical Energy Storage - Hydrogen

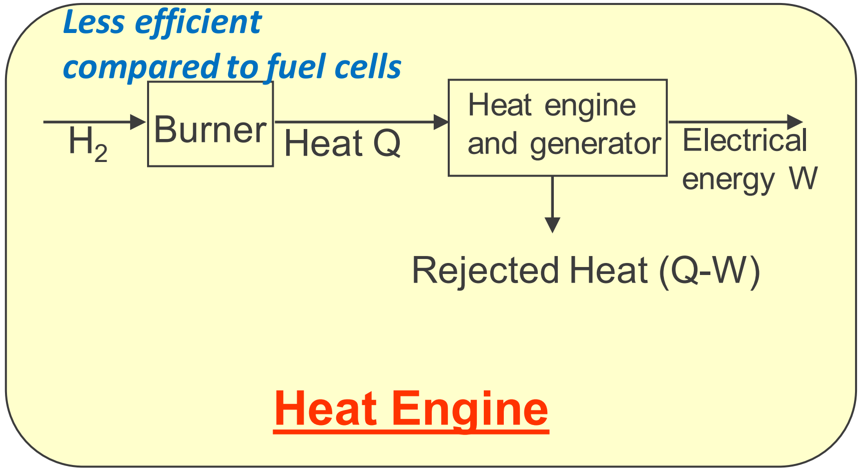
- **Different types of electrolysers**
  - Alkaline water electrolysers – most mature technology, least expensive
  - Polymer exchange membrane water electrolysers – higher efficiency, high purity gas, expensive
  - Solid oxide electrolysers – operates at a higher current density and efficiency. High T operation, degradation issues.
- **H_2 Storage**
  - Compressed Hydrogen
  - Liquid hydrogen
  - Metal hydrides
  - Physical absorbents
  - Liquid organic hydrogen carriers
- **H_2 Transportation**
  - Liquid hydrogen
  - Liquid organic hydrogen carriers
  - Compressed Hydrogen
  - CNG pipelines
- **Conversion of H_2 to other chemicals for storage**
  - Convert hydrogen into ammonia or hydrocarbon fuels.
  - Energy intensive processes, but these are convenient fuels for storage, transportation and use.

4. Conversion of Hydrogen into Electric Power

Two ways of converting chemical energy of hydrogen into electrical energy.

- Direct conversion of H_2 in a fuel cell
- Gas turbine power generator (heat engine)





Hydrogen, oxygen reaction: $2H_2 + O_2 \rightarrow 2H_2O$

- **Fuel cells** are electrochemical devices that converts the chemical energy of a reaction directly into electrical energy. Higher efficiency. $\Delta G = -nEF$, E= 1.23V gives a maximum eff of 83% eff. Actual operating **efficiency is 50-60%,** depending on the operating voltage and other losses.

- In **Heat engines**, fuel is combusted and the released heat is used to produce electricity. In heat engines maximum efficiency is **limited by the Carnot efficiency** $(1- T_{cold}/T_{hot})$.

4. Type of Fuel Cells

- **Polymer electrolyte membrane (PEM) fuel cells**
  •Electrolyte is perflurosulphonic acid membranes (Dupont – Nafion), 25 - 80°C operation, needs humidification, no CO tolerance (need clean hydrogen). The main issues are cost and life time for large utility scale applications.

- **DMFC – direct methanol fuel cells**
  •Fuel is a dilute solution of methanol in water. Electrolyte is same as with the H_2/O_2 fuel cells with few improvements to reduce the methanol cross-over. Electrocatalyst is different on the anode (Pt-Ru). Because it is a liquid fuel, it is very attractive. Issues are: low power density, high precious metal loading (expensive), methanol cross-over (lower efficiency), low methanol concentration (3-5 vol%) in the fuel (low energy density of the fuel). Not used for stationary power application.

