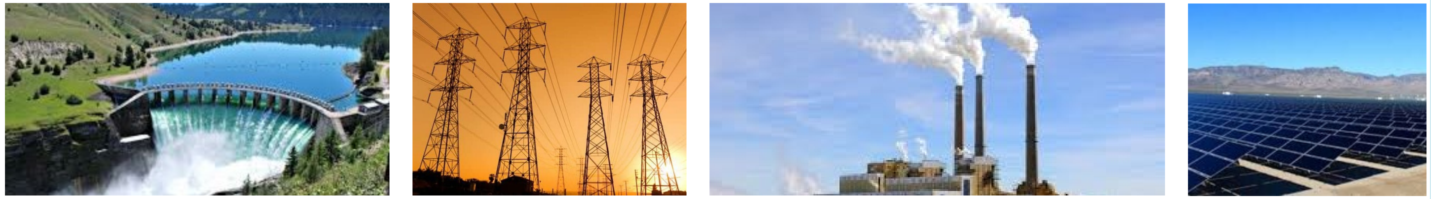
Introduction to Energy Storage



Ramesh Koripella, Ph.D.

Hawaii PUC webinar, Jan 10, 2024.

This work was supported by the DOE Office of Electricity Energy Storage program under the guidance of Dr. Imre Gyuk.

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
SAND2024-00084PE.

SNL-HPUC Energy Storage Webinars

This is the first part of the two part webinars.

January 10, 2024, 2 p.m. to 3:30 p.m. MT

- Introduction to Energy Storage Technologies—standard overview of all energy storage technologies
  - Will be inclusive of hydrogen, ammonia, pumped storage hydro (salt water, fresh water), and recognition that fuel is a form of stored energy.
  - Energy storage between summer and winter.

January 17, 2024, 2 p.m. to 3:30 p.m. MT This will be covered by Dr. Erik Spoerke

- Battery Technology "Deeper Dive"
- Emerging Technologies for Long-Duration Battery Storage
  - Emphasis placed on: Air-iron, solid state, other emerging battery-based storage technologies.
- Applications for Batteries on the Grid
  - Emphasis placed on: 1) various roles of batteries on the grid (e.g., resilience applications, load shedding), which can inform state modeling efforts and RFP planning processes; and 2) Case studies of how other utilities are currently utilizing battery storage systems for grid operations.

Outline

Feel free to interrupt and ask questions as we go along.

We should have sufficient time for Q&A

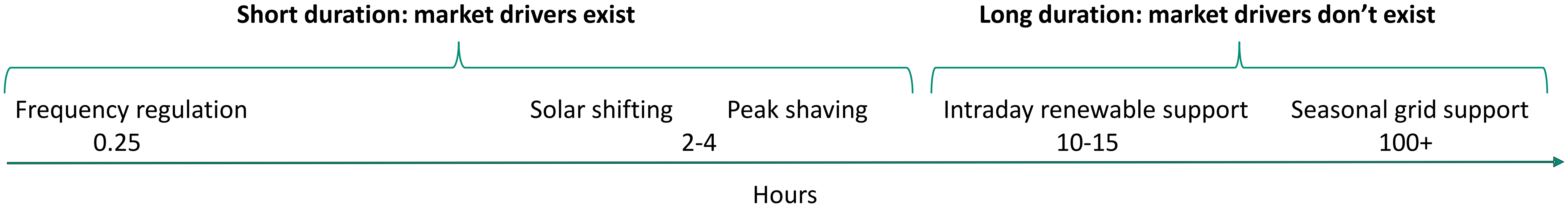
Long Duration Energy Storage (LDES) Need, Classifications

- **Why do we need energy storage?**
  - The supply of renewable power from solar and wind is variable, so flexible resources such as gas powered peaker plants and energy storage are needed to match grid supply and demand.
  - As the percentage of renewables in the grid increases, the need for LDES increases
    (for resiliency, prepare for unpredictable weather events, reduce curtailments and grid services such as frequency response, energy shift, reactive power and voltage control, black start etc)

- **Storage Classifications** (following DOE report – Pathways to commercial Liftoff: Long Duration Energy Storage, Mar 2023):
  - **Short Duration: ≤ 4hrs,** - Li ion batteries, mechanical storage technologies (fly wheels, Pumped Hydro Storage (PHS))
  - **Inter-day LDES: 10-36 hrs** (all mechanical storage, electrochemical technologies such as flow batteries)
  - **Multi-day/week LDES: 36-160+ hrs** (thermal storage, electrochemical technologies)
  - **Seasonal Storage: Several months** (primarily chemical storage – hydrogen, or natural gas with carbon capture)

There are few other different storage classifications in use: for example; Short <4hr, Medium 4-10 hrs, and LDE 10+ hrs

Energy Storage Market Drivers



Short duration: market drivers exist

Long duration: market drivers don't exist

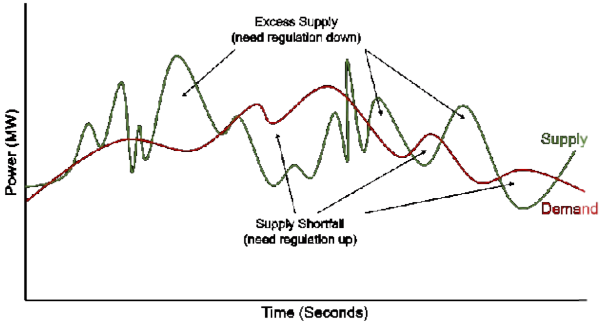
Frequency regulation
0.25

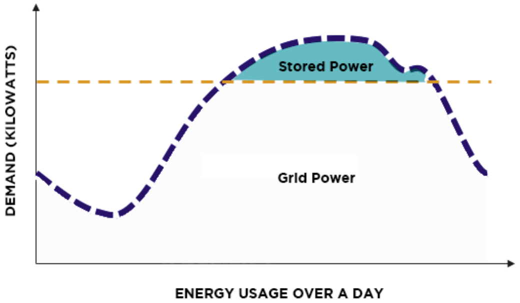
Solar shifting
Peak shaving
2-4

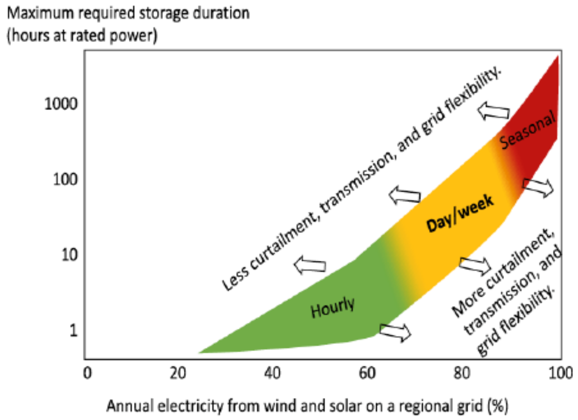
Intraday renewable support
10-15

Seasonal grid support
100+

Hours







Ref: Albertus et.al, Joule 4, 21-32, Jan15, 2020

ISO requirements for energy storage capacity resource

ISO	Capacity Duration (hours)
ISO-NE	2
MISO	4
CAISO	4
NYISO	4
SPP	4
PJM	10

Mainly Li ion batteries

- Market drivers exist for short and medium duration energy storage.
- Today no market mechanism exist to address LDES needs.
- ISO market operations are mostly a day-ahead and intraday spot market construct.
- There is a need for market products that explicitly reflect energy storage capabilities concerning time shifting production and delivery of energy and value storage in that capacity (hedge against uncertainties).
- **Hawaii do not participate in any RTO or ISO.**

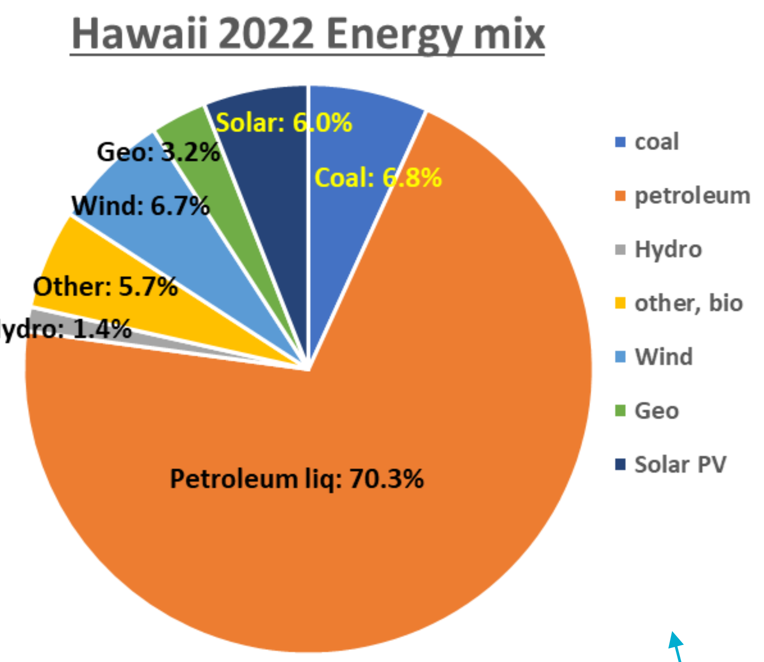
LDES Key Challenges

- **Reduction in cost**.
  - Simulations show that for LDES, cost < $20/kWh and RTE >50% are needed.
  - LDES technologies with low cost materials and volume manufacturing is needed.

- **Develop more use cases for the adaption of LDES for a broad range of grid service applications.**
  - Because of the huge capital investment for LDES, if the LDES is used only for few very long duration cycles, the pay back period will be long. To be competitive, we need to utilize them for more applications.
  - If we have 10+ hrs storage, can we meet 1-4hr needs also? – not necessarily! (currently it is technology and application specific).

- **Energy Storage technology limitations.**
  - Technology maturity, ability to respond quickly with load changes, RTE, self discharge.
  - Difficult to meet all requirements in an optimized LDES to apply for a wide range of use cases.

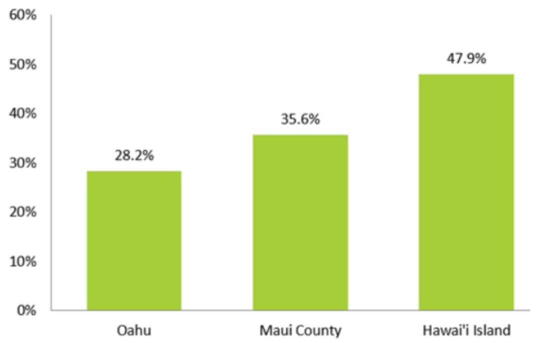
Electric Power Generation Sources in Hawii (2022 data)



Source: US EIA data, Electric Power monthly Feb 2023

This includes only Utility Scale solar

Percentage of generation from renewable energy

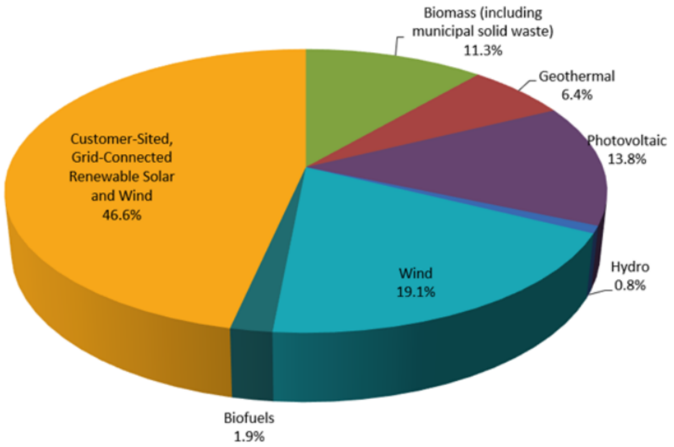


Percentage of generation from renewable energy in 2022

- Oahu - 28.2%
- Maui County - 35.6%
- Hawaii Island - 47.9%

This includes all solar

Where is this renewable energy coming from?

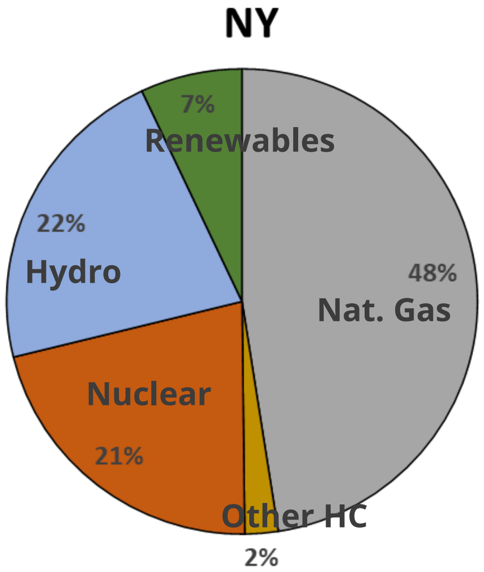


Gigawatt-hours of renewable energy produced in 2022

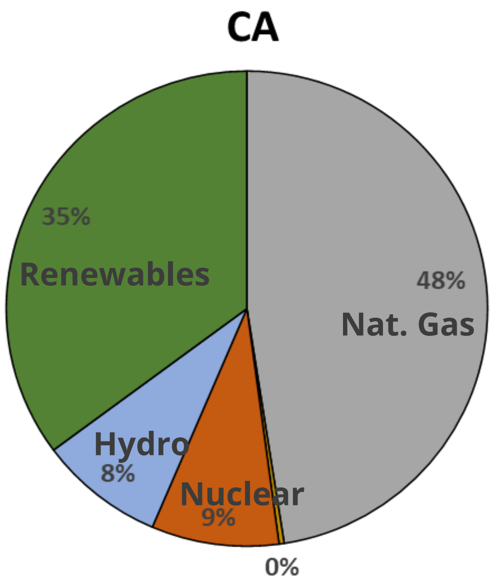
- Wind - 626
- Biomass (including waste-to-energy) - 371
- Solar Photovoltaic - 451
- Geothermal - 208
- Hydro-electricity - 27
- Biofuels - 63

- Hawaii Electricity (2022 EIA data): Total electricity generated: 9.182 TWh, conventional (hydrocarbon fuels): 77.1%, Renewables: 22.9%
- Total Solar in 2022 is 1833 GWh. However, Utility scale solar is 568 GWh and rest (customer sited) is 1265 GWh.
- Kauai Island Utility Coop (KIUC): total gen: 236 MW, renewables: 148 MW (62%).
- Hawaii shut down the last coal plant in Sept, 2022.
- 158 Tesla Mega packs (565 MW capacity), replaces key coal plant functions.

