Overview of Grid-Scale Machinery-Based Energy Storage Technologies

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SwRI

The world turns to Elliott.

Slide 2: Tutorial Authors

Dr. Tim Allison is director of the Machinery Department at Southwest Research Institute. His research at SwRI includes analysis, fabrication, and testing of turbomachinery and systems for advanced power applications including high-pressure turbomachinery, centrifugal compressors, expanders, gas turbines, reciprocating compressors, and test rigs for bearings, seals, blade dynamics, and aerodynamic performance. He has published over 60 articles on various turbomachinery topics and is an Associate Editor for the ASME Journal of Engineering for Gas Turbines & Power.

Aaron Rimpel is a Group Leader in the Rotating Machinery Dynamics Section at Southwest Research Institute, where he has been for ten years. His expertise is in mechanical system design, rotordynamics, and development of rigs for testing bearings and seals for conventional and oil-free machinery. Aaron earned his Master of Science degree from Texas A&M University with a focus on rotordynamics and gas bearings.

Dr. Natalie Smith is a Senior Research Engineer in the Rotating Machinery Dynamics Section at Southwest Research Institute in San Antonio, Texas. Her research experience includes aerodynamic design, analysis, and testing of turbomachinery for various applications including power generation, aviation, oil and gas, supercritical CO2, and energy storage. She earned her Ph.D. in Aeronautics and Astronautics from Purdue University.

Dr. Brun is the Director of Research & Development at Elliott Group where he leads a group of over 60 professionals in the development of turbomachinery and related systems for the energy industry. His past experience includes positions in product development, applications engineering, project management, and executive management at Southwest Research Institute, Solar Turbines, General Electric, and Alstom. He holds ten patents, has authored over 350 papers, and published four textbooks on energy systems and turbomachinery. Dr. Brun is a Fellow of the American Society of Mechanical Engineers (ASME), won the ASME Industrial Gas Turbine Award in 2016 and 11 individual ASME Turbo Expo Best Paper awards. D
several large conferences including the ASME Tu
Supercritical CO2 Power Cycles Symposium. Dr. Brun
Editor of several journal transactions.

Short Abstract

Grid-scale energy storage is needed to smooth variable renewable power sources and enable deep penetration of renewable power generators into the energy mix. There are many existing or developing machinery-based energy storage systems, including pumped hydro, flywheels, compressed air, gravitational, liquid air, pumped thermal, and various thermochemical technologies such as hydrogen, ammonia, synthetic natural gas, or sulfur. This tutorial reviews all of these technologies including basic working principles, role of turbomachinery, hybridization with existing power generators, state of development, advantages and disadvantages relative to other technologies, and research & development needs for system improvements and commercialization.

Large-Scale Long-Duration Energy Storage is Needed to Enable Deep Renewable Penetration

- Variability, demand mismatch of wind and solar
- Studies show that storage on the order of ~1x daily energy production may be needed[1]
- Storage at renewable plant or baseload plant absorbs ramps/transients
- The storage need for a large city ranges from ~ 25 GWh (4 hours storage in Phoenix) - 840 GWh (daily consumption in Tokyo)

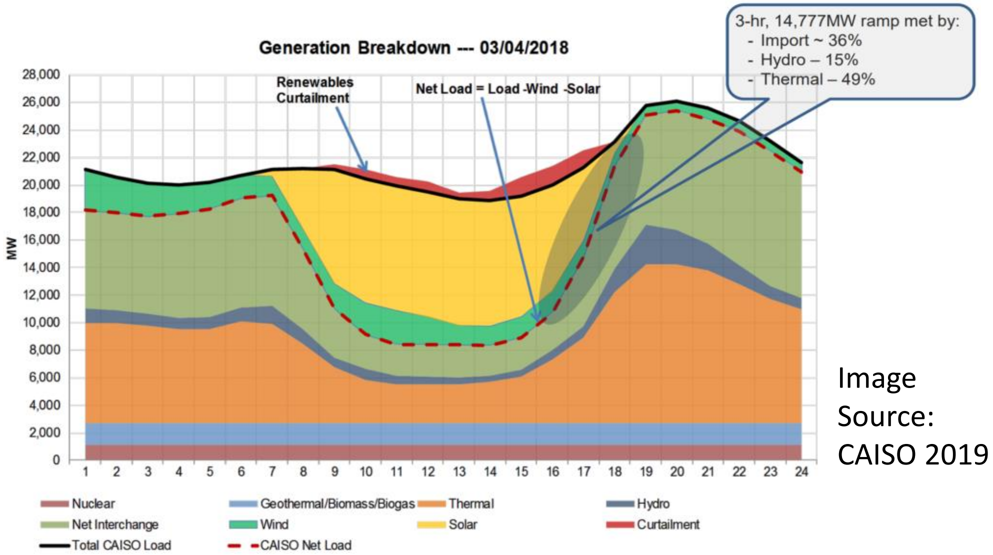


Image Source: CAISO 2019

1-35 of the world's largest pumped hydro system...

...or 2
molte

Why Not Batteries?

- Batteries offer low \$/MW but high \$/MWh for significant durations above 2-6 hours
  - Energy and power both scale by adding cells
- Other concerns:
  - Rare-earth material sourcing (lithium, cobalt)[2]
  - Degradation[3]
  - No viable recycling option[4]
  - Thermal management/runaway[5]
- Other technologies offer promise of decoupling power with low-cost energy storage

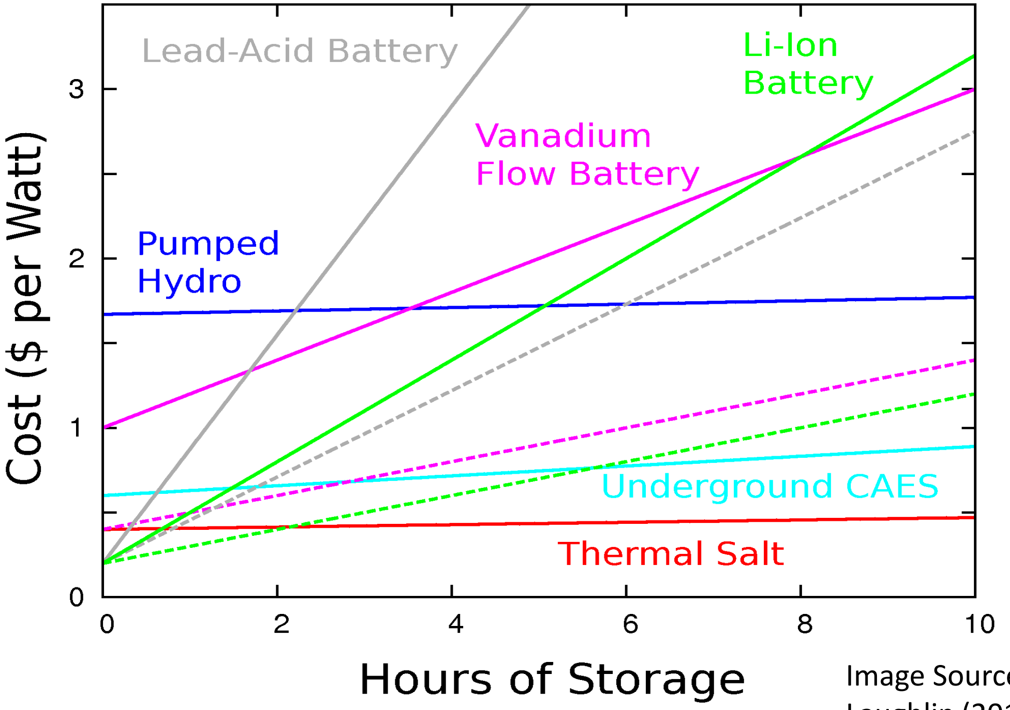
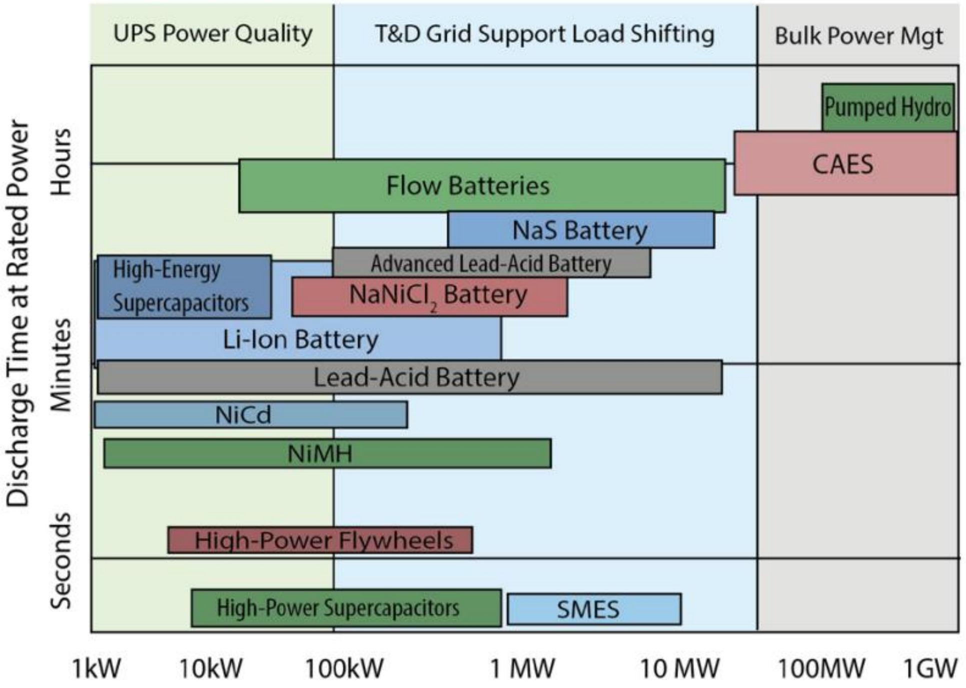
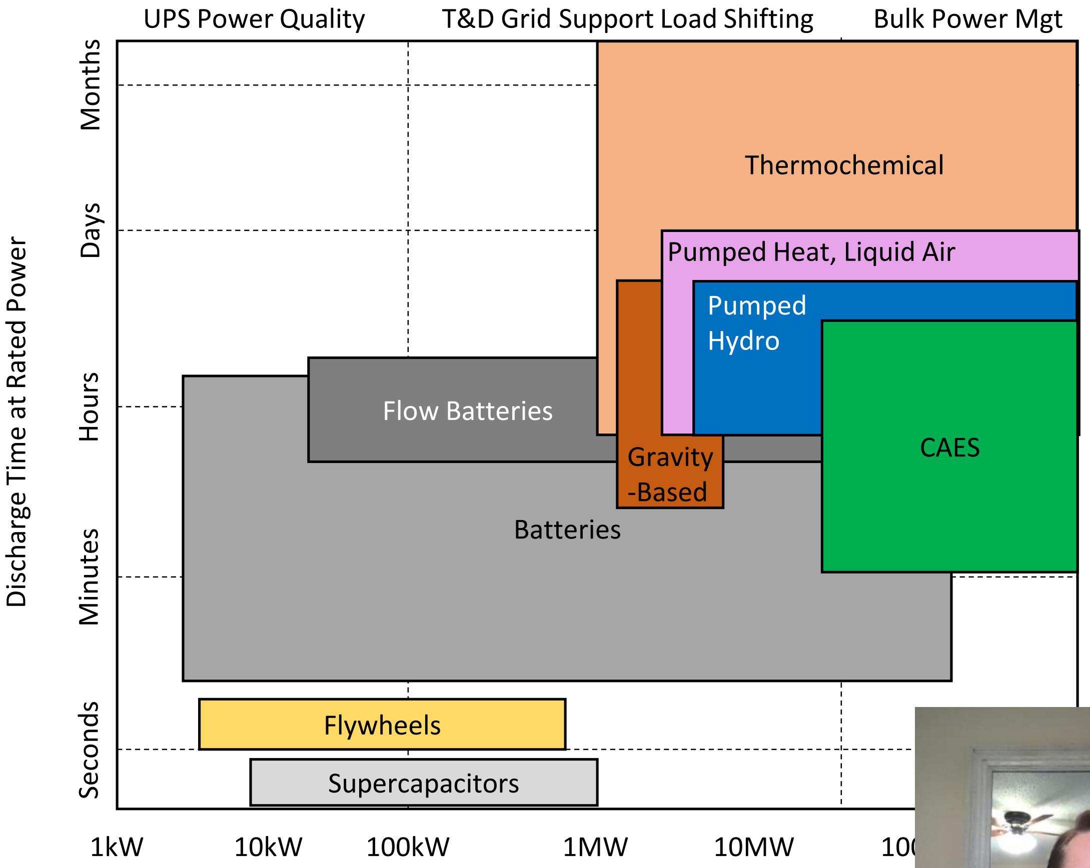


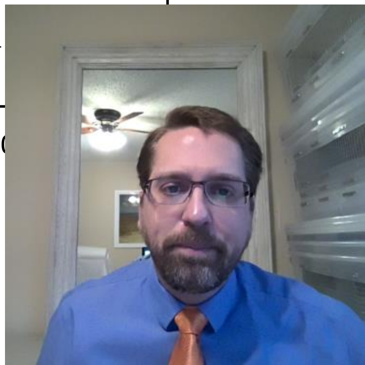
Image Source: Laughlin (2019)