- **Solid oxide fuel cells (SOFC)**
  •Electrolyte is a ceramic material, yttria stabilized zirconia, an oxygen ion conductor at high temperatures (800-1000°C). Uses non-precious metal electrodes (Ni anode, conducting ceramic cathode). Because of the high operating temperature – fuel flexible, with hydrocarbon fuels internal reforming is feasible. Issues are thermal shock reliability, high temperature interconnects etc.

- **Alkaline electrolyte (OH^-) fuel cells**
  •Concentrated KOH soln (20-40% KOH) is used as the electrolyte. No CO_2 tolerance. It will react with KOH forming bicarbonate, blocks porous Ni electrodes.

- **Phosphoric acid (H^+) fuel cells**
  •Electrolyte is phosphoric acid, 200°C operation, corrosion problems, cost.

- **Molten Carbonate (CO_3^{2-}) fuel cells**
  •Electrolyte is Li, Na and K carbonate or mixture of carbonates, 650°C operation. Corrosion problems

4. Hydrogen Combustion in Gas Turbines

- Gas turbines with 100% hydrogen combustion are still under development.
- Blending of natural gas and hydrogen is the near term opportunity. **Hydrogen blends up to 30% have been demonstrated.**
- Several large turbine manufacturers, including GE, Siemens, Mitsubishi, and Kawasaki, are in various stages of development and operational testing of hydrogen-powered turbines for electric grid use.

Few things to consider with H_2 combustion:

- The blend-in of hydrogen in gas turbines affects the **stability of the flame** because hydrogen changes the combustion chemistry. Careful design of the combustor is needed.
- With H_2, the **flame propagation velocity is very high** — up to seven times faster than natural gas, which may lead to flame instability, undesirable pressure fluctuations, and mechanical stress on the parts of the combustor.
- **Hydrogen burns at a higher temperature**, which leads to the production of up to three times as much nitrogen oxides (NOx) than the burning of natural gas.
- The oxidizer can be air or pure oxygen (to eliminate NOx emissions). However, it requires careful burner design, due to the high temperature and combustion characteristics of this flame option.
- On the mass basis, the heating value of hydrogen is ~2.5x higher than natural gas, but because its lower density, we need 3x more volume of H_2 for the same energy of natural gas. So the **heating value of the 30 vol% hydrogen blended gas will be lower than the 100% natural gas**.

4. Chemical Energy Storage Summary

- **H_2 is one of the good choices for seasonal storage.**
  - Because of the low RTE, it is not ideal for short and medium duration storage.
  - IRA tax credits of up to $3/Kg for onsite green hydrogen makes it very attractive for seasonal storage.
  - DOE announced 7 hydrogen hubs (focused effort with $7B spending) to accelerate H_2 economy. CA is part of one of the hubs.
- **Concerns:**
  - Low RTE (~ 30%) - Electrolysis to electric energy conversion (fuel cell or combustion turbines)
  - Generation of hydrogen - Green H_2 (electrolysis) versus alternatives (reforming hydrocarbons)
  - Need for CO_2 sequestration for H_2 generation from hydrocarbon fuels
  - Storage and transport of H_2
  - Self discharge losses
  - Low volumetric energy density
  - Safety
- **Alternatives:**
  - Convert hydrogen into ammonia or hydrocarbon fuels.
  - Energy intensive processes, but these are convenient fuels for storage, transportation and use.

Summary

- Currently Li ion battery is the most dominant storage technology for short and medium duration storage.
  - However, there are safety concerns and cost issues.
  - Costs are getting lower, but due to the inherent materials costs, the battery cost may not reduce <$20/kWh needed for wider deployment of LDES on the grid.

- Other than PHS, most LDES technologies are in the early stages of development. Costs are high, applications are limited.

- Thermal storage is economical if it is placed near a facility that can use thermal energy (industrial heat or process heat).

- For hydrogen storage RTE is low, but with excess renewable power generation, onsite hydrogen generation is a good option for storage, especially with IRA tax incentives.

- In general for all other types of mechanical and thermal energy storage technologies, costs need to be reduced, make the technology suitable for a broad range of storage applications (with high RTE, low self discharge, rapid rate of charge/discharge). Need more proof of concept demonstration installations for technology evaluation and maturity.