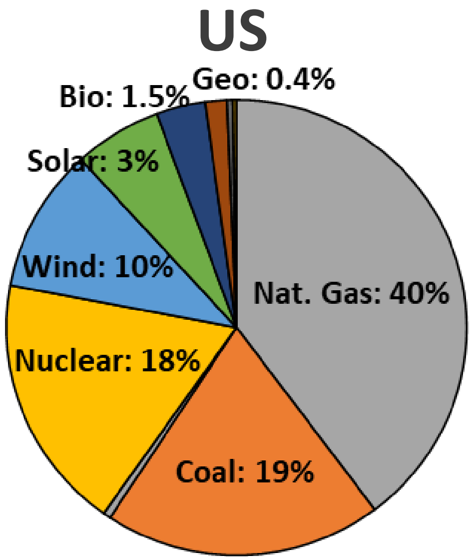
Electric Power Generation Sources in US. States of NY, CA and HI (2022 data)



Total: 125.2 TWh



Total: 205.2 TWh

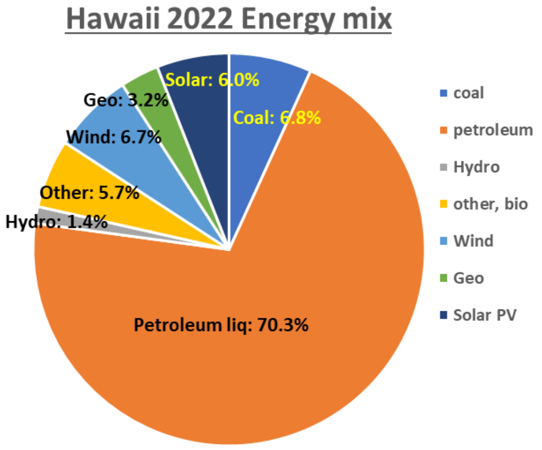


Total: 4248 TWh

Electric Power Generation Sources in 2022

	US		CA		NY		HI	
Source	**TWh**	**%**	**TWh**	**%**	**TWh**	**%**	**TWh**	**%**
Nat. Gas	1689	39.8%	97.6	47.5%	59.8	47.5%	0.0	0.0%
other HC	851	20.0%	0.7	0.3%	2.9	2.3%	7.6	79.9%
Nuclear	772	18.2%	17.6	8.6%	26.8	21.3%	0.0	0.0%
Hydro	262	6.2%	17.3	8.4%	27.5	21.8%	0.1	1.4%
Renewables	674	15.8%	72.2	35.1%	8.8	7.0%	1.8	18.7%
- Solar	*146*	*3.4%*	*62.4*	*30.4%*	*5.5*	*4.4%*	*0.57*	*6.0%*
- Wind	*435*	*10.2%*	*15.7*	*7.6%*	*4.8*	*3.8%*	*0.63*	*6.7%*
Total Gen. Energy (TWh)	**4248**		**205**		**126**		**9.5**	
PHS Storage Energy (TWh)	**6.03**		**0.155**		**0.451**		**0**	
Capacity (GW)								
Power Gen.	**1160.1**		**85.9**		**39.8**		**2.9**	
Storage								
- PHS	23.05		3.91		1.41		0	
- Other	8.82		4.72		0.15		0.11	

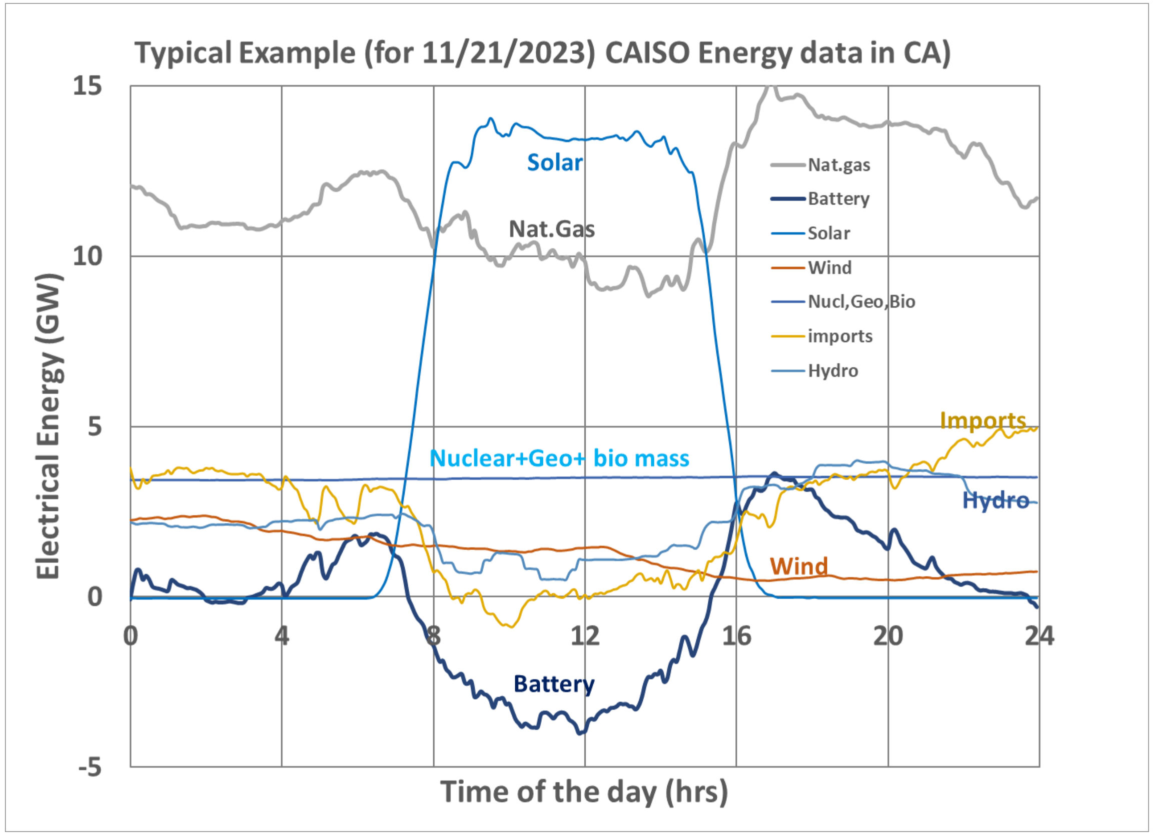
Source: EIA, Electric Power Monthly Feb 2023

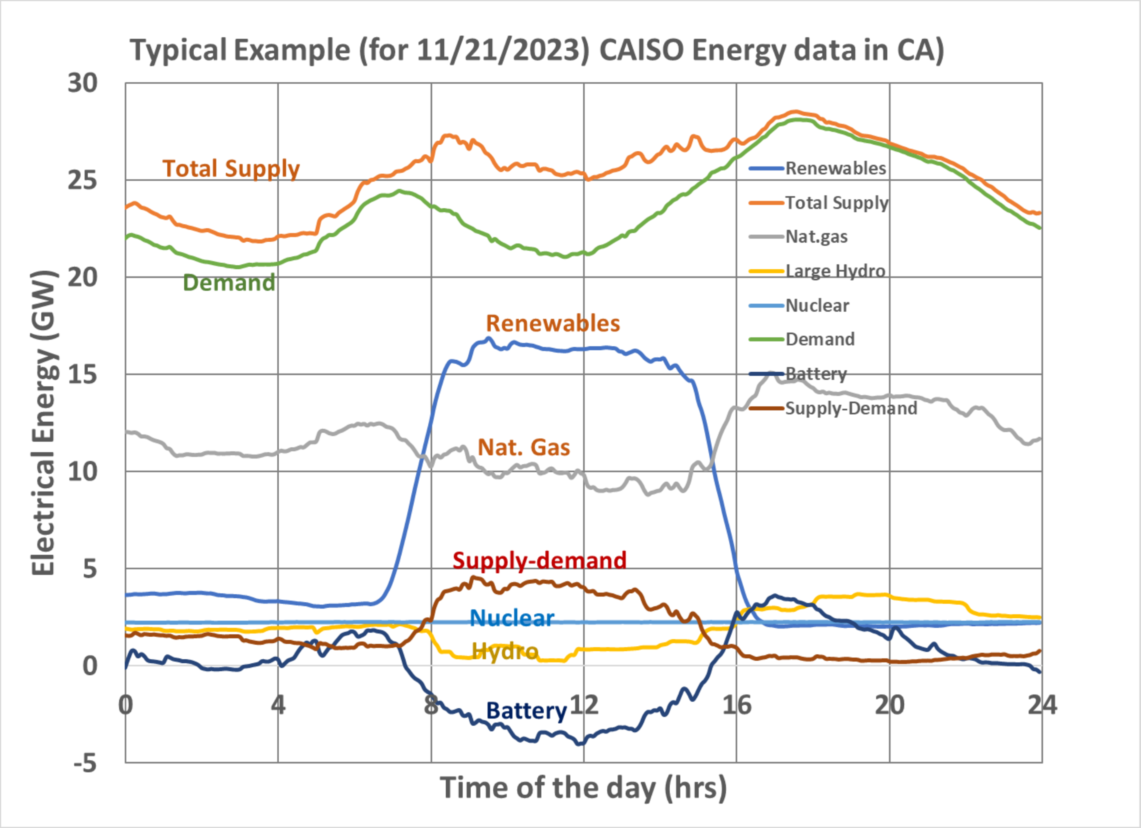


Total: 9.5 TWh

- Energy density of Diesel: 10.7kWh/L, it is ~ 1000x more than nat. gas, and 3000X more than H_2 gas.
- Diesel 12.7 kWh/Kg is also ~1.5 higher than coal.
- Economic reasons versus environmental concerns.

CAISO Electric Power Generation Sources (11/21/2023 CAISO data)





- Natural gas, imports, hydro and batteries are all responding to increasing load demand and falling solar supply (9GW/hr).
- Battery cycle: on average 2 cycles per day. Average energy is 20 GWh. CAISO has 5 GW of storage, so it is a 4 hr battery (aggregation of several battery storage sites). Peak is 4 GW.
- CAISO has 5 GW of battery storage on the grid, but average utilization during charge: 1.3 GW and discharge: 2.2 GW (26-44% range).

Energy, Power and Applications

Storage for Energy and Power applications:

- **Energy (KWh)** can be thought of as volume (power x time) or capacity, while **Power (KW)** can be thought of as the rate of flow.
- **Energy applications** involve continuous storage system discharges over periods of hours and correspondingly long charging periods. They typically involve **one or two charge-discharge cycle per day**. **Applications include**, peak shaving, load-leveling, transmission and distribution upgrade deferral, customer demand charge and energy charge reduction, renewables generation shifting and energy arbitrage or commodity storage.
- **Power applications** involve comparatively short periods of discharge (sec to minutes) and short recharging periods, often requires **many cycles per day**. **Applications include**, frequency and voltage regulation, power quality, renewables generation smoothing and ramp rate control and trackside regulation for electric rail operators. For example: Li ion batteries
- ***Evaluate and select the energy storage system for the application requirements.***

*(for example, **Form Energy** claims it is targeting energy application. They do not want to compete with Li battery in power application. It is positioning as a supplement to it for grid reliability (under multiple day uncertainties), rather than participating in power application. Can we build all Li battery LDES? - too expensive.*

Few Technology Options for LDES

Mechanical Storage (short, medium, long-term 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-term 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 term and seasonal storage)

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

Electrochemical (Batteries) **Storage** (short, medium, long-term storage) - covered 1/17/2024

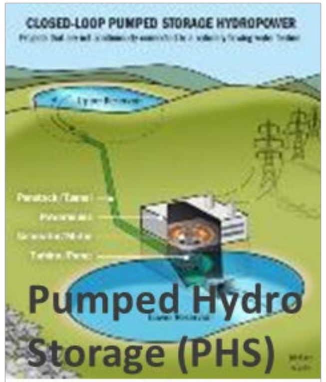
- Lithium-Ion Batteries,
- Sodium-Ion Batteries, Molten Sodium Batteries
- Zn-Based Batteries, Ni-H_2 batteries
- Metal-Air Batteries
- Flow Batteries

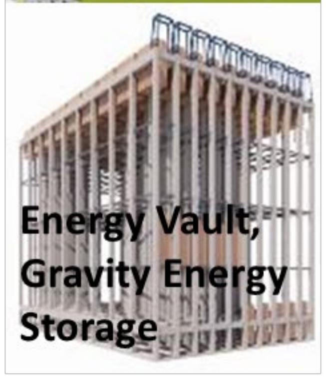
1. Mechanical Storage

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

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

Mechanical Energy Storage

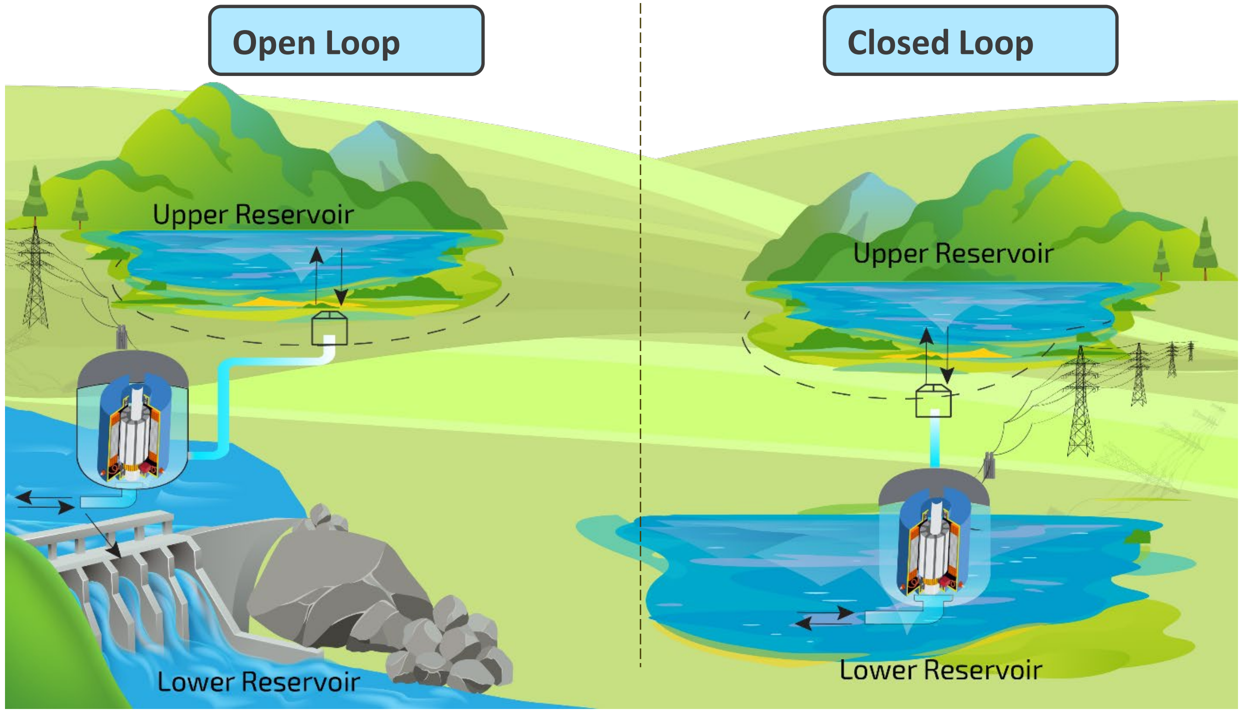




Pumped Hydro Storage (PHS)

- **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.