New Long-Duration Energy Storage Technologies are Needed



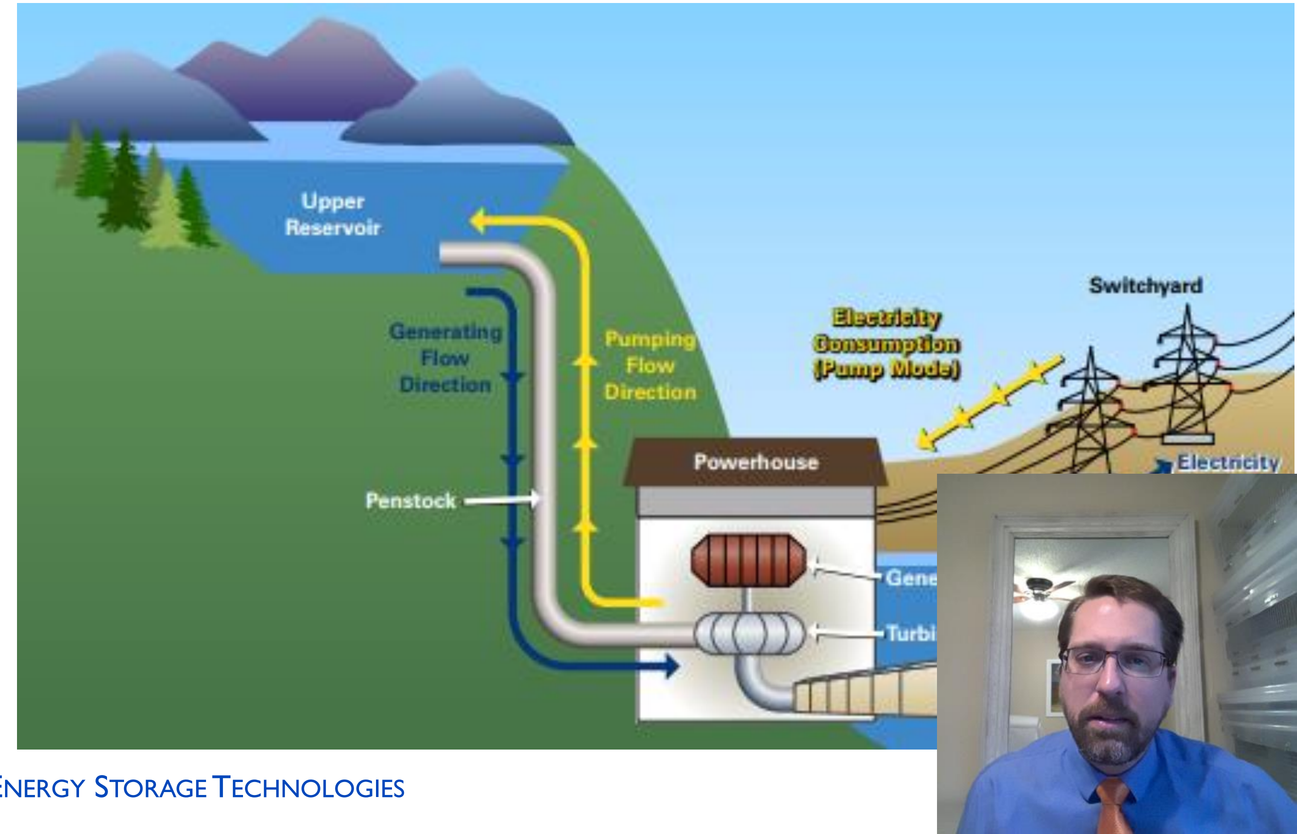
http://css.umich.edu/sites/default/files/U.S._Grid_Energy_Storage_Factsheet_CSS15-17_e2018.pdf





Mechanical ES: Pumped Hydro Storage (PHS)

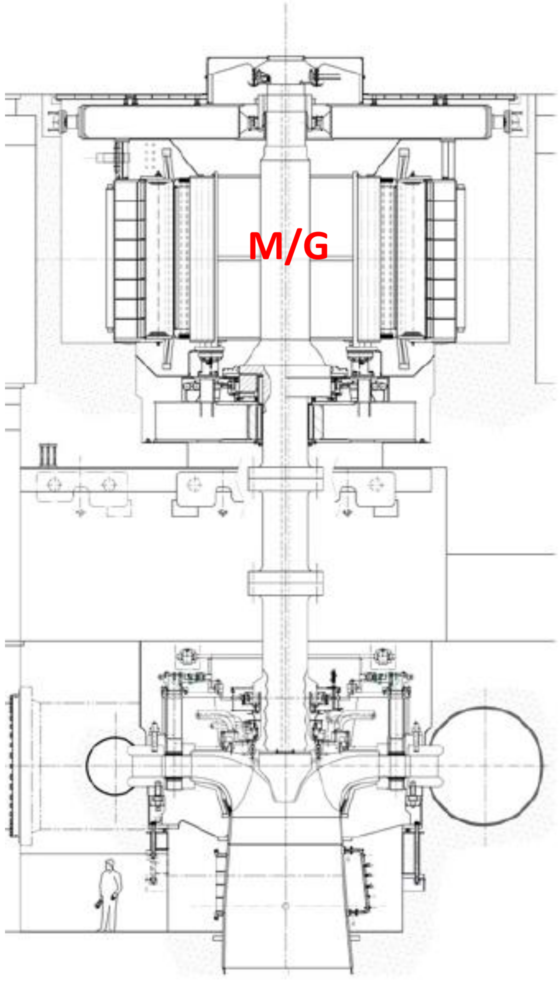
- Working Principles
  - Potential energy of water using reservoirs at different elevations
  - Lakes, rivers/oceans (as lower reservoirs)
  - Pump mode (charging), turbine mode (discharging)
- Current, TRL 9
  - Applications since 19th century
  - Many decades of commercial experience
- Technology Gaps
  - Geography-specific → siting limitations
  - High capital cost
- Expected Performance
  - 70-85%+ round trip efficiency
  - 80-100 year life, 50k storage cycles



Data Source: Luo *et al* (2015), Brun *et al* (2021)

PHS Turbomachinery

- Reversible (Francis) pump-turbines
  - Reverse direction of rotation for charge/discharge modes
  - Configuration for majority of installations
- Ternary sets (separate turbine and pump wheels)
  - Typically higher head
  - Pelton/Francis turbines most common, also Kaplan/Bulb
  - Capable of hydraulic short-circuit (simultaneous pump & turbine operation) for rapid mode change



Pump-Turbine

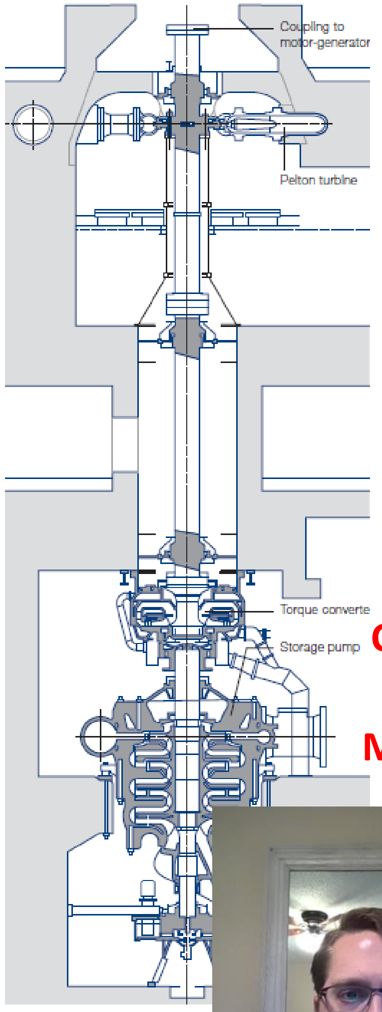
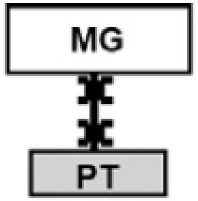
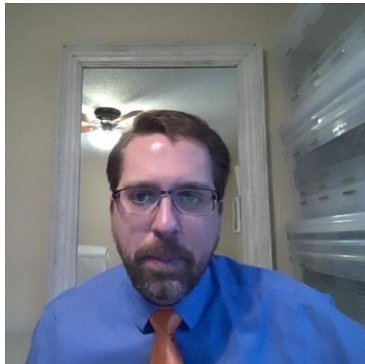


Image Source: Voith (2011)

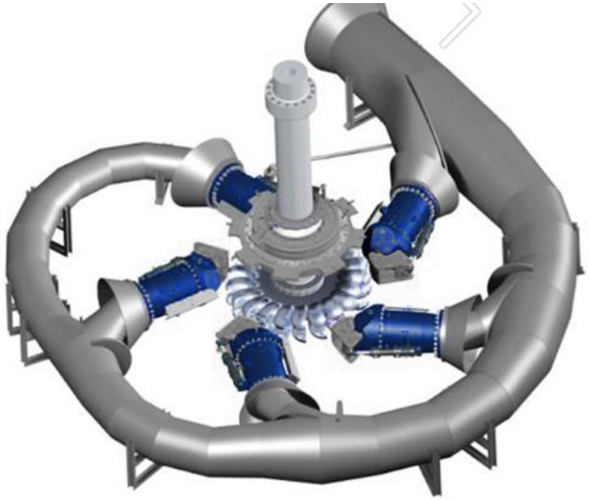
Ternary Set vs. Reversible P/T

Type of machine	Ternary Set 	Pump-Turbine 
Investments	☹	☺
Space requirements	☹	☺
Efficiency	☺	☹
Submergence	☺	☹
Transition times (e.g., T → P / P → T)	☺	☹
Hydraulic short circuit	☺	☹
High heads	☺	☹
Operation costs	☹	☺
Technical risks	☹	☺
Maintenance efforts	☹	☺

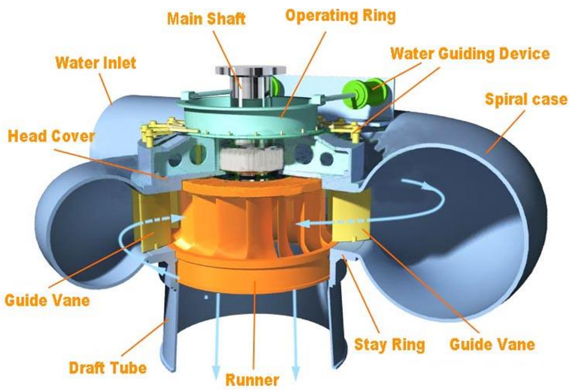
Source: Brun *et al* (2021)