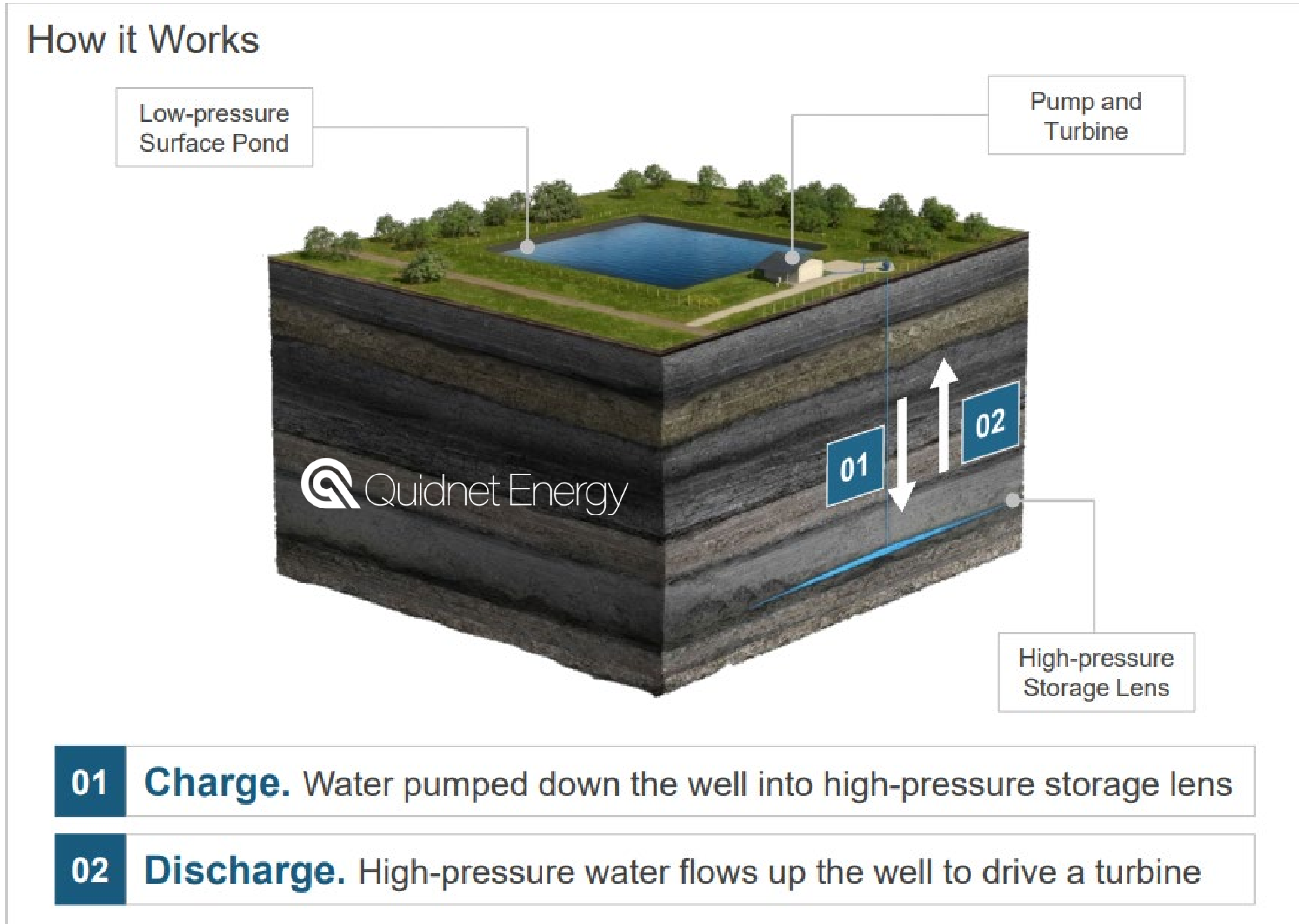
Closed loop:
- Comprises two reservoirs that are interconnected but otherwise separated from a natural water source.
- Have the advantage of limiting impact on the natural aquatic environment.

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

Variations of PHS- Quidnet Energy

Geomechanical Pumped Storge – Subsurface Pumped Hydro



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

Proof of concept stage

Storage Process

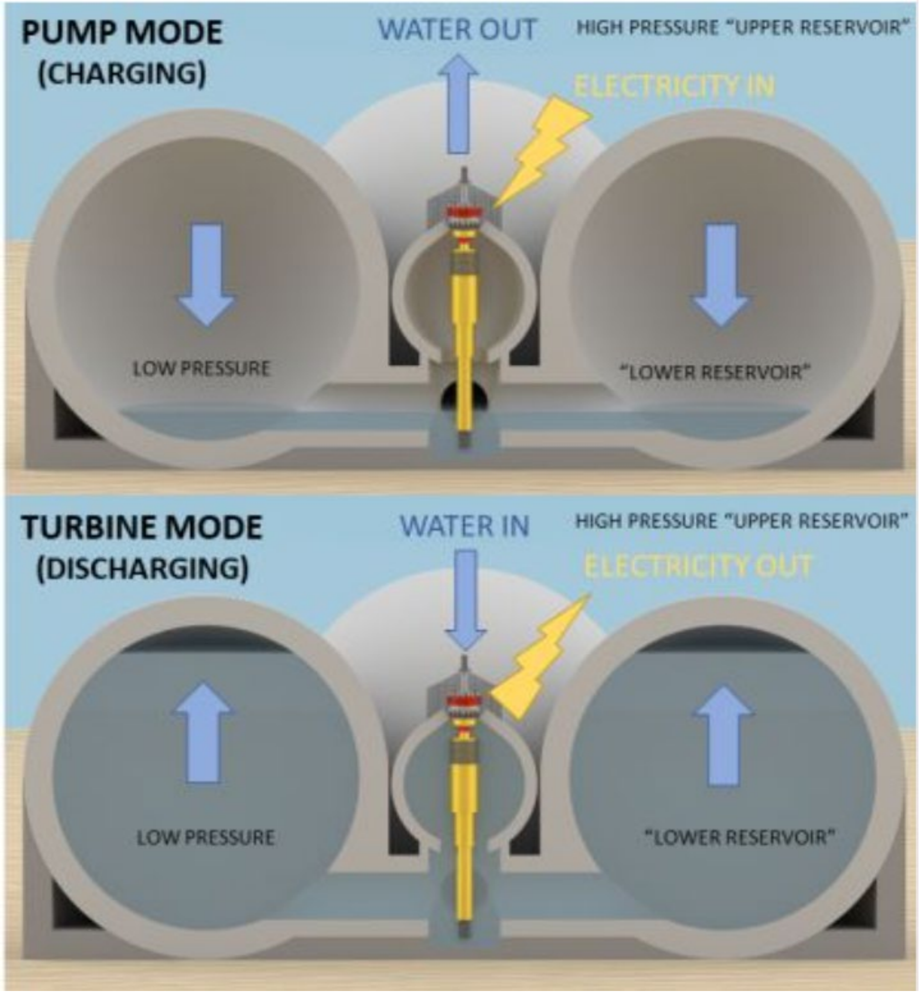
- Pump water from a pond down a well and into a body of rock.
- The well is closed, keeping the energy stored under pressure between rock layers for as long as needed.
- When electricity is needed, the well is opened to let the pressurized water pass through a turbine to generate electricity, and return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

1-10 MW systems,
10+ hour modules

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

1.1 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.
- Currently more than 95% of US energy storage is PHS. ~6.1 TWh in 2022.
- But it is only 2.3% of total Hydroelectric power generated (262 TWh) and 0.14% of total energy generated in the US (4248 TWh) in 2022.

Disadvantages:

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

Hawaii has none (or very little) PHS. It should be explored further. It may be possible to integrate PHS with some Hydroelectric generation (>100 GWh).

1.1 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.
- China is building several large PHS, but not much activity in the US. China recently opened a 3.66 GW facility in Hubei province, it consists of 12 reversible pump generation sets, each 300 MW capacity for a 6.61 TWh energy. (Compare with Hoover dam: name plate capacity 2.08GW and 4 TWh energy).
- New PHS in planning stage (US): rPLUS is planning to build a 1-gigawatt/8-gigawatt-hour (with 2200 ft elevation gap between two reservoirs) in White Pine County, NV, another 0.8MW project in Wyoming. These would be some of the large scale PHS projects built in US in decades. Construction not started yet. Both are closed loop systems.
- 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**. In some circumstances it may be economic to stop producing hydro electric power and do storage.
- Despite the challenges (long permitting and installation process, huge capital cost) a more detailed **techno economic analysis is needed for PHS storage**.

1.2. Flywheels, 1.3. 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. Safety issues. Scaling issues for GW scale.
  - Not many new grid scale installations. Li ion batteries pretty much taken over this market.

- **Gravity Based Energy Storage Systems:** Move a large mass with a crane or 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

1.3 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

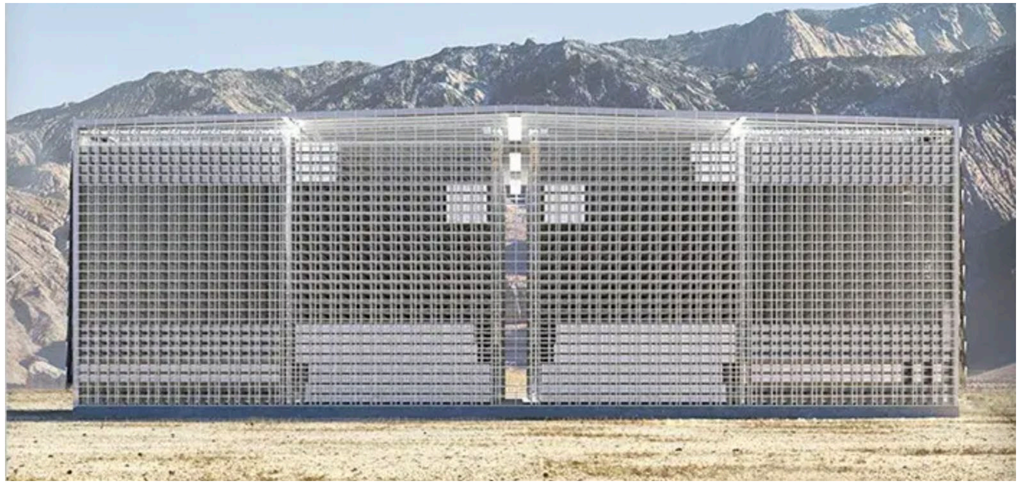
Prototype completed in July 2021 in Ticino, Switzerland

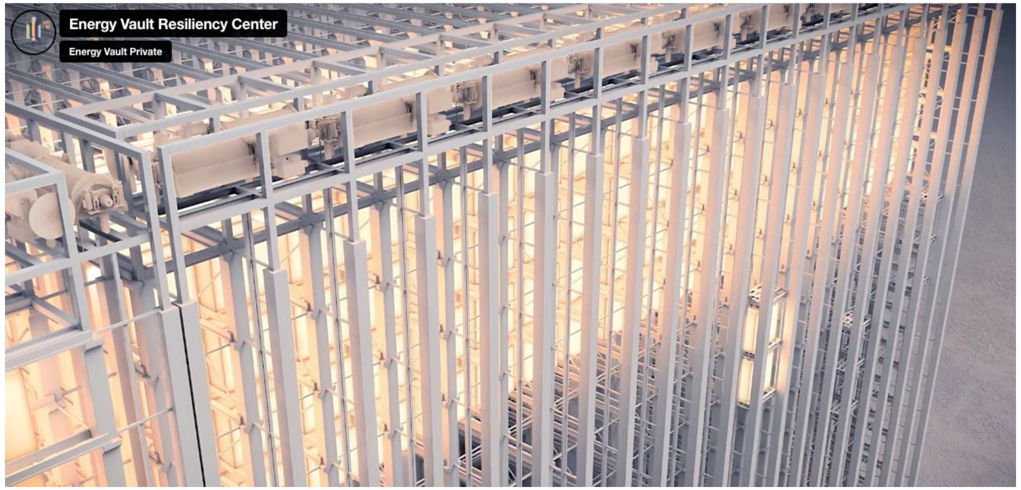
- Scalable in 10MWh increments
- 2-4 hour and 4-12+ hour duration
- Emphasizes local, sustainable sourcing of materials

Issues:

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

1.3 Gravity Storage: Stacked Blocks





- Energy Vault® EVx™ system raises/lowers 30 ton bricks
- Scalable in 10MWh modules
- China Tianying Group (CNTY) is installing a 25 MW/100MWh system in Rudong, China (near Shanghai)

ENERGY VAULT
Enabling a Renewable World

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

1.3 Gravity Storage: Rail Cars

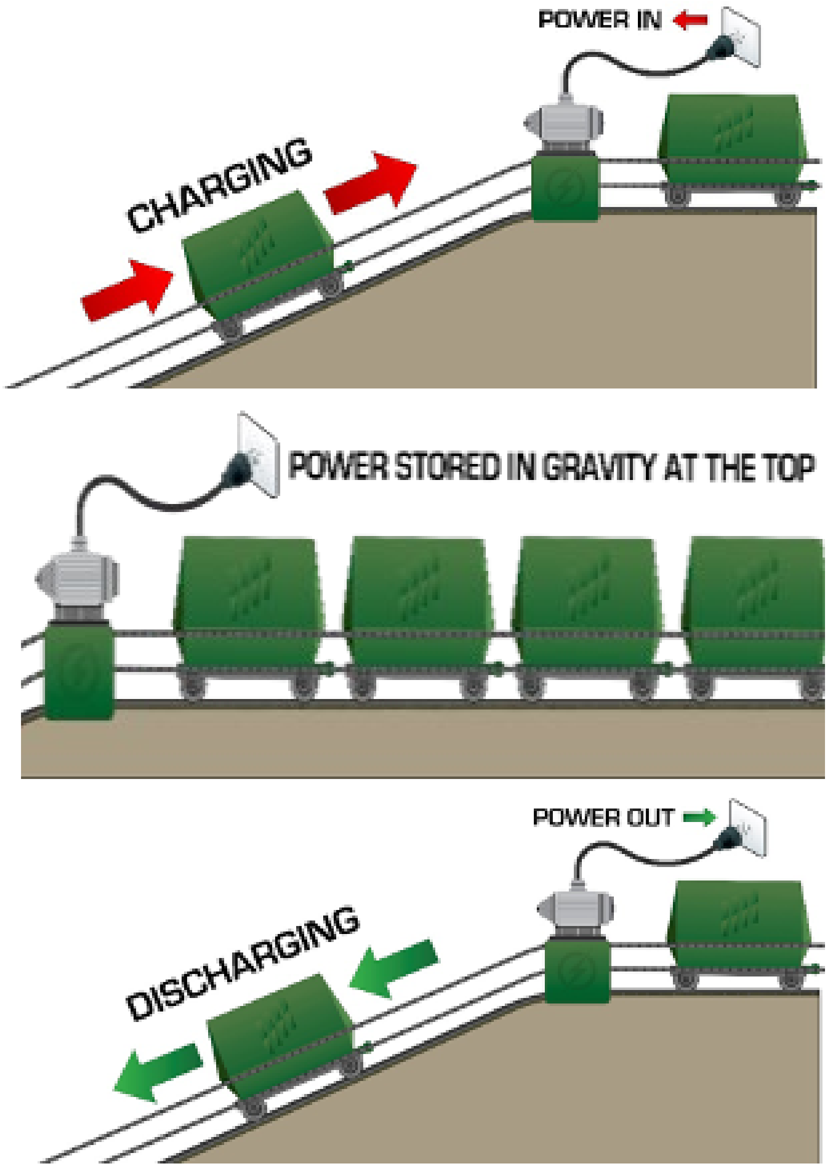
Advanced Rail Energy Storage (ARES)

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^{TM} 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.



1.4 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.

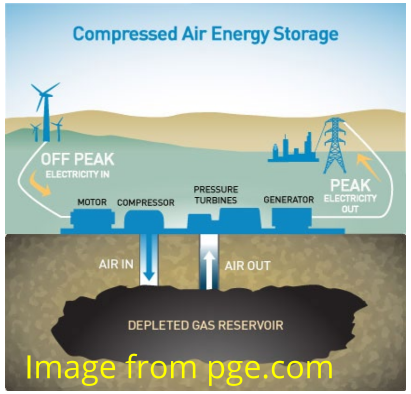
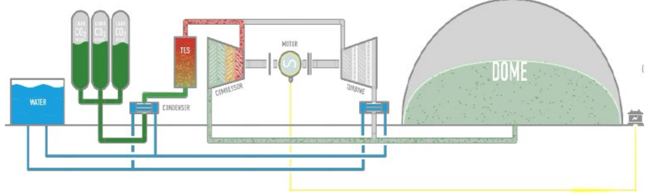


Image from pge.com

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

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

Energydome, https://energydome.com/



1.4 Compressed Air Energy Storage (CAES)

Examples of Current conventional CAES systems:

- Uniper Kraftwerke GmbH (Huntorf, Germany) 290 MW, 2 hour discharge time operational 1978
- Power South Energy Coop (McIntosh, Alabama) 110 MW, 26 hour discharge time (2.86GWh), operational 1991

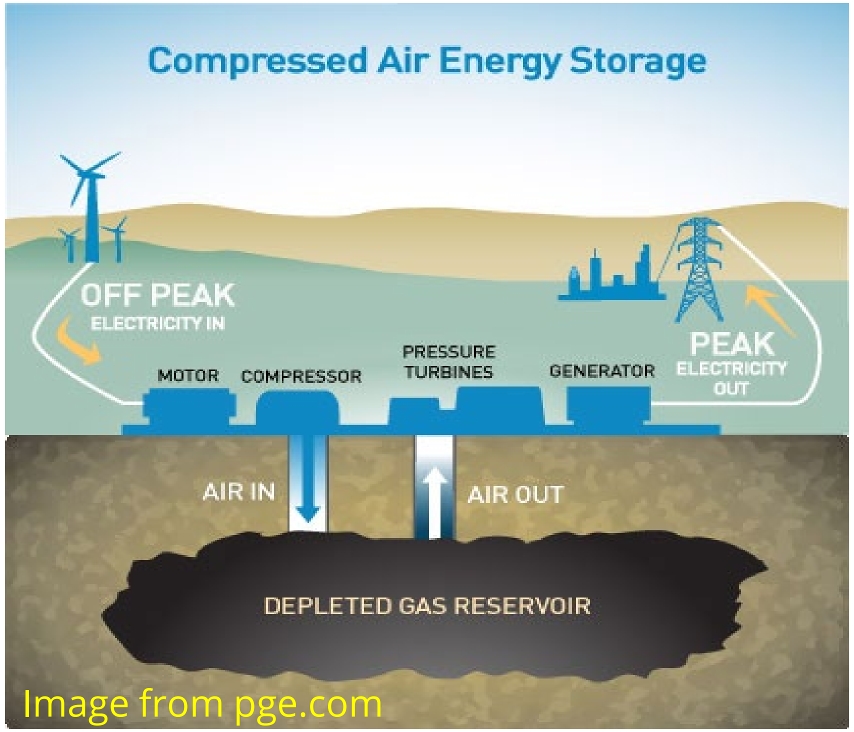


Image from pge.com

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

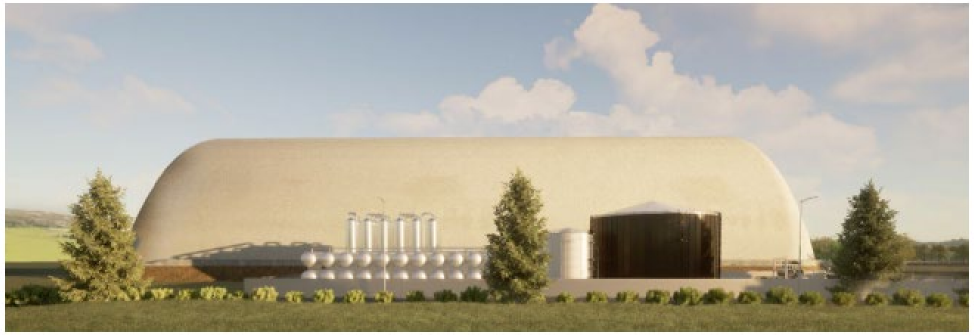
Proposed Hydrostar plant, planned to provide 500 MW, 4GWh, (Rosamond, CA)

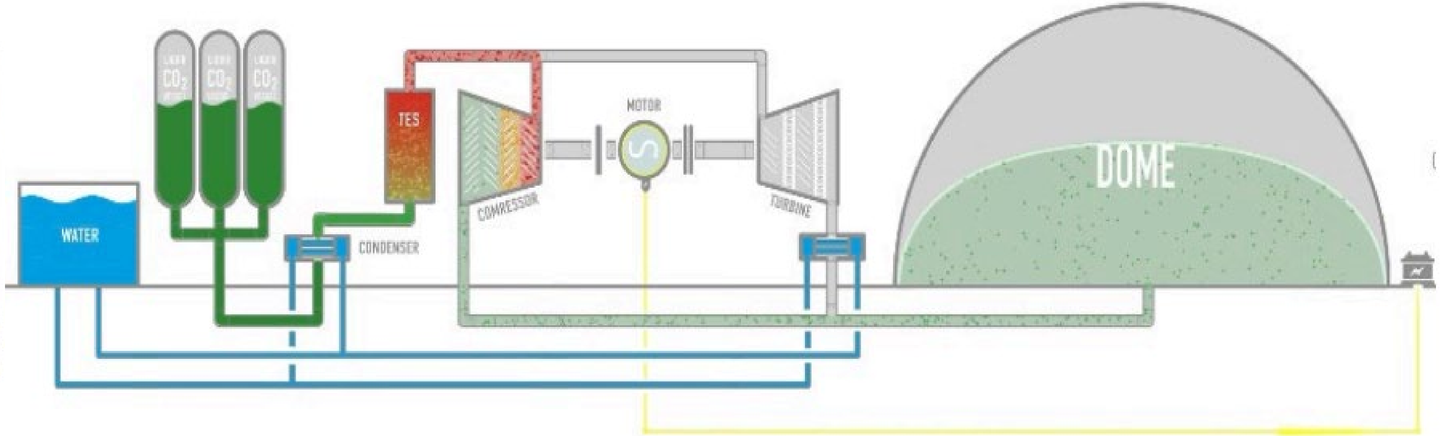
Only two operational commercial units, which were built several years ago. None since then. Several new proposals.

Issues:

Need stable depleted gas reservoirs. Contamination of working fluid. Higher self discharge. Capturing and storing heat for high efficiency. Over all low RTE.

1.4 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).
- 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.
- Development started on CO2B Version 3.0, unit with larger turbine/compressor and higher efficiency (Pilot plant V1.0, Commercial Plant V2.0).

Proof of concept demonstrated. 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

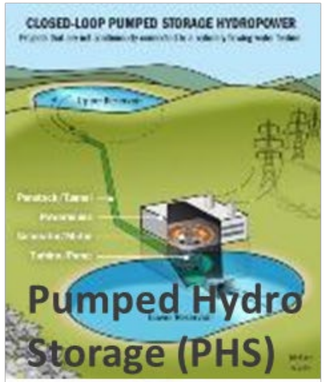
② **Idle**
- Liquid CO2 stored at ambient temperature in CO2 vessels

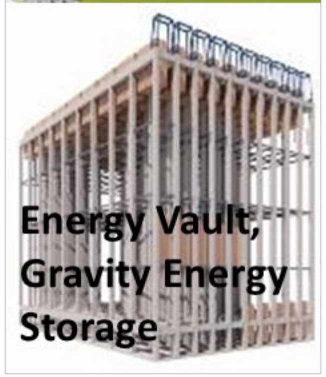
③ **Discharging**
- Liquid CO2 is evaporated and heated by recovering heat from TES
- Reheated CO2 expands in turbine, returning power to the grid
- Gaseous CO2 is stored in Dome at ambient temperature and pressure without emissions to atmosphere

1. 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 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





2. Thermal Storage

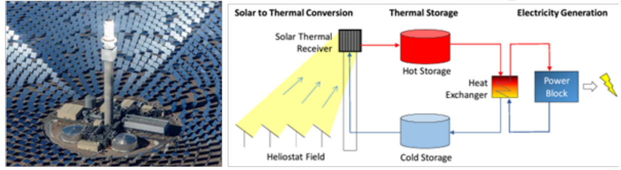
Thermal Storage

- 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 (industrial heat or process heat).