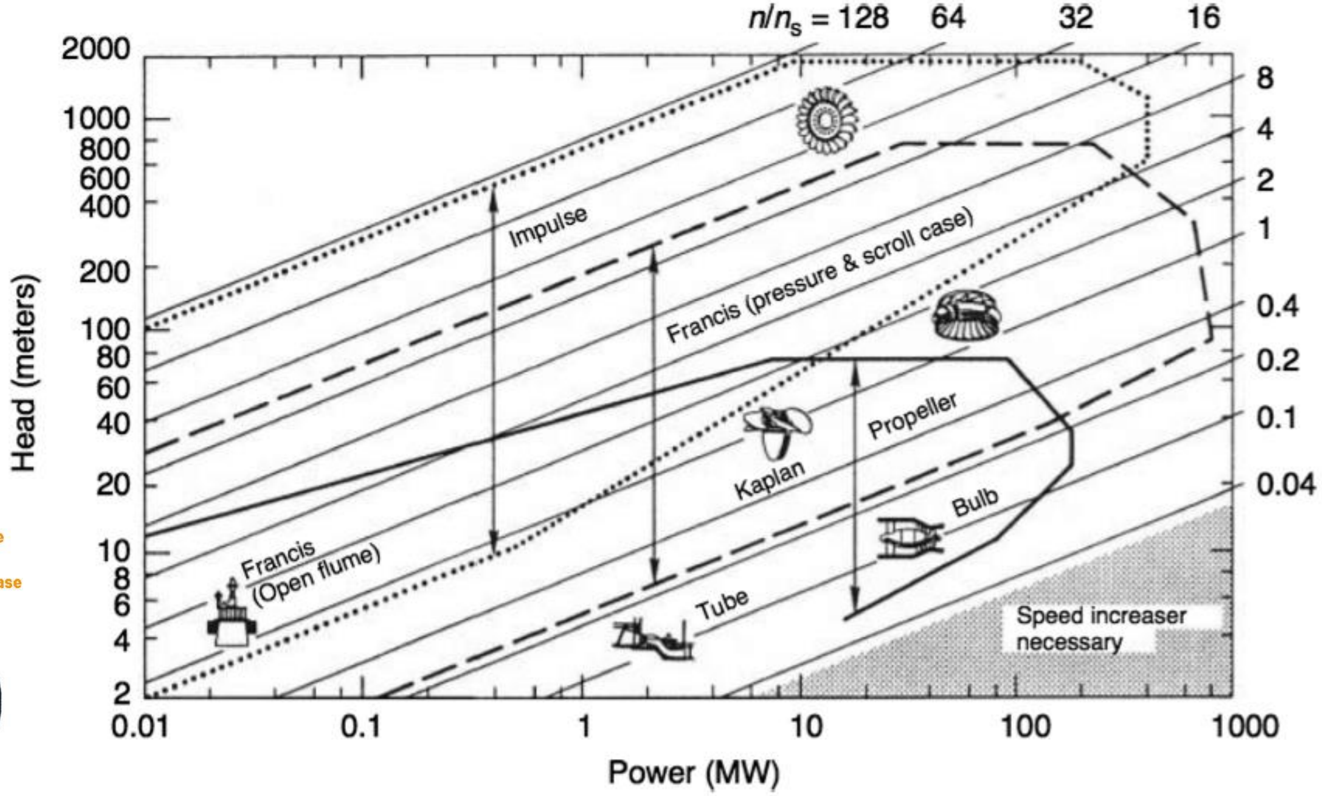
Performance of Different Turbines



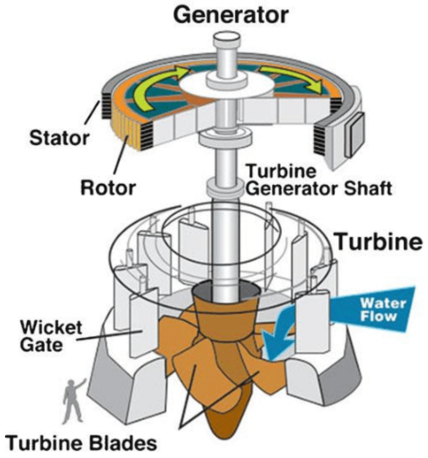
Pelton



Francis



Hydro Turbine Application Chart



Kaplan

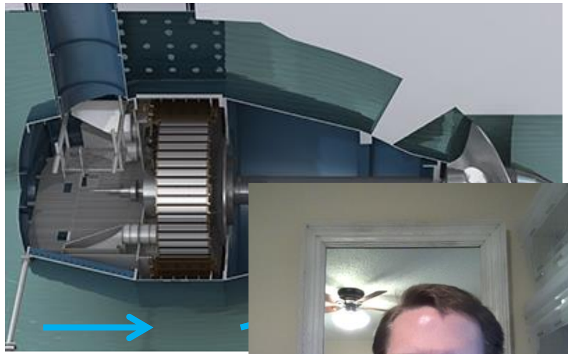
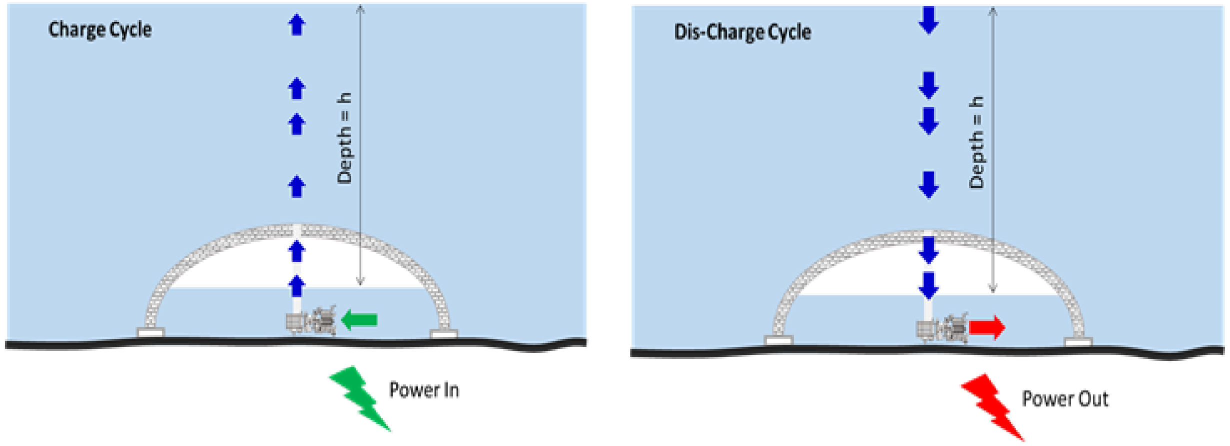


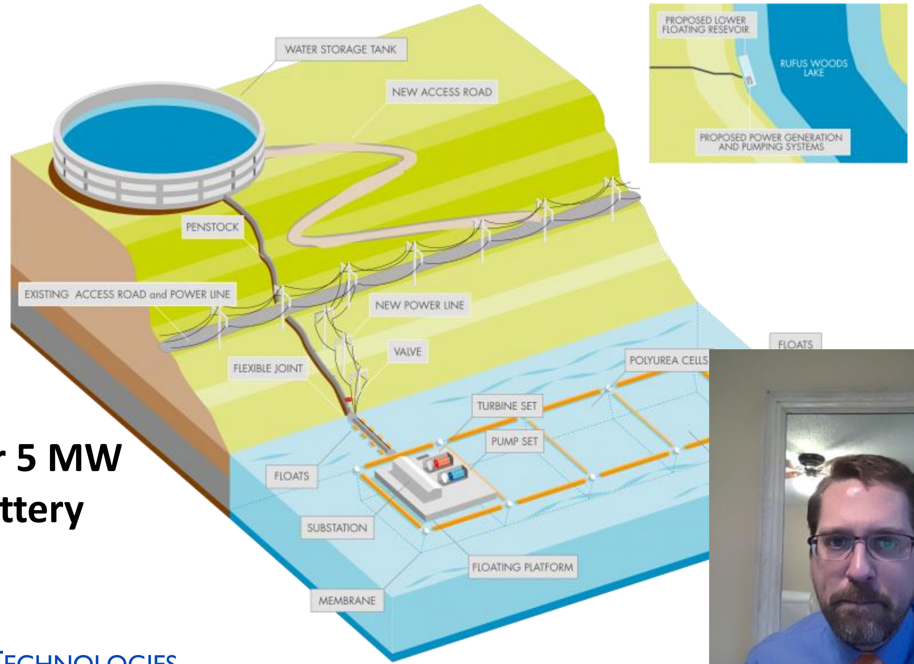
Image Sources: Morabito (2016), GE (2019), Elbatran (
(2011), MechanicalBooster (2019)

PHS Advanced Concepts

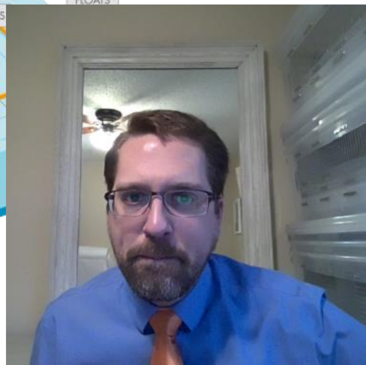
- Subsea pumped hydro to minimize costs
- Subsurface pumped hydro at retired oil & gas or geothermal wells, storing energy in formation compression
- Small modular open-loop PHS for reduced-cost lower reservoir (floating membrane and power block barge)

Subsea PHS





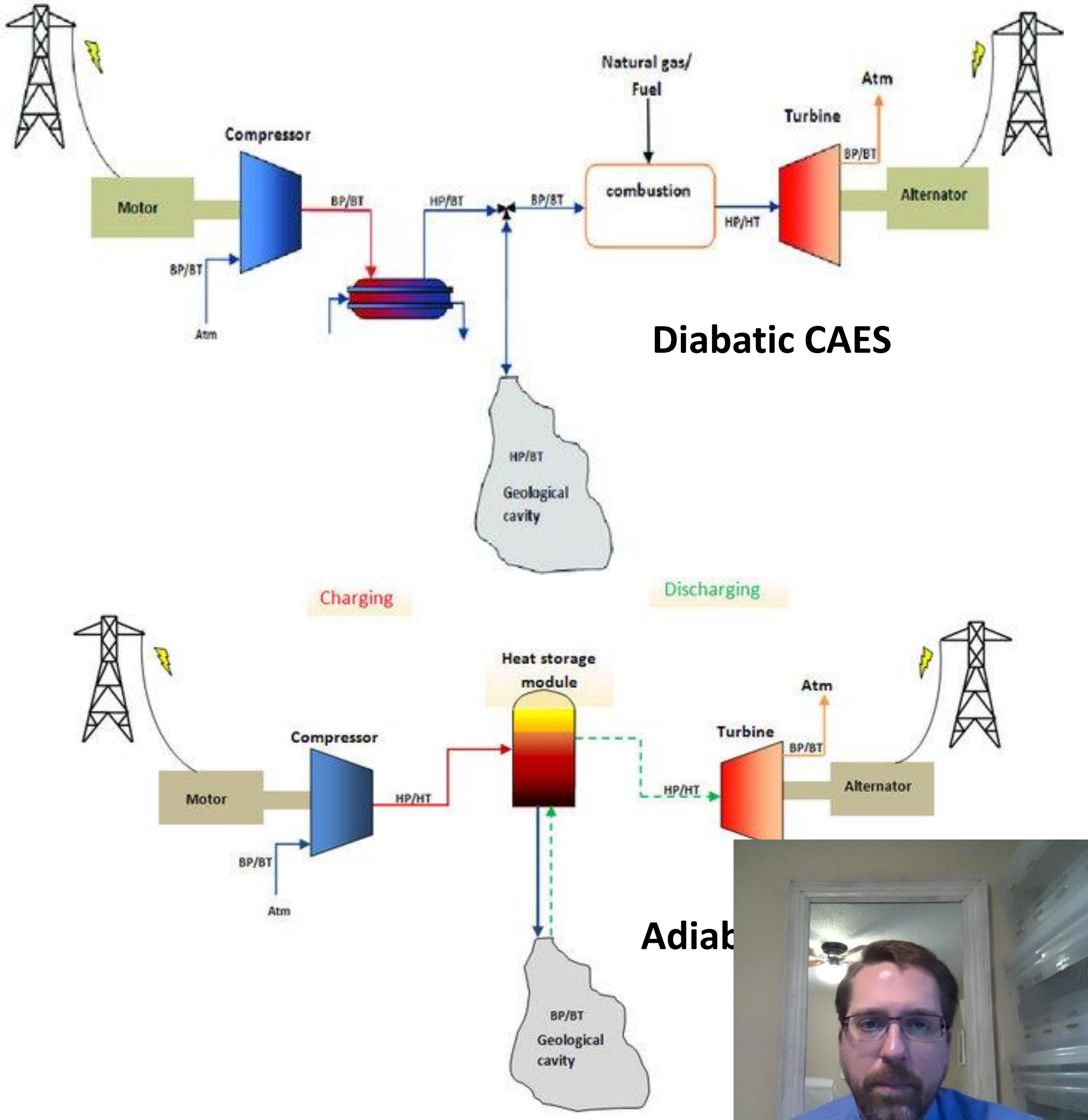
Shell Power 5 MW Hydro Battery



Sources: Karman Inc. (2017), Quidnet (2019), DOE

Mechanical ES: Compressed Air Energy Storage (CAES)

- Working Principles
  - Energy stored in large volumes of compressed air
  - **Diabatic CAES:** Gas-fired heat addition before expansion
  - **Adiabatic CAES:** Heat of compression stored in oil/molten salt, used for heat addition before expansion
- Turbomachinery Integration
  - Compression and expansion
  - Reciprocating and centrifugal/axial machinery
- Current TRL
  - Diabatic CAES: TRL 9
  - Adiabatic CAES: TRL 5-6
- Expected round-trip efficiency
  - Diabatic CAES: 40-50%
  - Adiabatic CAES: 60-80%



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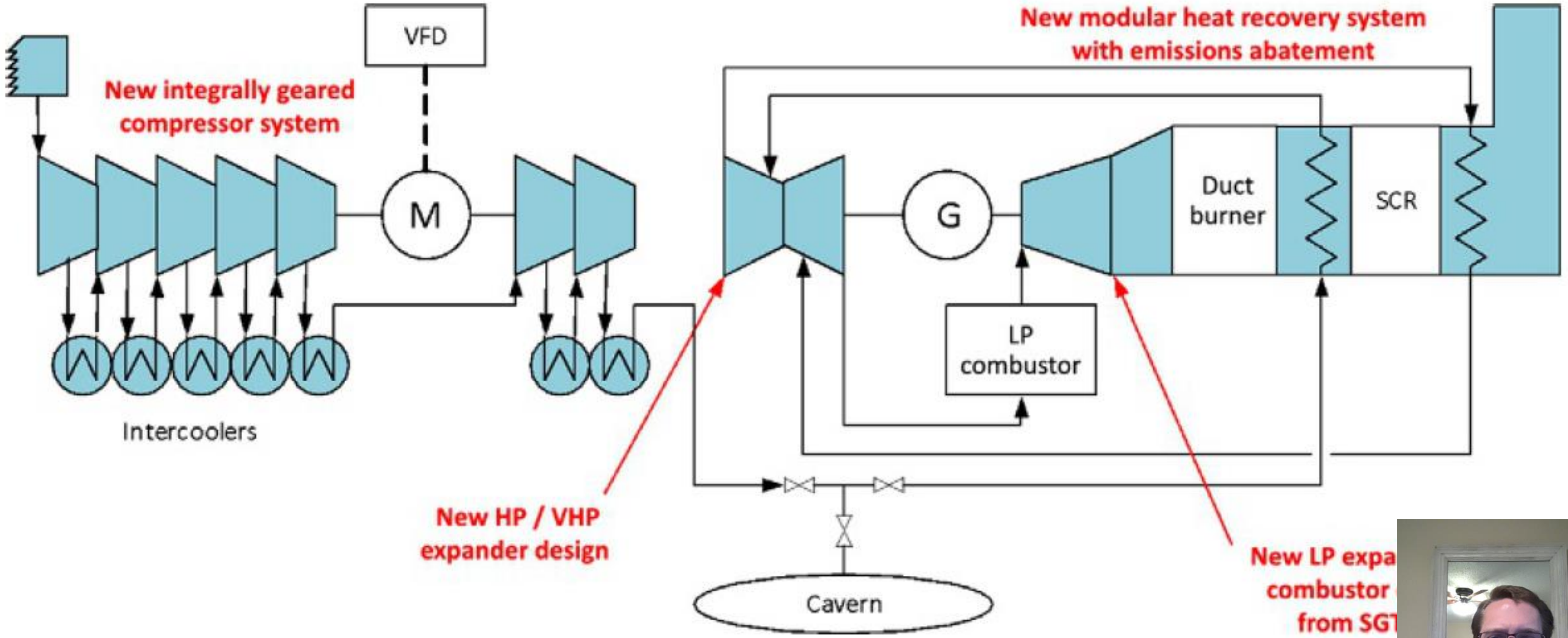
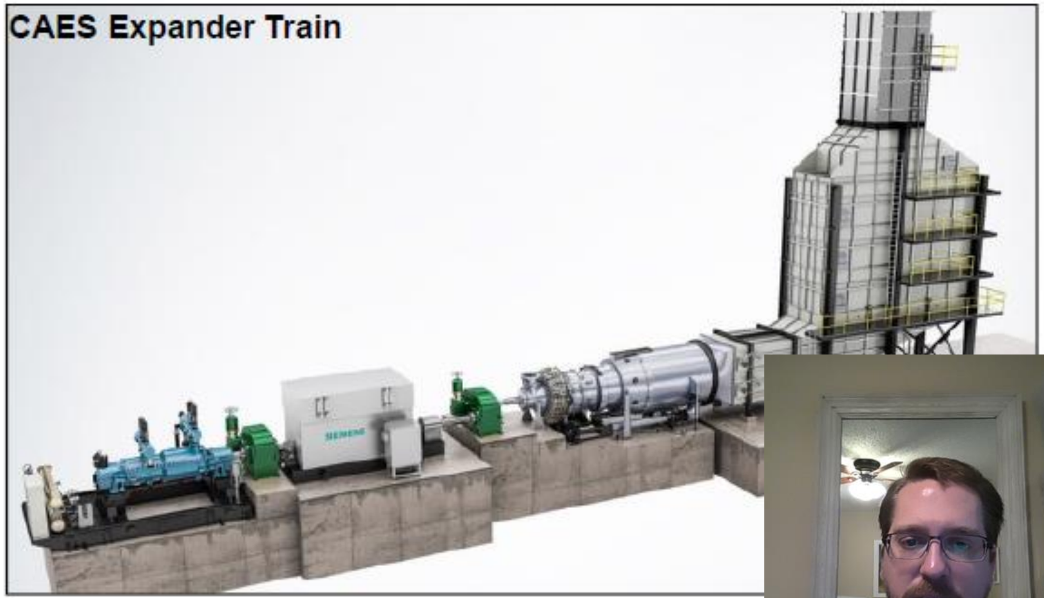
Diabatic CAES Concept with Existing Turbomachinery



Source: Brun *et al* (2021)

Diabatic CAES Concept with Existing Turbomachinery

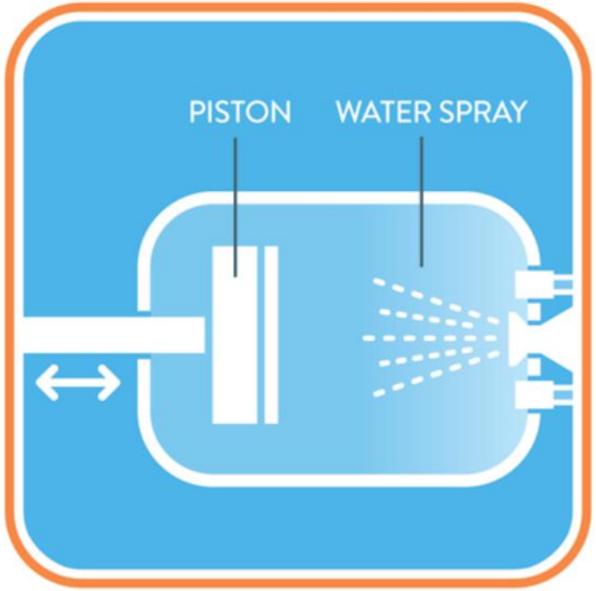
- Integrally geared compression with interstage cooling
- Steam turbine-based high pressure expander
- Low-pressure turbine combustor and expander off of a SGT-800 industrial gas turbine
- Standard heat recovery system reduces air consumption and improves heat rate



Courtesy of Siemens

Other CAES Concepts

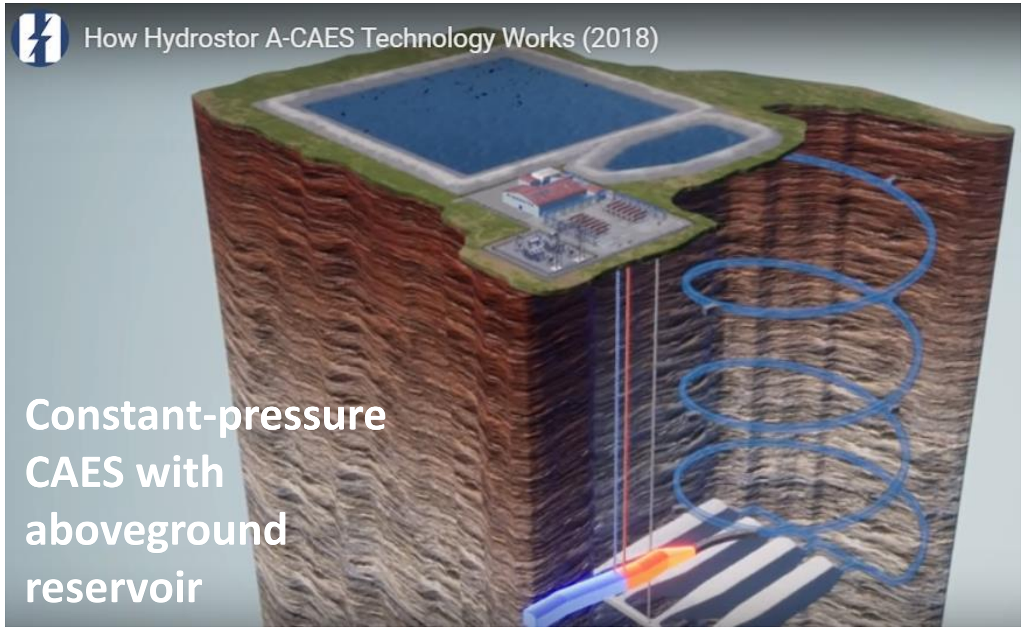
- Lightsail Energy (Ref: https://www.facebook.com/LightSailEnergy/)
- Injects water during compression, separates warm water in tanks, reinjects during expansion to capture heat of compression



500 kW demonstrator

Other CAES Concepts

- Small-scale aboveground CAES
- Isothermal CAES
  - Constant-temperature compression and expansion
- Subsea/Hydrostatic CAES
  - Utilizing natural or man-made subsurface caverns with hydrostatic head
  - Constant-pressure storage
- Hydraulic Compression
  - Using liquid pumps to compress air



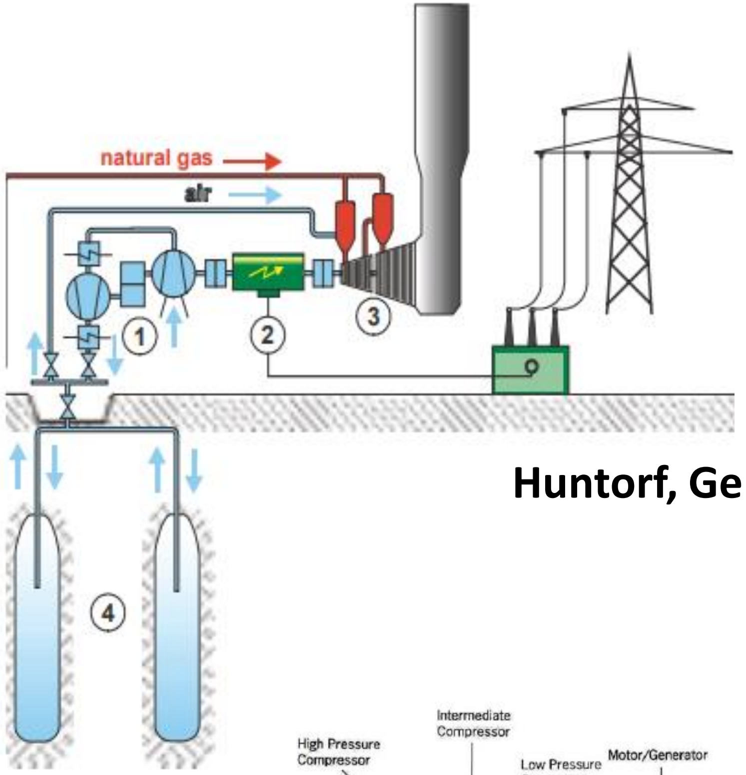
Subsea CAES accumulator

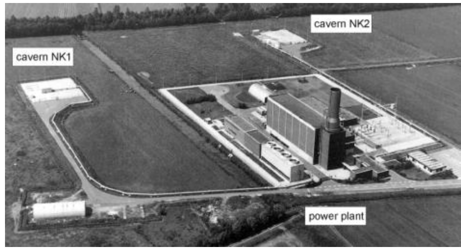
Image Sources:Hydrostor (2017), Windpower Engineering (2014)

Commercial Diabatic CAES Plants

- Huntorf, Germany
  - 290 MW discharge (turbine), 3 hours
  - 60 MW charge (compressor), 12 hours
  - 3.1e5 m^3 volume, up to 70 bar in two underground salt caverns
  - 29-42% storage efficiency

- McIntosh, Alabama, USA
  - 110 MW
  - 5.6e5 m^3 volume, up to 75 bar
  - Employs recuperated expansion and Dresser-Rand turbomachinery
  - 36-55% storage efficiency





Huntorf, Germany

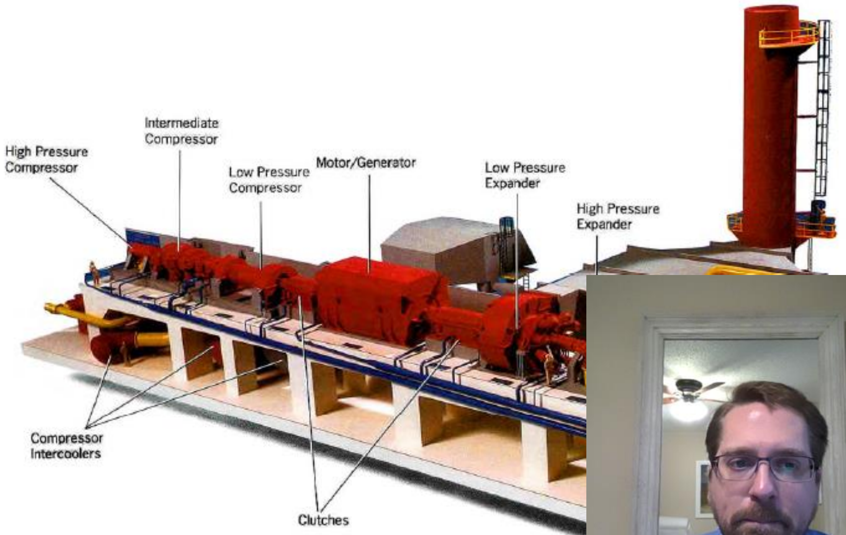
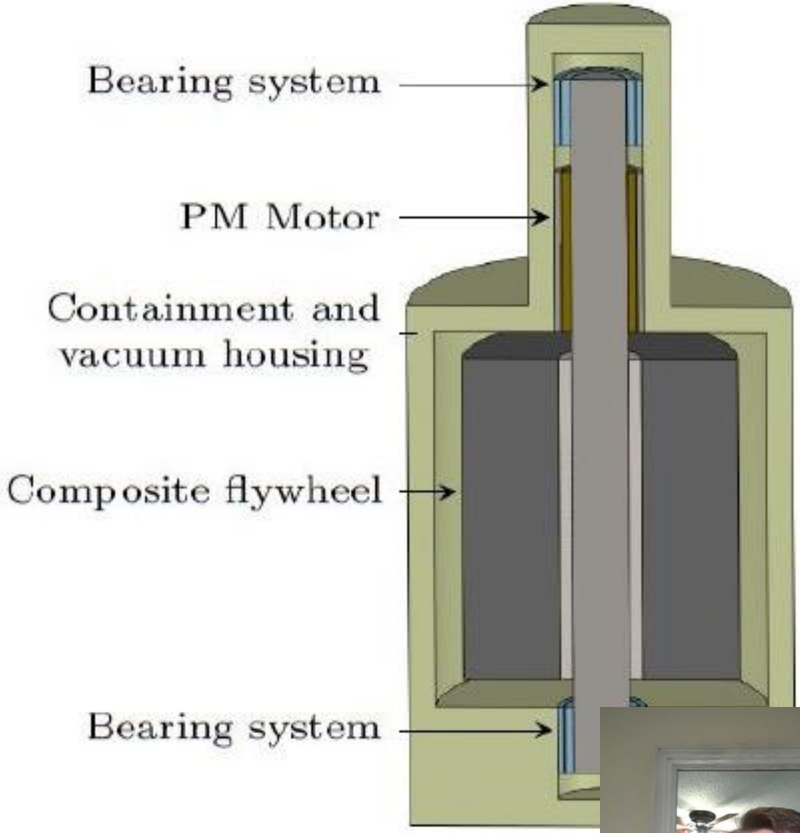