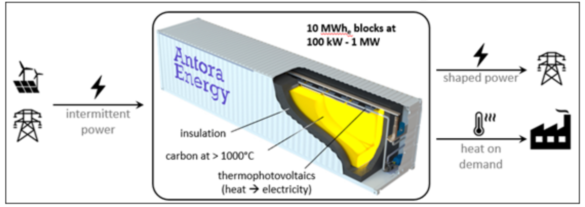
- **Different variations:**
  - Molten salt thermal storage. *– more mature*
  - Ceramic particle storage media. *– early R&D*
  - Fixed bed thermal storage. *– early R&D*
  - Heated brick or carbon blocks *– proof of concept stage*
  - Molten metal. *– early R&D*
  - Liquid metal battery. *– proof of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

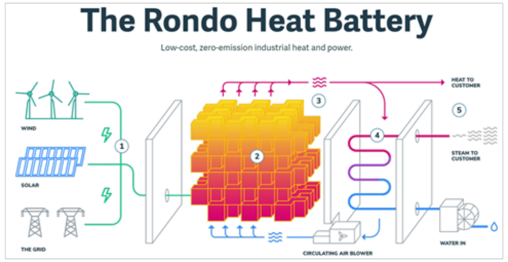
Thermal Energy Storage

Concentrated Solar Thermal Storage

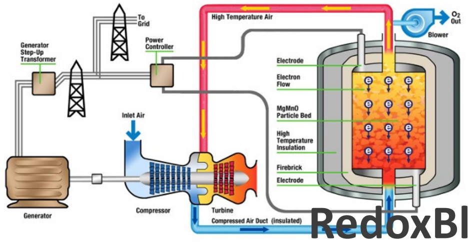


Antora, Thermal Storage





Malta



RedoxBlox

2. Molten Salt Thermal Storage

- More developed technology with concentrated solar power.
- Similar technology, but grid scale applications using renewable electrical energy to thermal conversion (for storage) is relatively new.
- 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 ~200-300C 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)
280MWhe 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$_e$)

2. Thermal Storage Examples

MALTA

Molten salt storage

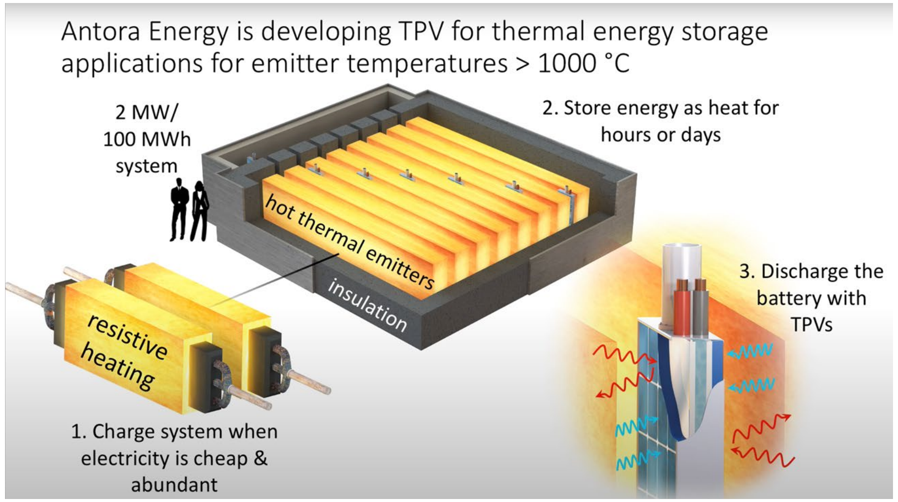
[Proof of concept stage]()

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 750^{o}C. Using steam turbine, generator to produce 24 hour storage at 1.5MW

[Proof of concept stage]()

2. Thermal Storage Examples

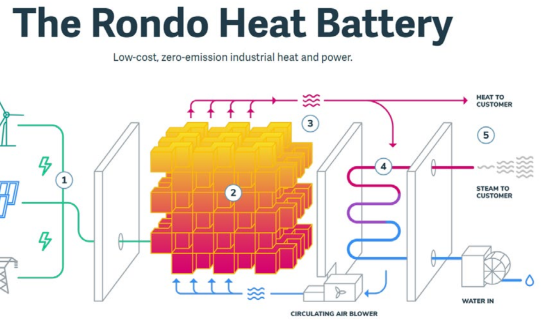


Antora Energy is developing TPV for thermal energy storage applications for emitter temperatures > 1000 °C

ANTORA

Use renewable power to heat graphite blocks. Store thermal energy. Use TPV to convert into electrical power.

Proof of concept stage

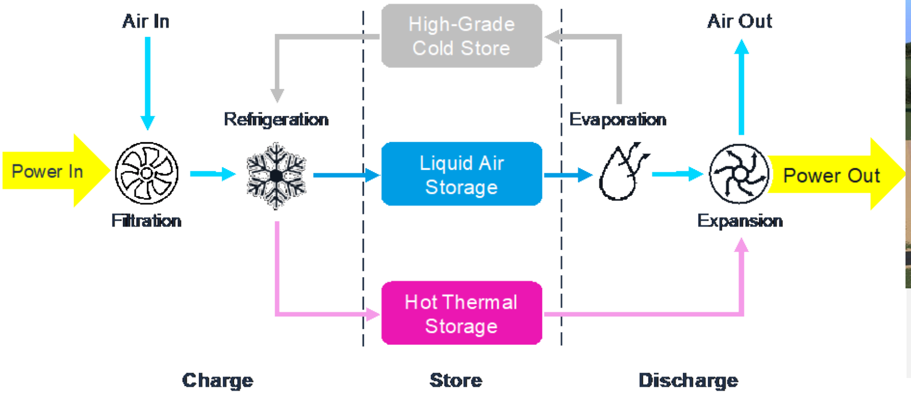


Use renewable power to heat ceramic bricks with heaters. Store thermal energy. Air is the working fluid for heat transfer. Initially targeting thermal storage only for industrial use.

Proof of concept stage

2. Thermal Storage Examples

Liquid Air Energy Storage



50 MW Facility (400 MWh) concept

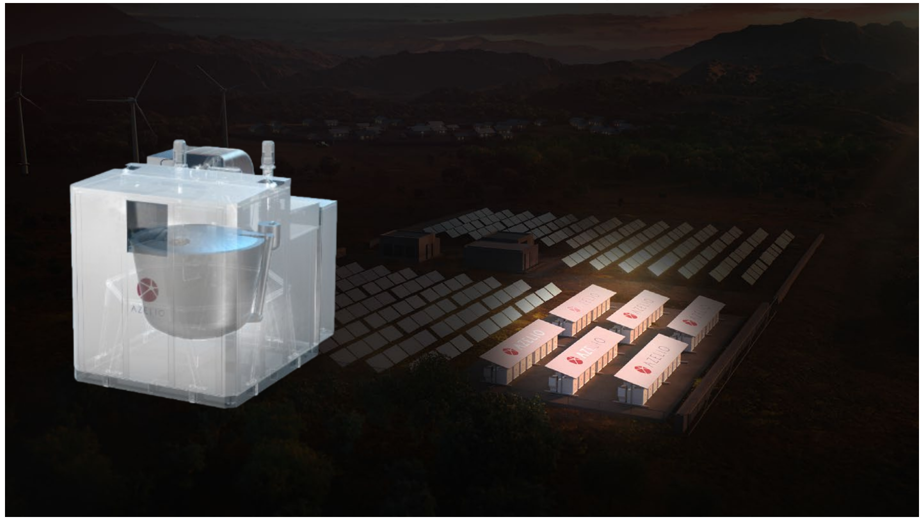
Highview Power®

Charge: Store energy through condensation of refrigerated air.

Discharge: Gaseous air generated during reheating turns a turbine to generate power.

Proof of concept stage

Liquid Metal Energy Storage



AZELIO

- Electrically-generated heat stored in a recycled aluminium phase change alloy at the melting point of 600°C
- Heat transferred to Stirling engine to provide power

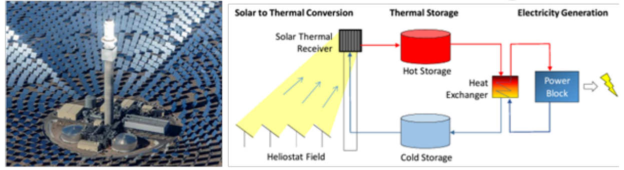
Proof of concept stage

2. Thermal Storage Summary

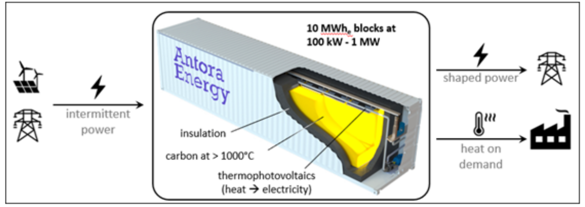
- **General issues:**
  - Suitable for long duration storage. Not ideal for short or medium duration (not competitive with batteries).
  - RTE: 55-65% range.
  - Ideal if co-located with a facility where heat can be used for process heat.
  - Compressors, heat exchangers are known technology.
  - Molten 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, 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**.

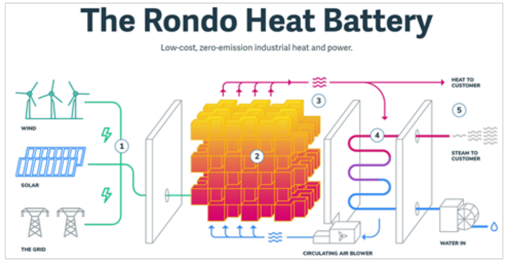
Thermal Energy Storage

Concentrated Solar Thermal Storage



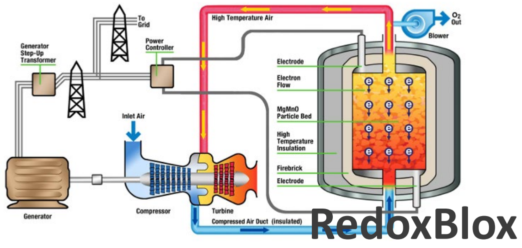
Antora, Thermal Storage




The Rondo Heat Battery

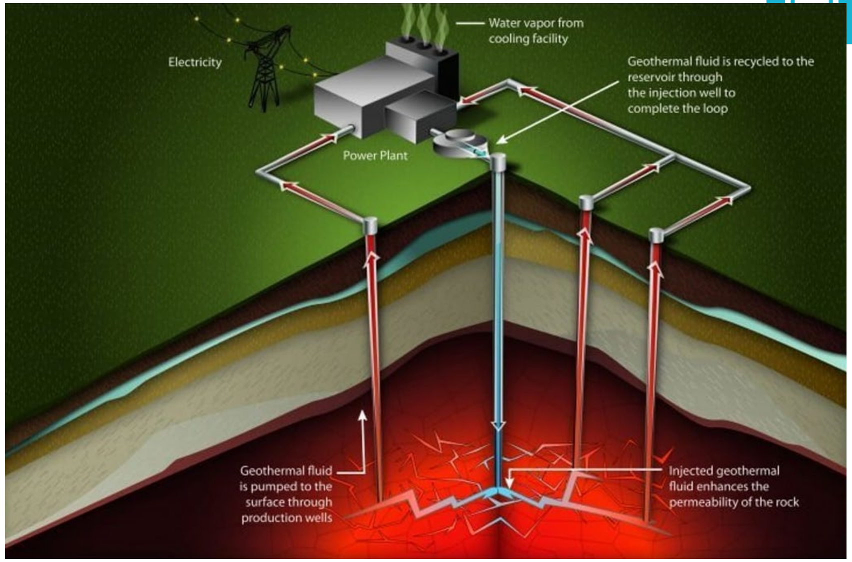
Low-cost, zero-emission industrial heat and power.


Malta


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 time shift production.



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

Yesterday (1/9/24) MIT Tech Review Magazine included it in the 2024 list of 10 breakthrough technologies.

Geothermal Energy

- **Available Heat flow**
- Q (heat flow W/m^2) = K_t (W/m.C) * dT (temp diff °C) /d (depth, m)

- **Available Energy, Key factors**
  - The temperature of the hot rock
  - The flow rate of water through the hot rocks
  - The volume and surface area of the hot rock exposed to the circulating water
  - The permeability in the hot rock (Sufficient to allow free flow of injected water through a large volume of rock)
  - The energy needed to drive the water pumping system (Efficiency loss)

- **Depletion**
  - Over time, the hot rock source will cool as heat is continually extracted from it by the circulating water. Calculations indicate that in some locations it could take 30 years to cool and then 20 years to regenerate sufficient heat again.
  - In an operating hot dry rock geothermal system, this would necessitate shifting of the circulation cell to another part of the hot dry rock body to allow time for heat regeneration.

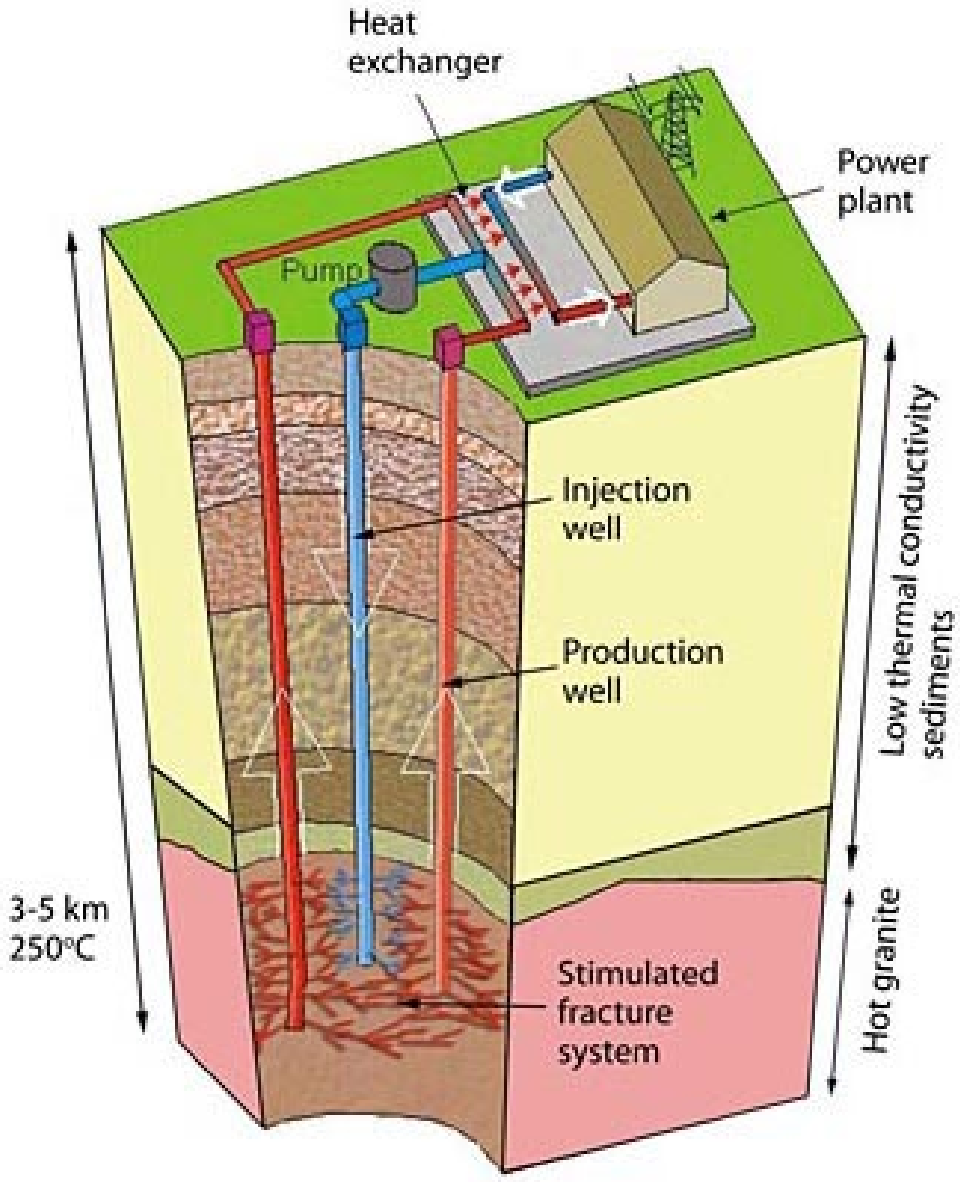
- **Efficiency**

Maximum efficiency is limited by Carnot efficiency ($1-T_c/T_h$)