Image and Data Sources: Crotogino (2001), Elmegaard *et al* (2011), PowerSouth (2017), Kerth (2019)

McIntosh, Alabama

Mechanical ES: Flywheels

- Working Principles
  - Store energy as rotating kinetic energy
  - Vacuum environment for loss minimization
- Current TRL 9
  - Commercially available as UPS
- Expected performance
  - 90-95% round-trip efficiency (affected by self-discharge rates)
  - Nearly infinite cycle lifetime
  - Very short response time

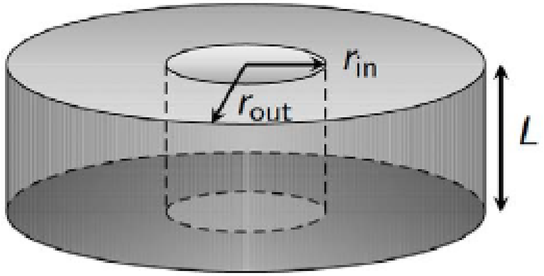


Courtesy of University of Wis

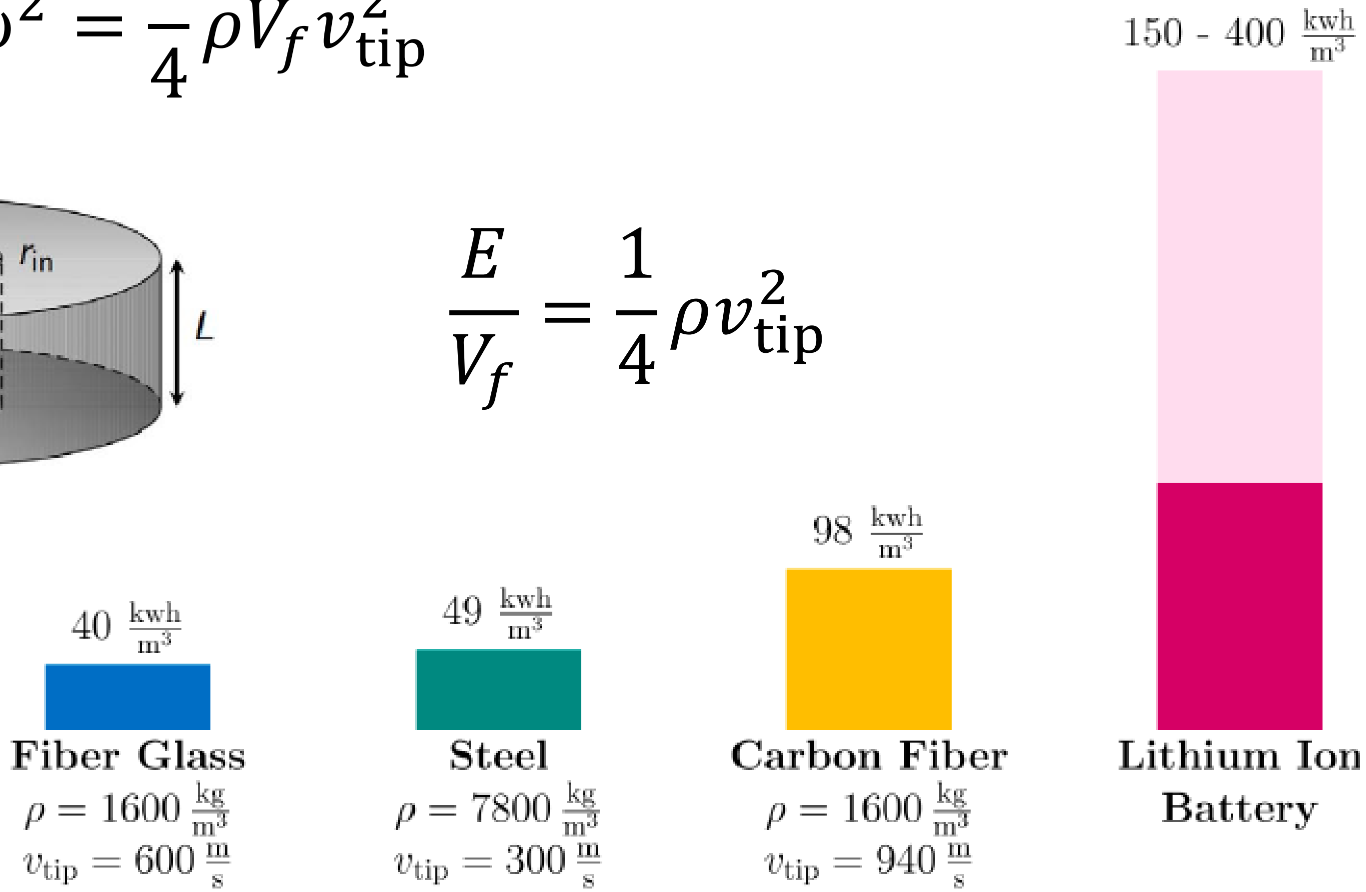
Data Source: Amiryar and Puleln (2017), Luo *et al* (2015)

Flywheel Energy Density Comparison

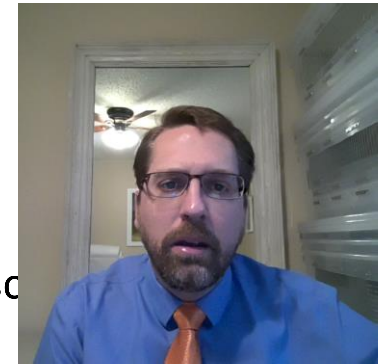
$$E = \frac{1}{2} I_p \omega^2 = \frac{1}{4} \rho V_f v_{\text{tip}}^2$$



$$\frac{E}{V_f} = \frac{1}{4} \rho v_{\text{tip}}^2$$



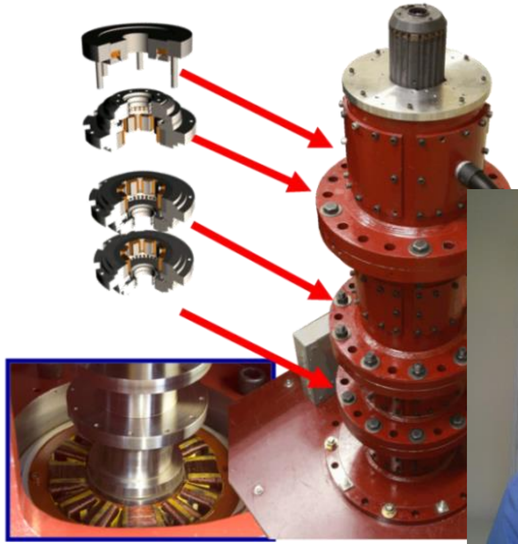
Courtesy of University of Wisc



Flywheel Misc.

- Bearings
  - Rolling element bearings for large flywheels
  - Magnetic bearings for high-speed flywheels, reduce losses
- Largest challenges are cost and self-discharge
  - 5-20% discharge rate per hour
  - Research needed to reduce electrical losses
  - Need for low cost materials with high strength-to-weight ratios
- Additional R&D Topics
  - Superconducting magnetic bearings
  - Improved bearing load capacity while minimizing losses
  - Auxiliary / backup bearings and rotordynamics

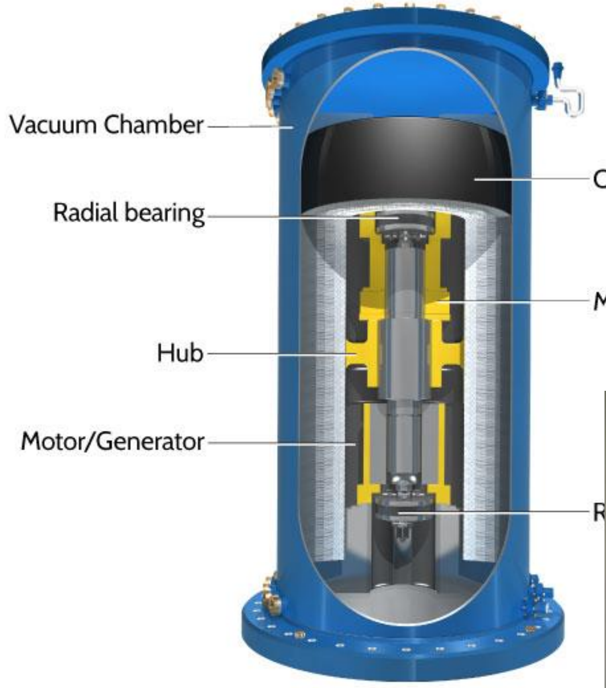
NASA G2
0.5 kWh
1kW
115 kg



Backup bearing drop testing at

Flywheel Application

- Stephentown, New York, Beacon Power
  - 20 MW flywheel storage power plant
  - 200 flywheels, each 7’ tall by 3’ diameter
    - 25 kWh, 100 kW each
- Used to stabilize the grid and for frequency control for NYISO, meeting 10% of state’s regulation demand
- 16,000 rpm carbon-fiber vertical rotor weighs 2,500 lbf
- Permanent magnet lift system, radial rolling-element bearings



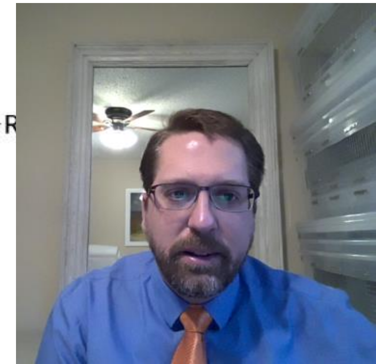


Image and Data Sources: Amiryar and Pullen (2017), Luo *et al* (2014), Beacon Power (2019)

Gravitational Energy Storage Concepts

www.aresnorthamerica.com

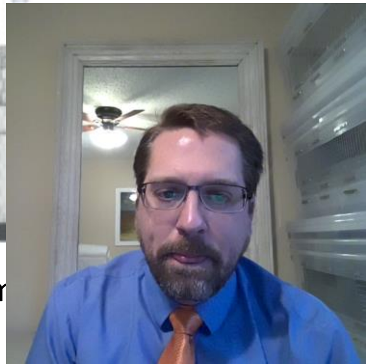
ARES (Advanced Rail Energy Storage)

- Weighted rail cars
- Compete with PHS power and storage capacity but simpler siting/permitting, much lower cost
- Pilot test completed in 2013 (California)
- First commercial application (Nevada)
  - 50 MW, 12.5 MWh
  - 8600 ton, 9 km of track, 610 m elevation

Energy Vault

- Cranes raise and lower concrete weights
- Highly modular, high TRL components
- Commercial application
  - Nominal 35 MWh, 4 MW
  - Anticipate less than 1/3 cost of PHS

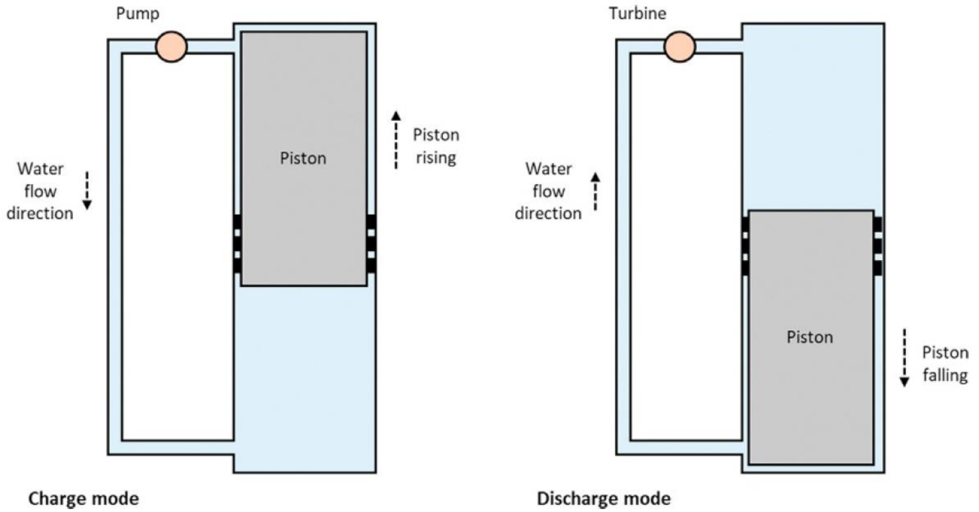
www.energyvault.com



Gravitational Energy Storage Concepts

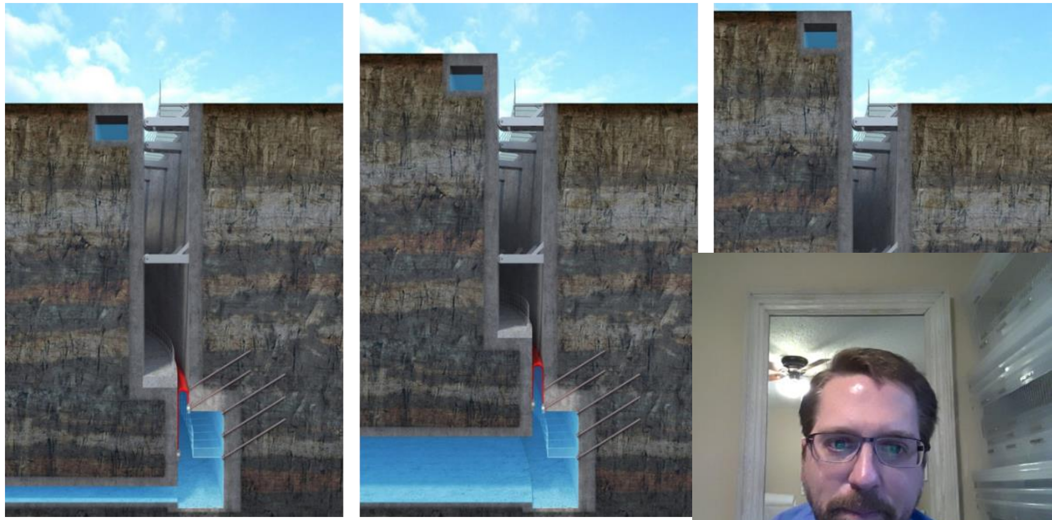
Gravitricity

- Raise and lower weight in abandoned mine shaft
- Fast response times comparable to battery
- Possible for 3000 ton, 1500 m
- 250 kW demonstration
- 4 MW full-scale prototype planned



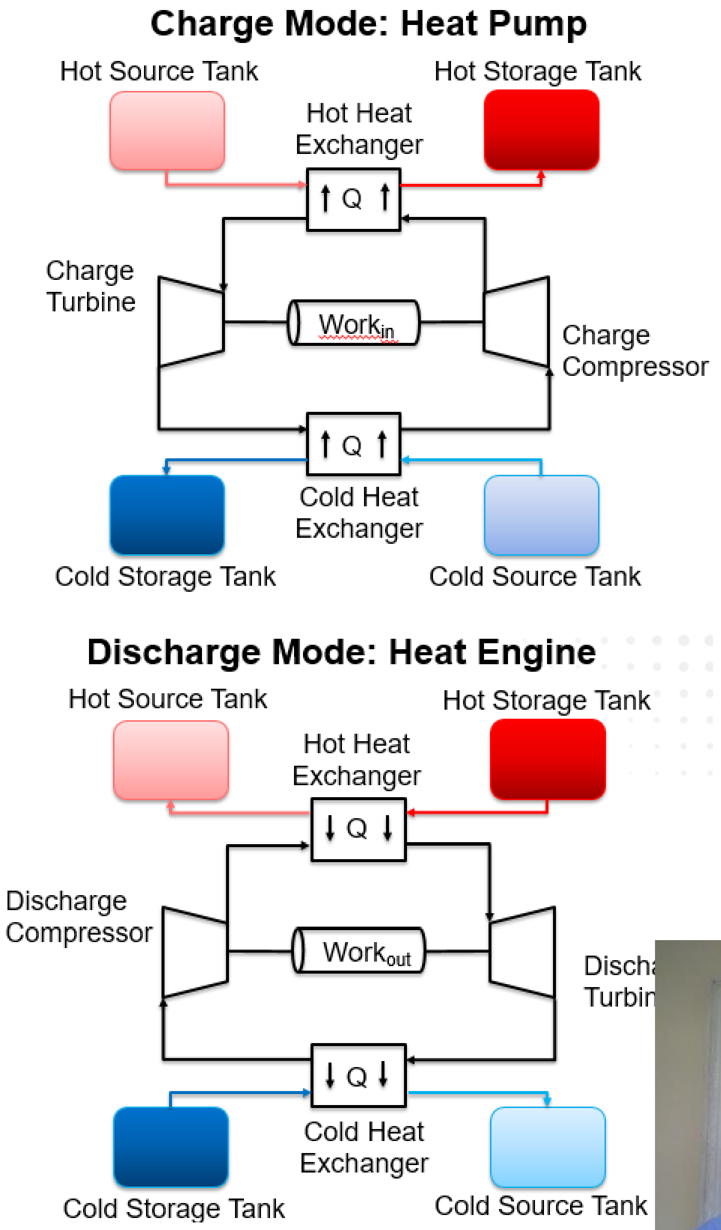
Heindl Energy and Gravity Power

- Raise and lower weight using pumps and water pressure
- Commercial concepts up to 10 GWh
- Economy of scale: Storage ~L^4, Cost ~L^2
- Requires dynamic seal
- Reference: heindl-energy.com and gravitypower.net



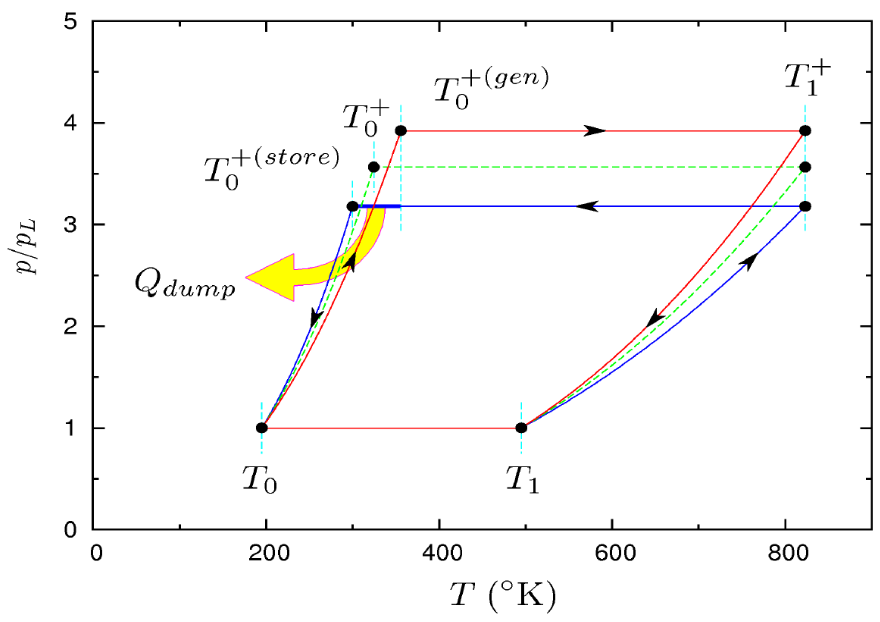
Thermal ES: Pumped Heat

- Working Principles
  - Electricity in drives heat pump to charge system
  - Heat engine discharges system to produce energy
- Prominent Designs
  - Thermoclines: Isentropic UK, TRL 4
    - Packed bed stores (gravel)
  - Heat exchangers: Brayton Battery, TRL 2
    - Hot store- molten salt
    - Cold store- refrigerant
  - Working fluids: Argon, air, sCO_2
- Theoretical 50-70% RTE



Thermal ES: Brayton Battery

- Turbomachinery Integration
  - Development for high efficiency turbomachinery capable of required temperatures
  - Designs for high component ramp rates (rapid response)
  - Axial or radial machines
- R&D Activities
  - SwRI developing kW-scale proof of concept demonstratior system focusing on system integration and controls, transients
  - High-temperature compressor development
  - Turbomachinery range extension
  - Brayton Energy under ARPA-E DAYS developing a reversible turbine design
  - Malta Inc. developing 10 MW pilot plant



Charge Mode (Example Conditions)	
Compressor Inlet	226 °C
Compressor Exit	[illegible]
Turbine Inlet	[illegible]
Turbine Exit	[illegible]

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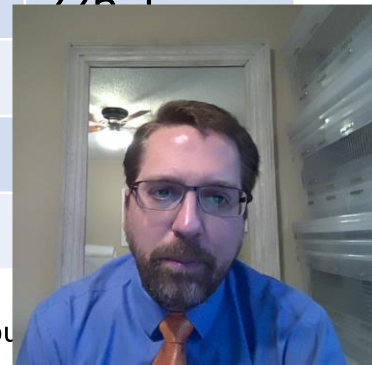
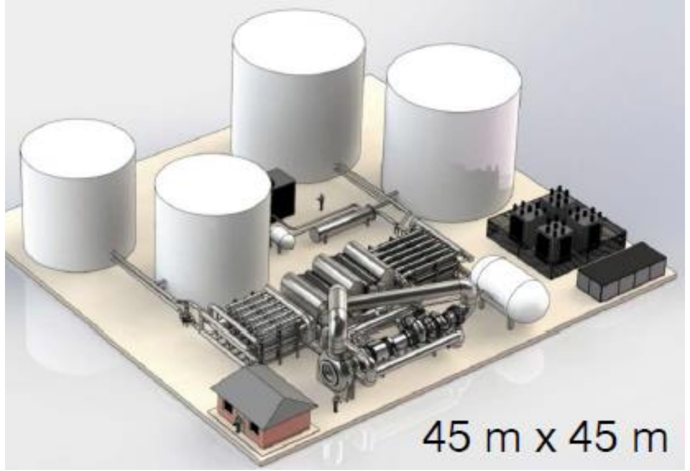
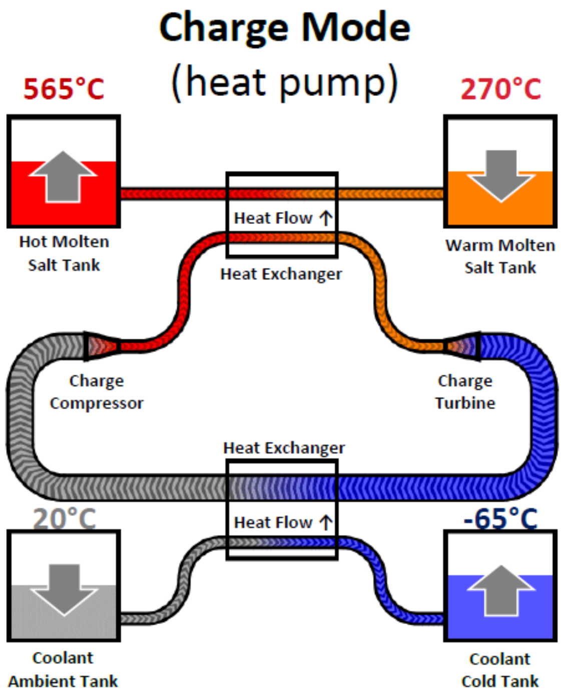


Application – Pumped Thermal ES

Planned pilot facility by Malta, Inc.

- 10 MW, 100 MWh (10 hours)
- Molten salt + refrigerant storage
- AC-AC Input/Output



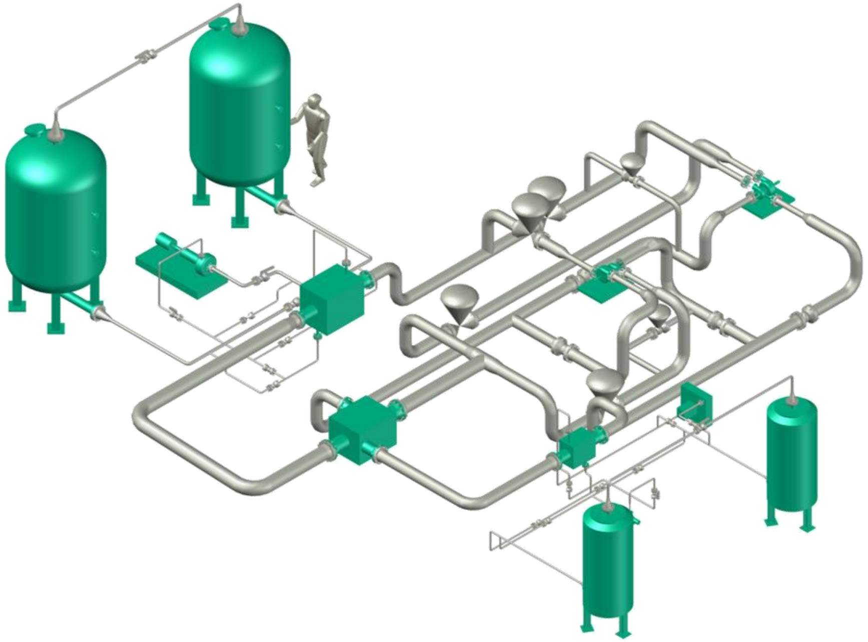


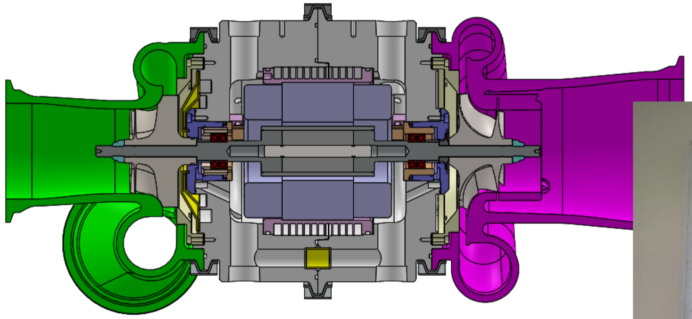
Data and Image Sources:
Little (2019)
https://www.bostonglobe.com/business/2018/12/27/moonshot-from-alphabet-effort-has-landed-cambridge/8cQ8D9ZQeITb3jt6nydBgN/story.html
https://qz.com/1503405/bill-gates-led-fund-is-investing-in-a-startup-to-build-a-cheap-battery-using-a-refrigerator-on-steroids/