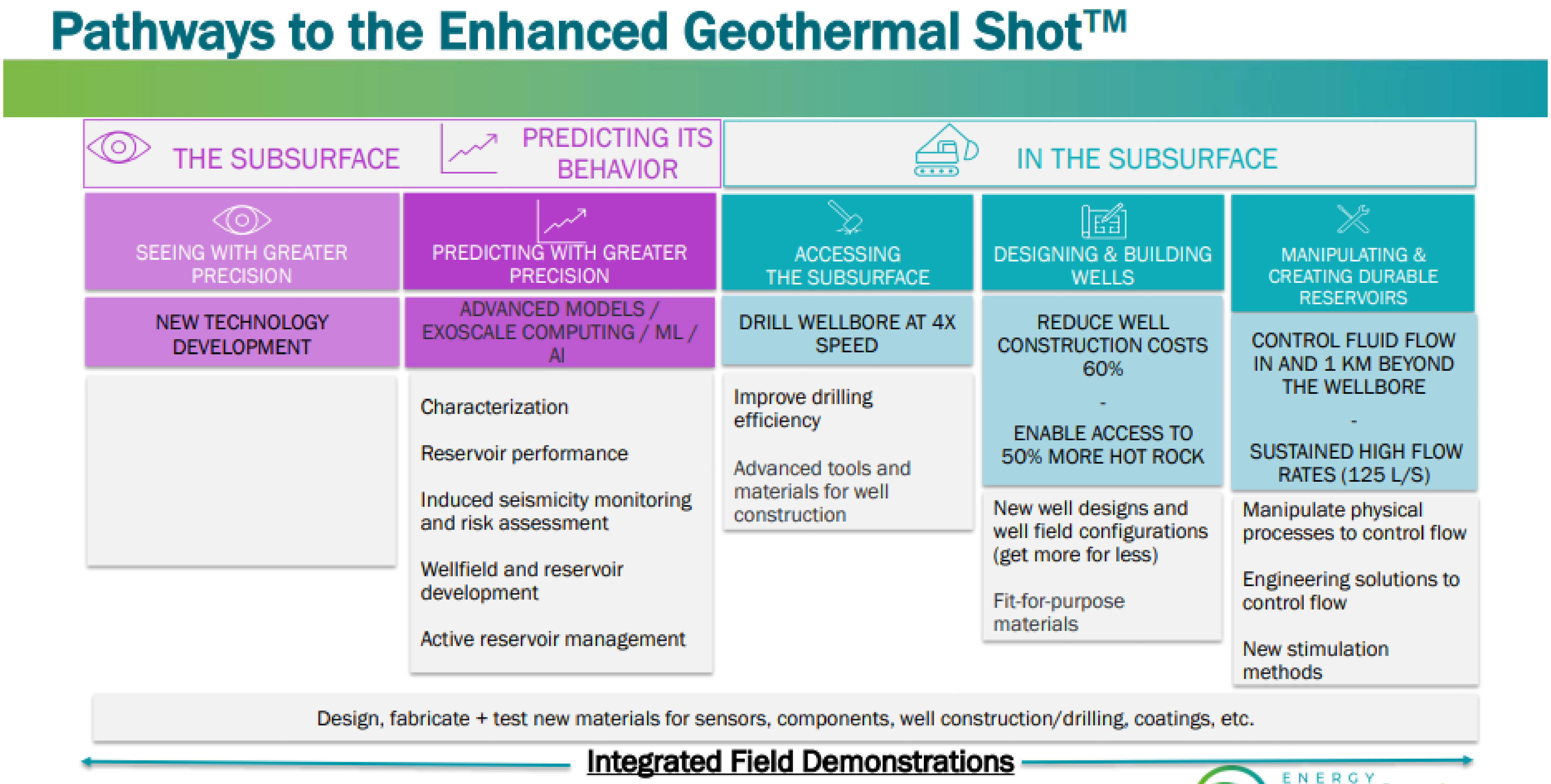
For water supply temperature of 200°C and a return temperature of 35°C, the maximum possible thermal efficiency will be

$$1 - (35+273)/(200+273) = 35\%$$

Including heat losses, pump losses, conversion losses, the total efficiency may be half of this value.



Enhanced Geothermal Shot™ Technology Pathways



Pathways to the Enhanced Geothermal Shot™

THE SUBSURFACE	PREDICTING ITS BEHAVIOR	IN THE SUBSURFACE		
SEEING WITH GREATER PRECISION	PREDICTING WITH GREATER PRECISION	ACCESSING THE SUBSURFACE	DESIGNING & BUILDING WELLS	MANIPULATING & CREATING DURABLE RESERVOIRS
NEW TECHNOLOGY DEVELOPMENT	ADVANCED MODELS / EXOSCALE COMPUTING / ML / AI	DRILL WELLBORE AT 4X SPEED	REDUCE WELL CONSTRUCTION COSTS 60% - ENABLE ACCESS TO 50% MORE HOT ROCK	CONTROL FLUID FLOW IN AND 1 KM BEYOND THE WELLBORE - SUSTAINED HIGH FLOW RATES (125 L/S)
	Characterization Reservoir performance Induced seismicity monitoring and risk assessment Wellfield and reservoir development Active reservoir management	Improve drilling efficiency Advanced tools and materials for well construction	New well designs and well field configurations (get more for less) Fit-for-purpose materials	Manipulate physical processes to control flow Engineering solutions to control flow New stimulation methods

Design, fabricate + test new materials for sensors, components, well construction/drilling, coatings, etc.

Integrated Field Demonstrations

ENERGY earthshots
U.S. DEPARTMENT OF ENERGY

3. Chemical Storage - Hydrogen

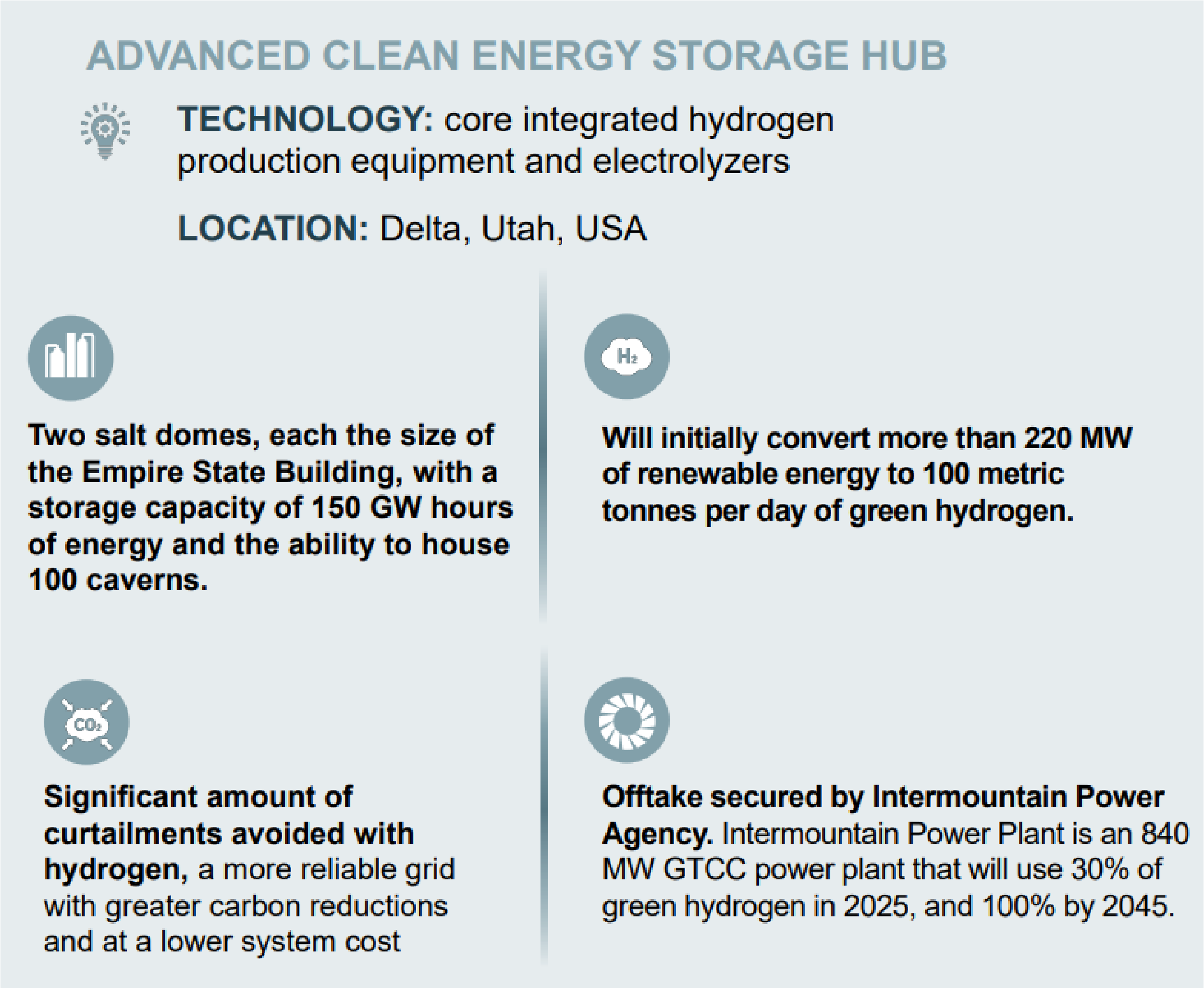
- **Pros:**
  - Clean fuel. No greenhouse gases. It can be stored, transported and good for seasonal storage.
- **Cons:**
  - Low RTE. Flammable gas. difficult to store and transport, leakage or self discharge.
- From electrolysis of water for H_2 generation and electricity conversion using fuel cell, 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.

3. 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

3. 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.

3. Different Ways of Generating Hydrogen

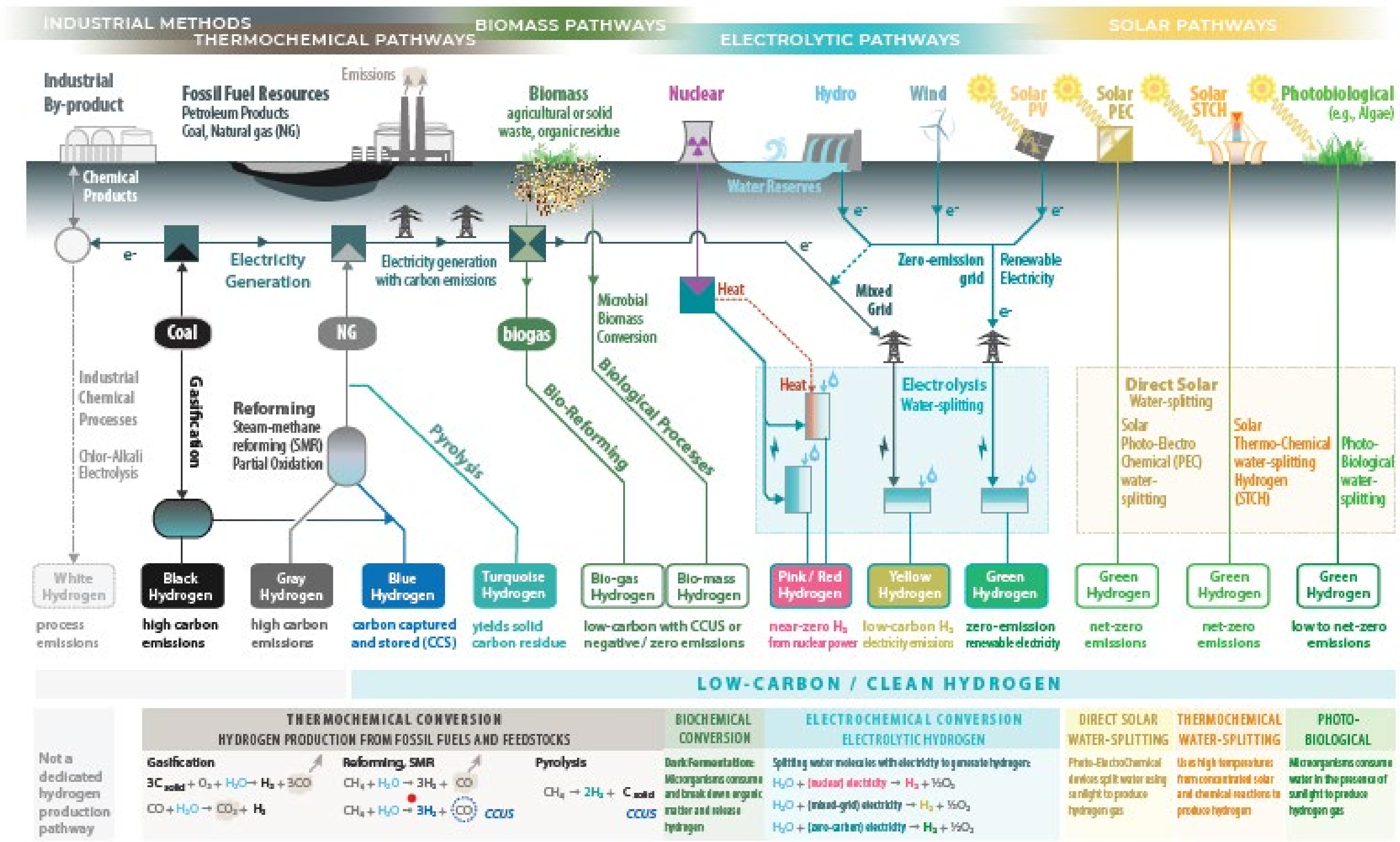
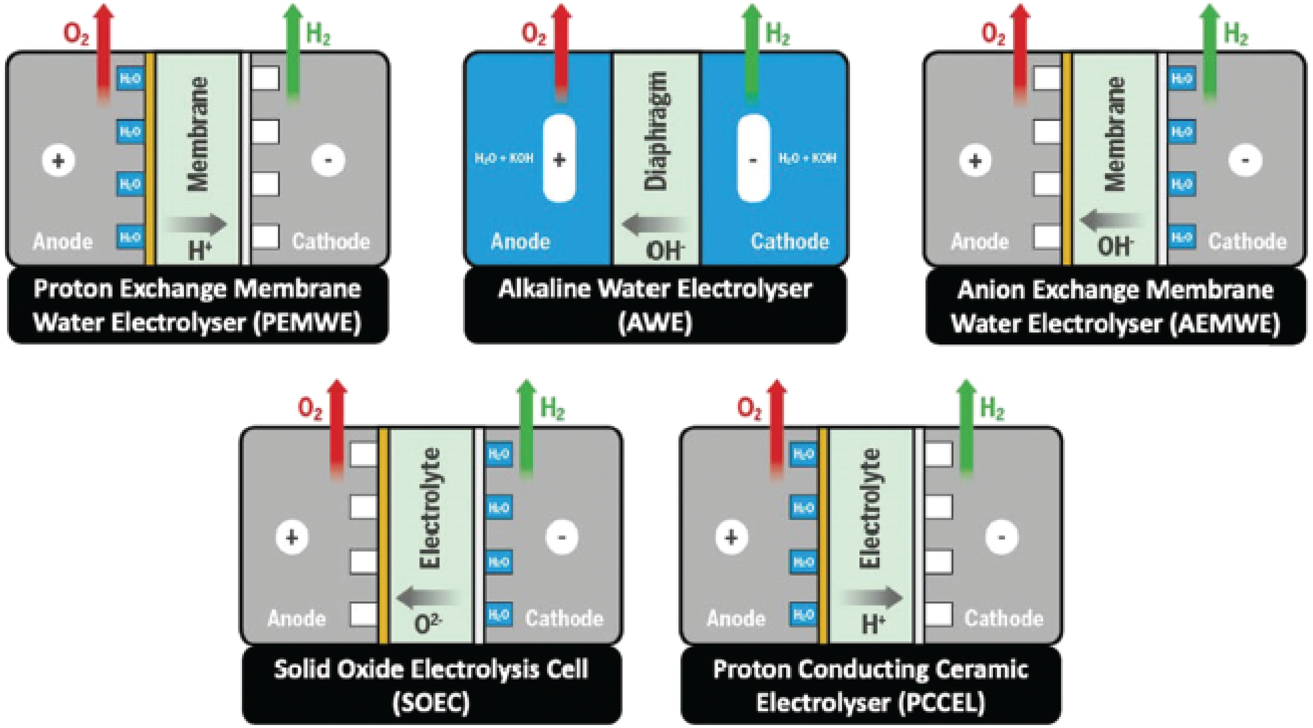