Demonstration – Pumped Thermal ES

Demonstration facility by SwRI (ARPA-E)

- kW-scale demonstration
- Thermal Oil + Glycol/Water storage
- AC-AC Input/Output
- Objective to verify control strategies, reduce risk for full-scale application, and provide data from transient and steady state operation

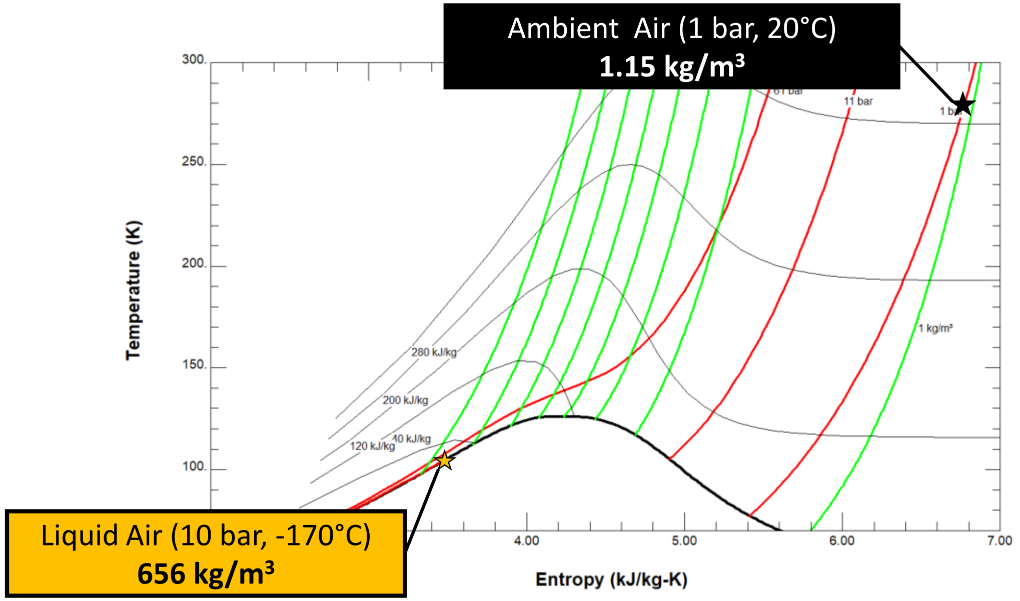




Tom, Smith, McClung, 2020, "Cycle Considerations for the Conceptual Design of a PHES," *Proc. of ASME Turbo Expo,* GT2020-15657.

Thermal ES: Liquid Air

- Principle
  - Utilize the high density of liquid air for compact, portable storage
- Technology Gaps
  - Overall system efficiency via turbomachinery and heat exchanger development
  - Lower system costs
- Expected Performance
  - 60-70% efficiency and 30-40 year lifespan
  - Highest performance when coupled with waste heat
  - Storage losses as low as 0.05% by volume per day (Yang, 2006)



E

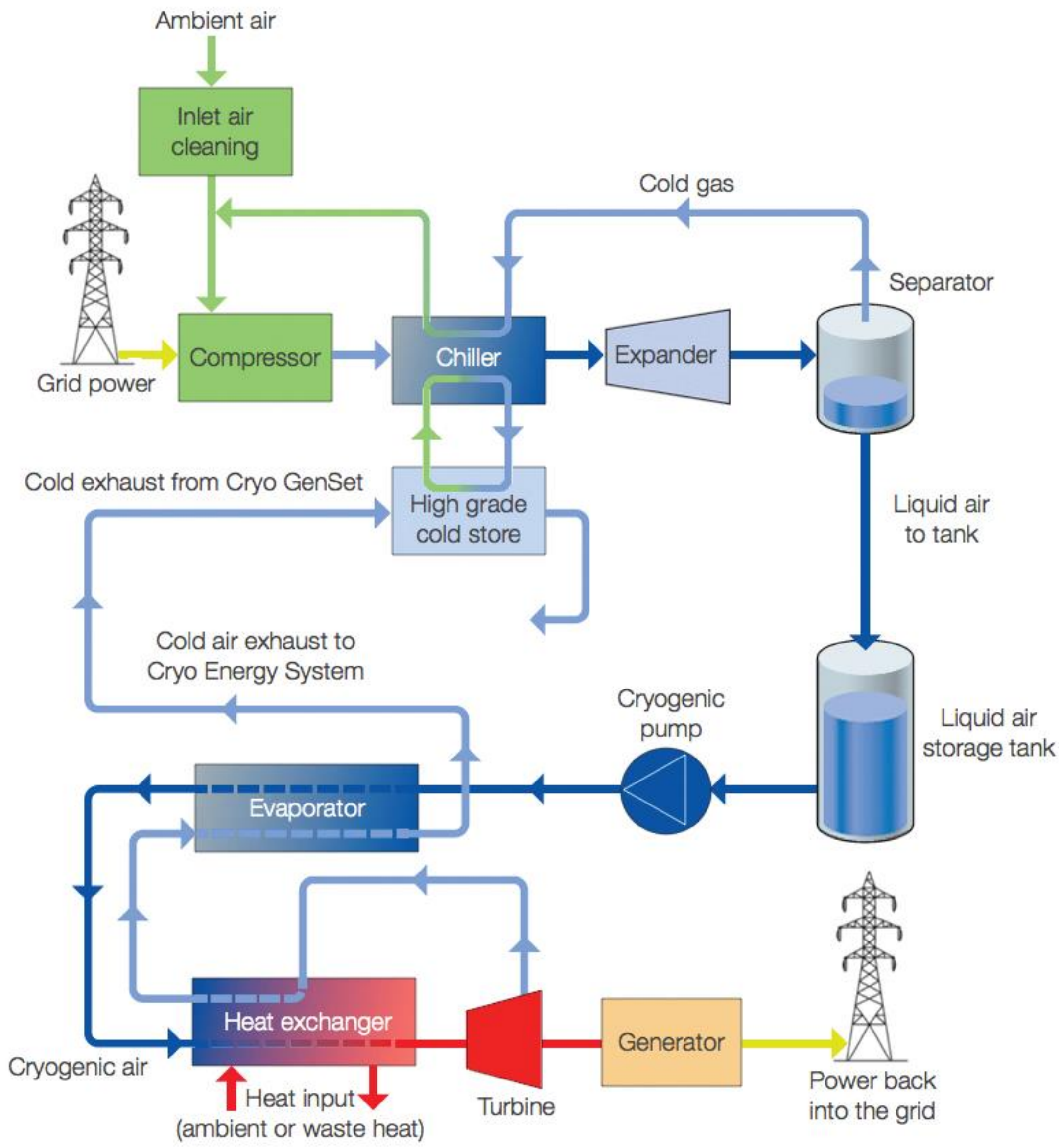
Charge
Liquefy air with refrigeration cycle

Store
Cold Liquid Air at low pressure in insulated tanks

Discharge
Pump air to high pressure
release by expanding across

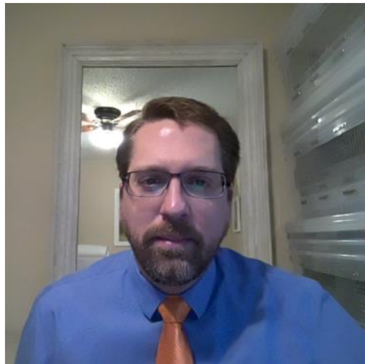
Thermal ES: Liquid Air Process

Charge:
Air Liquefaction



Store:
Liquid air in insulated tanks

Discharge:
Cryogenic Power Cycle

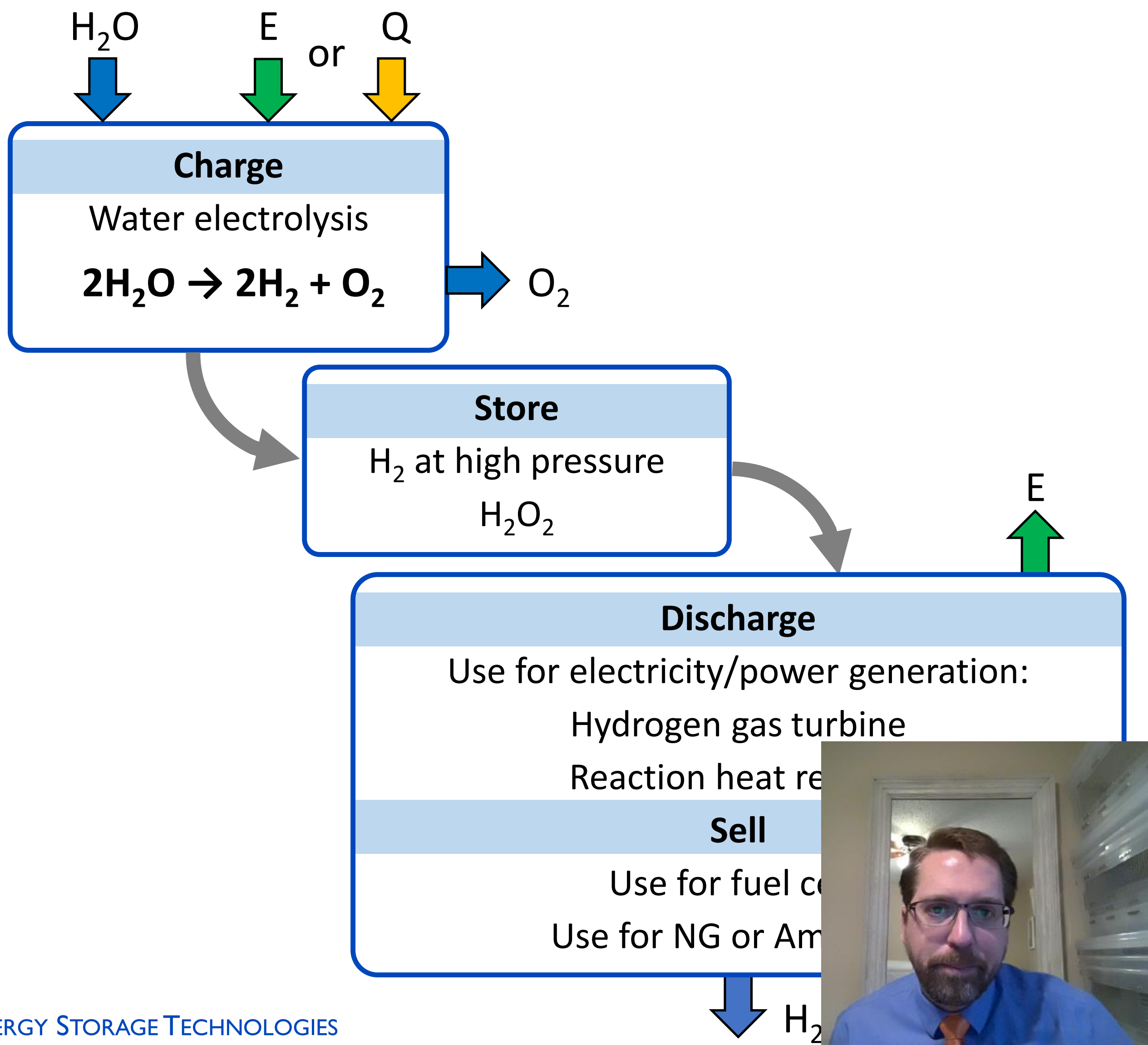


Thermal ES: Liquid Air R&D Activities

- Turbomachinery Integration
  - Liquefaction:
    - Centrifugal compressors, radial expanders, heat exchangers
  - Power recovery:
    - Cryogenic pumps, turbines, heat exchangers
- Current R&D Activities
  - Highview Power
    - Grid-scale Demonstration Pilsworth Plant in Greater Manchester, April 2018 (TRL 7)
    - Pilot Plant with waste heat operated under full testing conditions at a biomass plant (Greater London) in 2011-2014. Plant now located at University of Birmingham. (TRL 6)