FIG. 2. *Illustration of hydrogen pathways and associated colors (bottom boxes) based on the conventional assignment. The diagram includes both mature technologies that represent the majority of the hydrogen production today and emerging technologies for producing low-carbon or clean hydrogen as well as advanced pathways (open boxes) for carbon-neutral or carbon-negative hydrogen that are in early stages of R&D—as of the time of the publication of this article. Despite the variations in colors for some processes or their lack thereof, electrolytic, solar, and bio-mass pathways offer the prospect of clean hydrogen.*

For reference only

The Electrochemical Society *Interface* • Winter 2021 • www.electrochem.org

3. Different types of Water Electrolysers



Scheme 3 Schematic presentation of the five main types of water electrolysers.

Ref: Chem. Soc. Rev., 2022, 51, 4583

- Polymer exchange membrane water electrolyser (PEMWE) - higher efficiency, generates high purity gas, but expensive.
- Alkaline water electrolyser (AWE) - most mature technology. Least expensive.
- Solid Oxide Electrolysis Cell (SOEC) - operates at a higher current density and efficiency. High temperature operation, degradation issues.
- AEMWE and PCCEL - still under development

Electrolyser Type	Oper. Temp (°C)	Oper. Pressure (bar)	Electrolyte	Electrode/ Catalyst Oxygen side	Electrode/ Catalyst side	Bipolar plate Anode	Bipolar plate Cathode
AWE	70-90	1-30	KOH	Ni coated SS	Ni coated SS	Ni coated SS	Ni coated SS
PEMWE	50-80	<70	PFSA membranes	Iridium oxide	Pt on C	Pt coated Ti	Au coated Ti
AEMWE	40-60	<35	DVB Polymer support with KOH or NaHCO3	Ni or NiFeCo aloys	Ni	Ni coated SS	Ni coated SS
SOFC	700-850	1	Yttria stabilized zirconia (YSZ)	Pervskite type (LSCF, LSM	Ni/YSZ	None	Co coated SS
PCCEL	300-600	1	Ba(Ce, Zr)O3	Pervskite type (LSCF, LSM	Ni-YSZ, Ni-BZY	None	Co coated SS

3. Hydrogen Storage

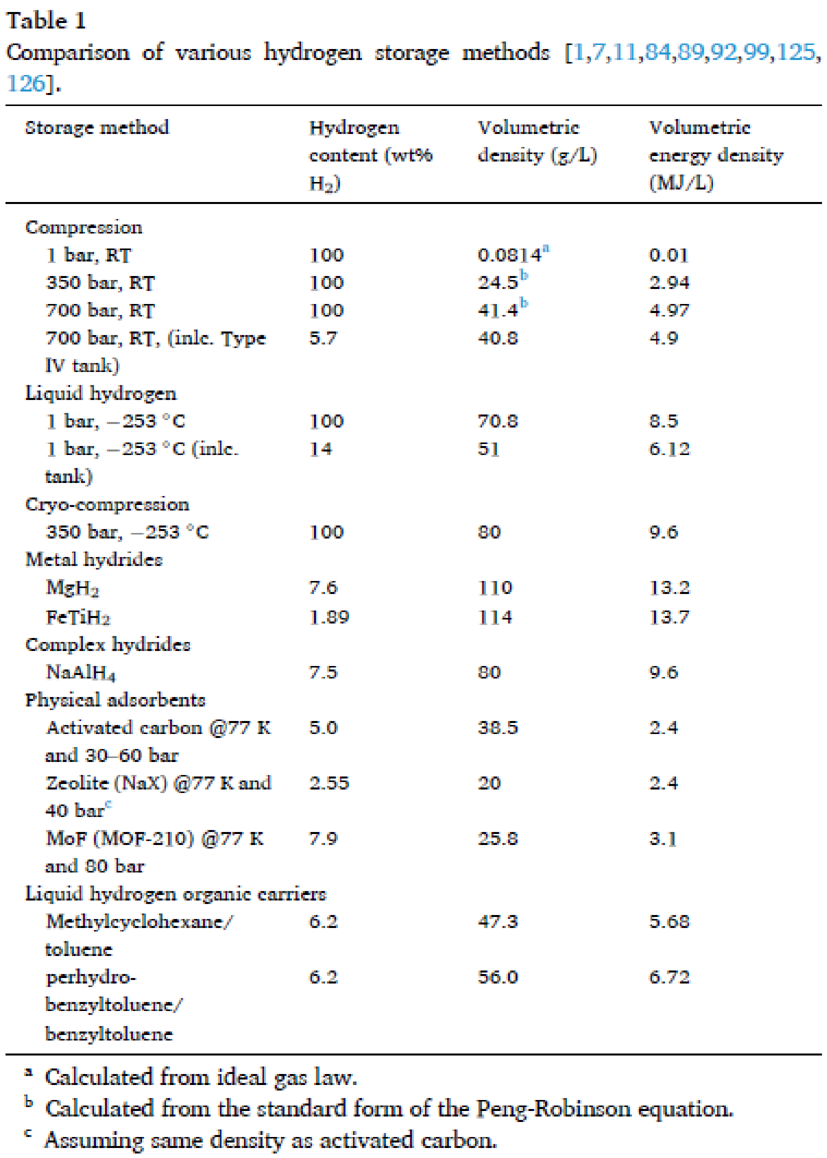


Table 1
Comparison of various hydrogen storage methods [1,7,11,84,89,92,99,125,126].

Storage method	Hydrogen content (wt% H_2)	Volumetric density (g/L)	Volumetric energy density (MJ/L)
Compression			
1 bar, RT	100	0.0814[a]	0.01
350 bar, RT	100	24.5[b]	2.94
700 bar, RT	100	41.4[b]	4.97
700 bar, RT, (inlc. Type IV tank)	5.7	40.8	4.9
Liquid hydrogen			
1 bar, −253 °C	100	70.8	8.5
1 bar, −253 °C (inlc. tank)	14	51	6.12
Cryo-compression			
350 bar, −253 °C	100	80	9.6
Metal hydrides			
MgH_2	7.6	110	13.2
$FeTiH_2$	1.89	114	13.7
Complex hydrides			
$NaAlH_4$	7.5	80	9.6
Physical adsorbents			
Activated carbon @77 K and 30–60 bar	5.0	38.5	2.4
Zeolite (NaX) @77 K and 40 bar[c]	2.55	20	2.4
MoF (MOF-210) @77 K and 80 bar	7.9	25.8	3.1
Liquid hydrogen organic carriers			
Methylcyclohexane/toluene	6.2	47.3	5.68
perhydro-benzyltoluene/benzyltoluene	6.2	56.0	6.72

[a] Calculated from ideal gas law.
[b] Calculated from the standard form of the Peng-Robinson equation.
[c] Assuming same density as activated carbon.

Different Storage Methods:

Compressed Hydrogen
Liquid Hydrogen
Cryo-compression
Metal Hydrides
Physical Adsorbents
Liquid Hydrogen Organic Carriers

Reference: Muhammad R. Usman, Renewable and Sustainable Energy Reviews 167 (2022) 112743

3. Transportation of Hydrogen

- **Liquid Hydrogen:** Compress the hydrogen to liquid state for ease of transport.
  - Higher volumetric energy density, but energy intensive process.
  - It takes approximately 12 kWh of energy per Kg of hydrogen, equivalent to 25% of the energy that H_2 would release in a fuel cell.
- **LOHC (Liquid Organic Hydrogen Carrier):** Involves hydrogenation, where hydrogen is reacted with an organic carrier for ease of transport and dehydrogenation to release hydrogen and regenerate the organic carrier for reuse. Noble metal catalysts and high temperatures (150-300C) are needed for hydrogenation and dehydrogenation reactions.
  - Few example LOHC systems: methylcyclohexane (MCH)/toluene (TOL), perhydro-dibenzyl-toluene (H18-DBT)/dibenzyl-toluene (H0-DBT).
- **Compressed Hydrogen:** Compress hydrogen gas and transport it in fiber reinforced carriers. It takes approximately 6-8 kWh per kg for H_2 compression (~7000 psi).
- Other hydrogen storage options such as metal hydrides and metal organic frame works are still in development stage.

3. Storage of Hydrogen in Methanol and Ammonia

- Methanol (CH_3OH) is the simplest alcohol. Gravimetric H_2 storage 12 wt%, volumetric H_2 storage 99 Kg/m^3.
- Produce methanol through the hydrogenation of carbon dioxide (CO_2). This is exothermic reaction. Also works as CO_2 sequestration.
- From Methanol, H_2 is released by the reaction with water in steam reforming (SMR), or by reaction with oxygen in partial oxidation or through methanol thermolysis (Decomposition).
- SMR is more efficient process. Operating temperature of 230-330 °C and a catalyst is needed (typically Cu on ZnO/Al_2O_3 support.
- Ammonia (NH_3): Gravimetric H_2 storage density is 17.7% by wt, volumetric storage density is 123 Kg/m^3 for liquid ammonia at 10 bar. Its synthesis, handling and transportation is very mature.
- Ammonia is synthesized using the Haber Bosch process. Reactions are at 300-550 °C and 200-350 bar pressure.
- Dehydrogenation(H_2 release) is by thermolysis, the exact reverse of ammonia synthesis. Ammonia starts decomposing at 200 °C, but high T>650 °C must be applied for complete conversion. The most active catalyst for this process is Ru. Ni work at >900 °C.

3. Properties of H_2 related to safety

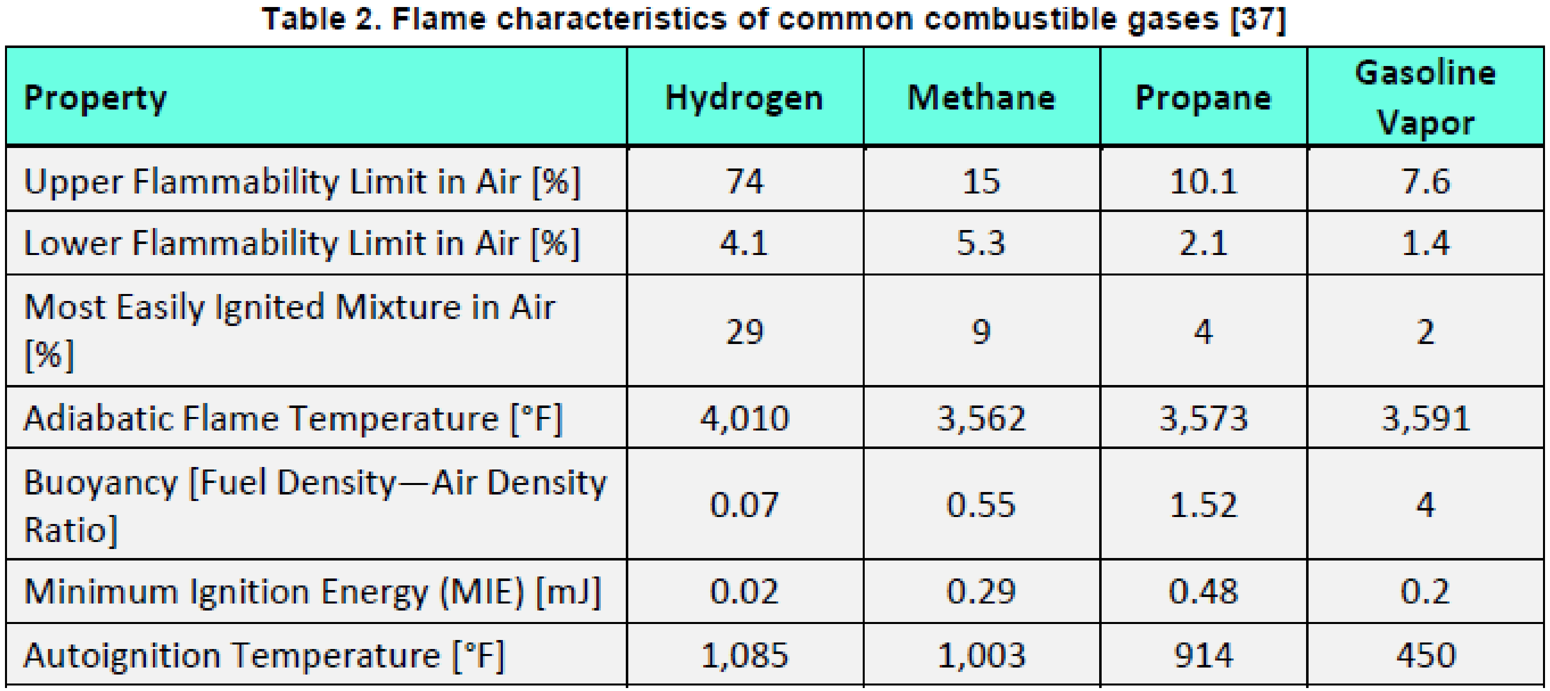


Table 2. Flame characteristics of common combustible gases [37]

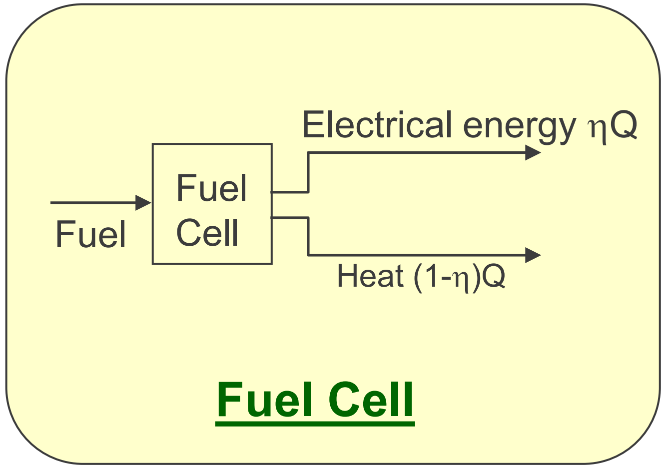
Property	Hydrogen	Methane	Propane	Gasoline Vapor
Upper Flammability Limit in Air [%]	74	15	10.1	7.6
Lower Flammability Limit in Air [%]	4.1	5.3	2.1	1.4
Most Easily Ignited Mixture in Air [%]	29	9	4	2
Adiabatic Flame Temperature [°F]	4,010	3,562	3,573	3,591
Buoyancy [Fuel Density—Air Density Ratio]	0.07	0.55	1.52	4
Minimum Ignition Energy (MIE) [mJ]	0.02	0.29	0.48	0.2
Autoignition Temperature [°F]	1,085	1,003	914	450

- The rapid dispersion of Hydrogen in air is its greatest safety asset.
- H_2 raises more rapidly (14x lighter than air), moves fast upward.
- H_2 is detonable over a wide range of concentration.
- Flame velocity is faster. Difficult to arrest H_2 flames.
- H_2 flame temperatures are higher than Natural gas.

3. 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)



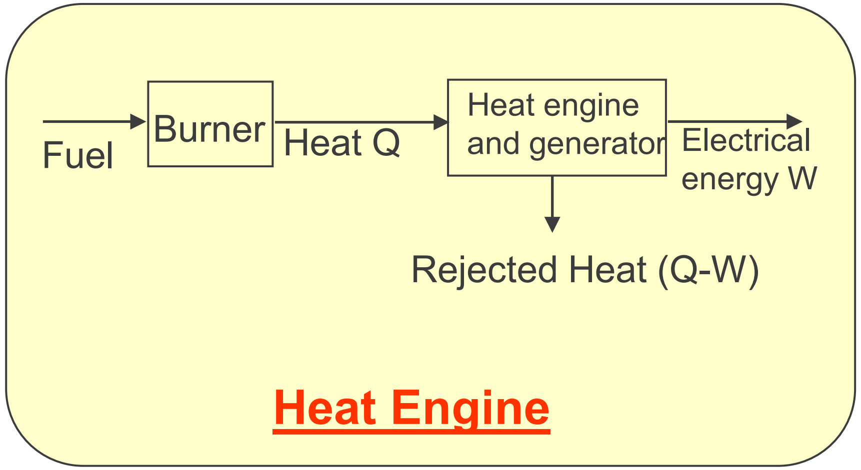
Fuel

Fuel Cell

Electrical energy ηQ

Heat $(1-\eta)Q$

Fuel Cell



Fuel

Burner

Heat Q

Heat engine and generator

Electrical energy W

Rejected Heat (Q-W)

Heat Engine

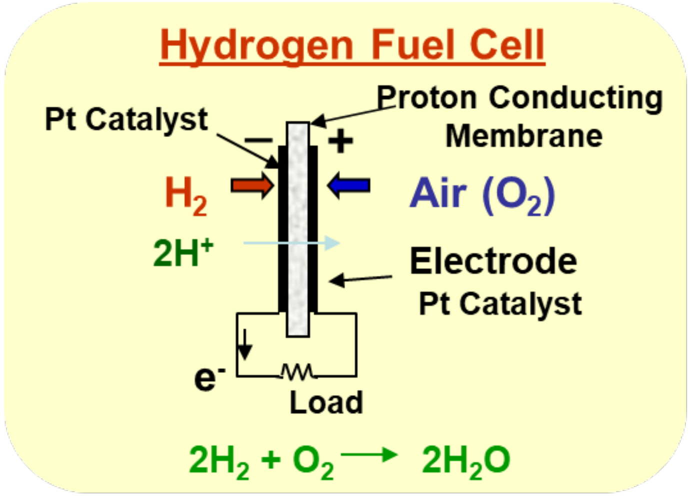
Hydrogen, oxygen reaction: $2H_2 + O_2 \rightarrow 2H_2O$

- 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.

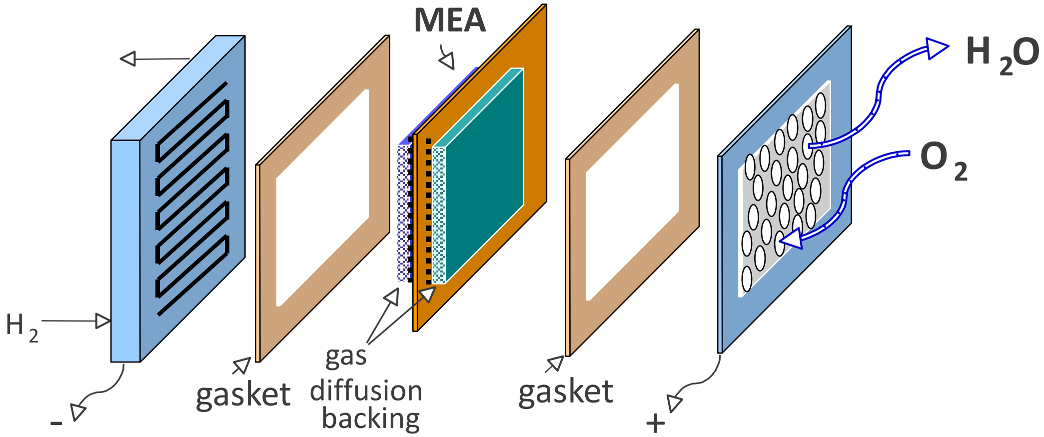
- In Heat engines, fuel is combusted and the released heat is used to produce electricity. In heat engines maximum efficiency is limited by the Carnot efficiency $(1- T_{cold}/T_{hot})$.

3. Fuel Cell Key Components

MEA - Membrane electrode assembly



H_2/O_2 Fuel Cell



- Proton Conducting Membrane - Ex: Nafion sold by Dupont
- Electrocatalyst layer - usually Pt supported on Carbon
- Gas diffusion backing - carbon cloth with some PTFE added
- Sealing gaskets - to prevent fuel/oxidant leaking
- Current collectors - usually gold plated metal
- Flow fields - for uniform fuel/oxidant distribution to the MEA
- BOP(balance of plant) – pumps, sensors, water management, temperature management

Technology is known and demonstrated in large scale. Issues are cost and life time.

3. 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. 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**
  - 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

3. Types of Fuel Cells

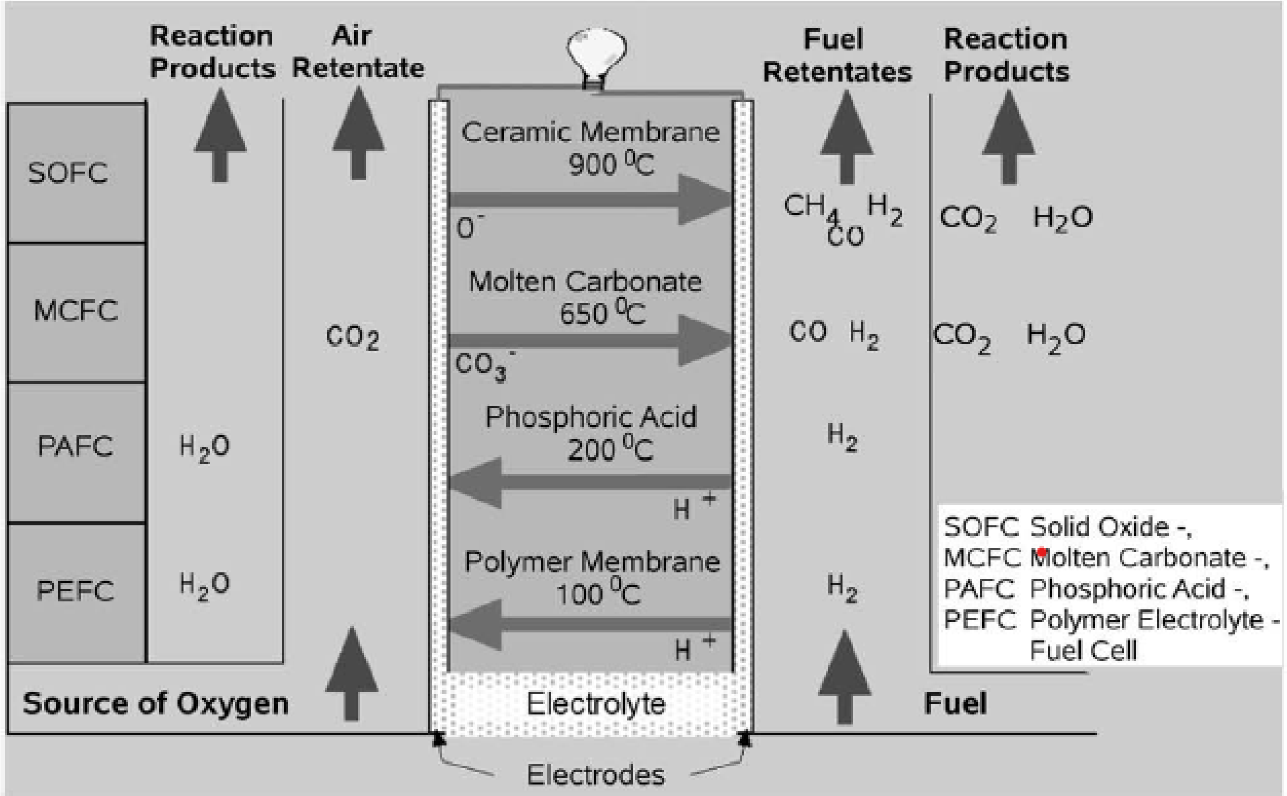


Fig. 19 – Various fuel cell systems. SOFC Solid Oxide Fuel Cell; MCFC Molten Carbonate Fuel Cell; PAFC Phosphoric Acid Fuel Cell; PEFC Polymer Electrolyte Fuel Cell.

FC Types:
Solid Oxide Fuel Cells (SOFC)
Polymer Exchange Membrane Fuel Cells(PEMFC)
Moten Carbonate Fuel cells (MCFC)
Phosphoric Acid Fuel Cells (PAFC)

- **Technology is Known. The issues are cost, life time.**
- **The most common types are: SOFC and PEM.**
- **PEM fuel cells use noble metal catalysts**
- **SOFC operate at higher temperatures. Seals, reliability issues.**

Reference: Carl-Jochem Winter, International journal of hydrogen energy 34 (2009) S1-S52.

3. Hydrogen Combustion in Gas Turbines

- Gas turbines with 100% hydrogen 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.

3. Chemical Energy Storage Summary

- H_2 is a good choice 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.
- **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
  - Safety
- **Alternatives:**
  - Convert hydrogen into ammonia or hydrocarbon fuels.
  - Energy intensive processes, but these are convenient fuels for storage, transportation and use.

Summary

- The percentage of renewables as well as natural gas generation are increasing in the US grid.
- Currently natural gas plants are looked at as a good option to meet grid supply and demand fluctuations. This is not a good option without viable CO_2 sequestration technologies, we need to evaluate ES options.
- Currently Li ion 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, they 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.
- Hawaii should look into PHS additions to the existing hydroelectric generators and also stand alone reservoirs, and Enhanced Geothermal energy (for base load, as well as possible time shift. There is a lot of geothermal activity in Hawaii).
- For hydrogen storage RTE is low, but with excess renewable power generation, onsite hydrogen 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.

Thank you.

Q &A

Next Topic – Electrochemical energy storage (various types of batteries)

covered in 1/17/24 webinar – Erik Spoerke