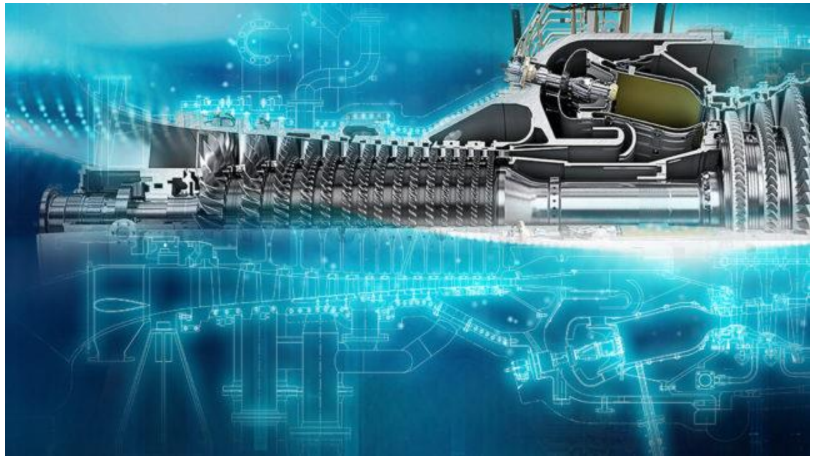
Thermochemical ES: Hydrogen

- Principle
  - Use access grid energy to split water in to H2 with electrolysis
  - Couple with CSP or other heat source instead of using surplus energy to drive electrolysis
- Turbomachinery Integration
  - Hydrogen compressors
  - Hydrogen gas turbines
  - Other gas turbine development topics
- Current TRL: 3-9 depending on application
- Technology Gaps
  - High temperature electrolysis
  - Fully reversible energy storage process less viable
  - Feedstock availability required
  - High pressure storage – location and safety
- Expected Performance
  - Up to about 50% round trip efficiency



Thermochemical ES: Hydrogen R&D Activities

- Hydrogen Gas Turbines
  - Many OEMs have been developing capabilities to run their GTs on hydrogen for decades (Mitsubishi Hitachi, GE, Solar Turbines, Siemens)
  - Organizations like EU Turbines support and direct goals and funding
  - To date, significant research has been conducted on combustion with fuels containing larger percentages of hydrogen
- Hydrogen Storage Salt Caverns
  - Three full size in operation in Texas, USA
  - Three older caverns in operation in Teesside, UK
- Electrolysis & Fuel Cells
  - University of Tennessee Knoxville working on electrolyzer/fuel cell with ARPA-E DAYS



https://www.turbomachinerymag.com/fuel-switching/

https://www.edie.net/news/6/Work-to-being-on-pioneering-salt-c

Thermochemical ES: Hydrogen Gas Turbines

Advantages

Availability

Historically used as rocket fuel

Potential for carbon and ash free combustion

Fewer corrosion and after-treatment complexities

Many GTs already a H2 blend

High combustion temperature

Challenges

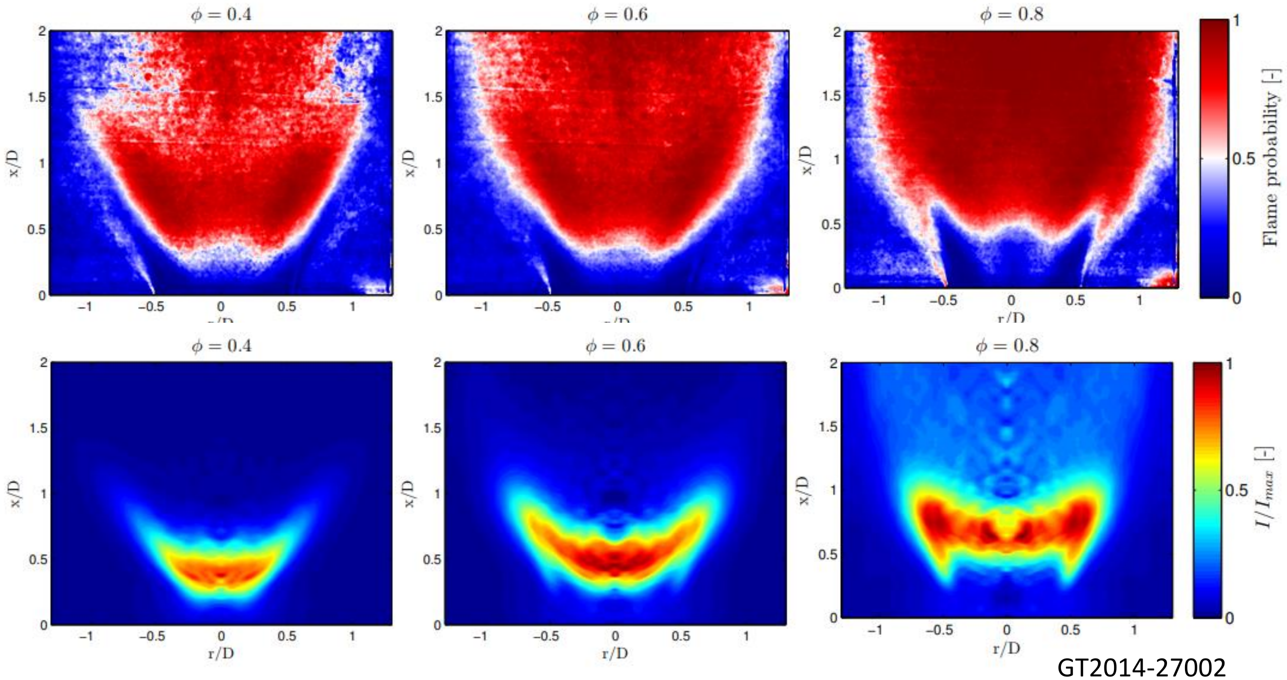
High flame speeds

Combustion kinetics

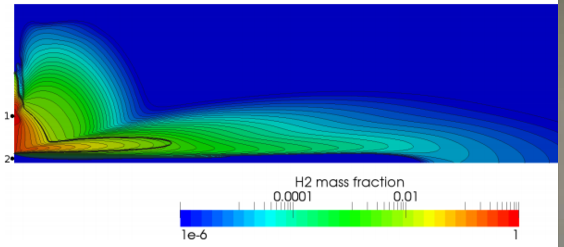
Combustion stability

Increased cooling requirements

NOx emissions still a factor



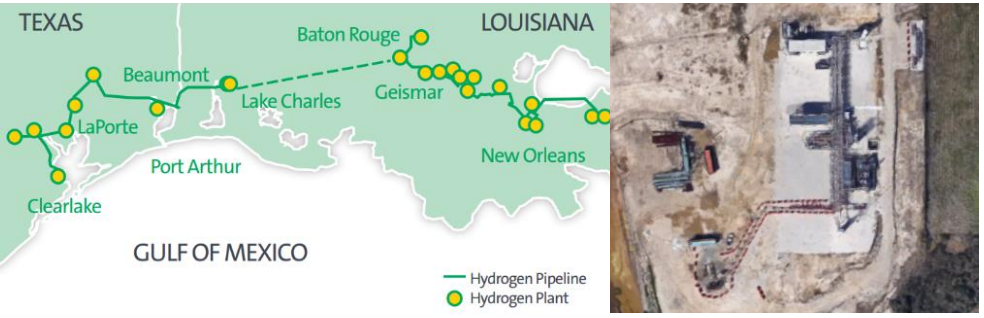
GT2014-27002



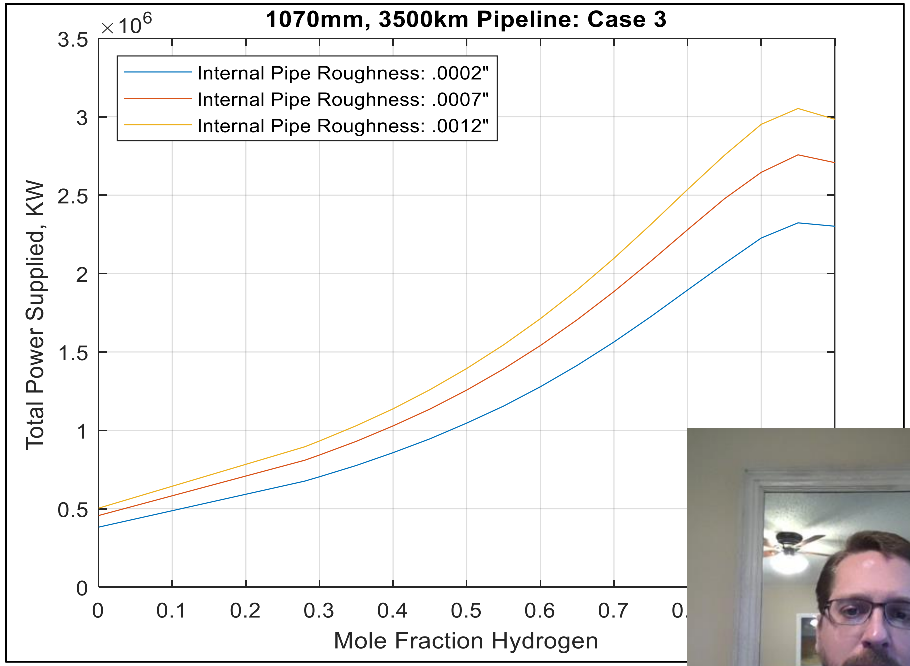
GT2014-

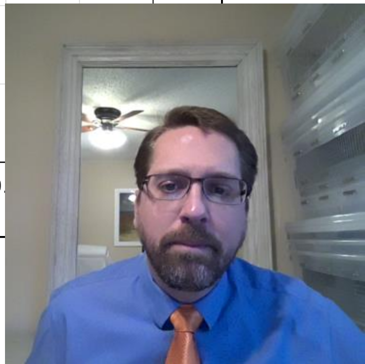
Integrated ES: Hydrogen in Gas Pipelines

- Hydrogen pipelines exist but at small scale
- Primarily non-lubricated reciprocating compressors
- Research needed to address technical challenges with hydrogen blending in gas pipelines
  - Decrease in volumetric energy density
  - Decrease in pipeline efficiency
  - Compression requirements for high flow, high head
  - Combustion in pipeline gas turbines
  - Materials compatibility
  - Leakage / flammability



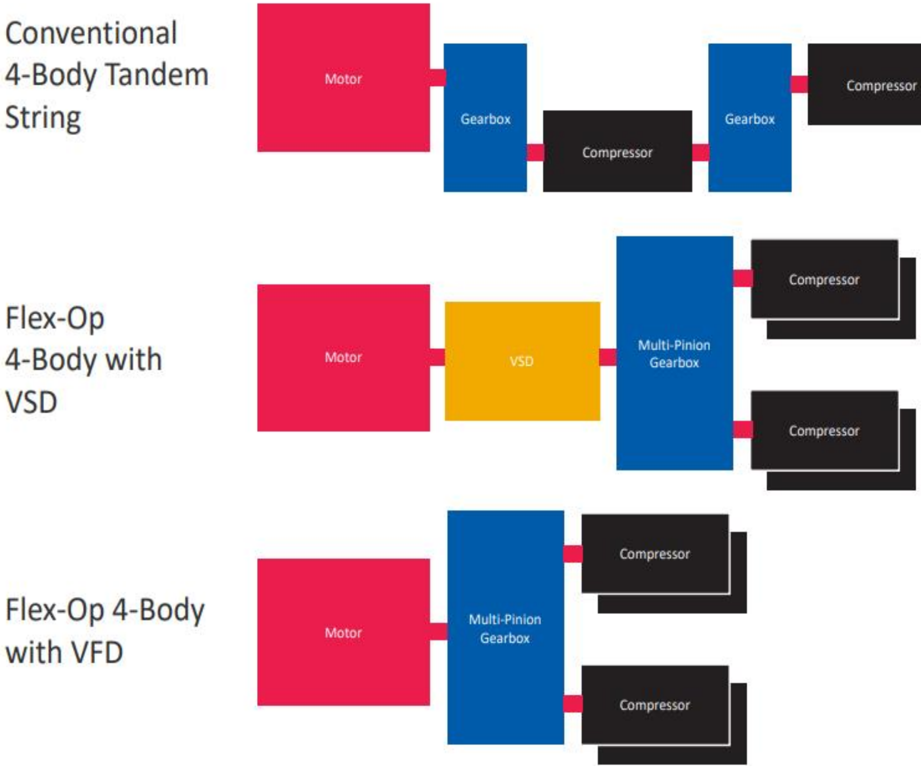
Images Courtesy Air Liquide

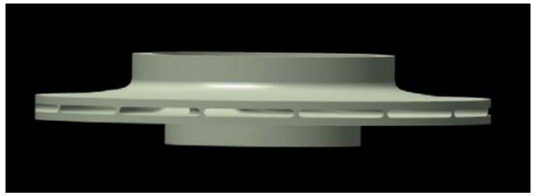




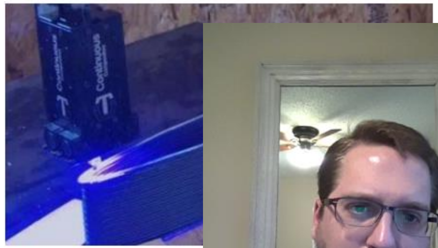
Hydrogen Centrifugal Compressors

- Experience in refining applications for over 65 years, >100 trains
- Multibody and integrally-geared trains for high head
- High tip speed impellers
  - API 617 requires <120 ksi YS, material testing
  - Currently use 17-4PH or 13Cr-4Ni steel
  - Consider Ti alloys (Ti-6-4)
  - R&D in carbon fiber and ceramic materials





Model of Ceramic Impeller



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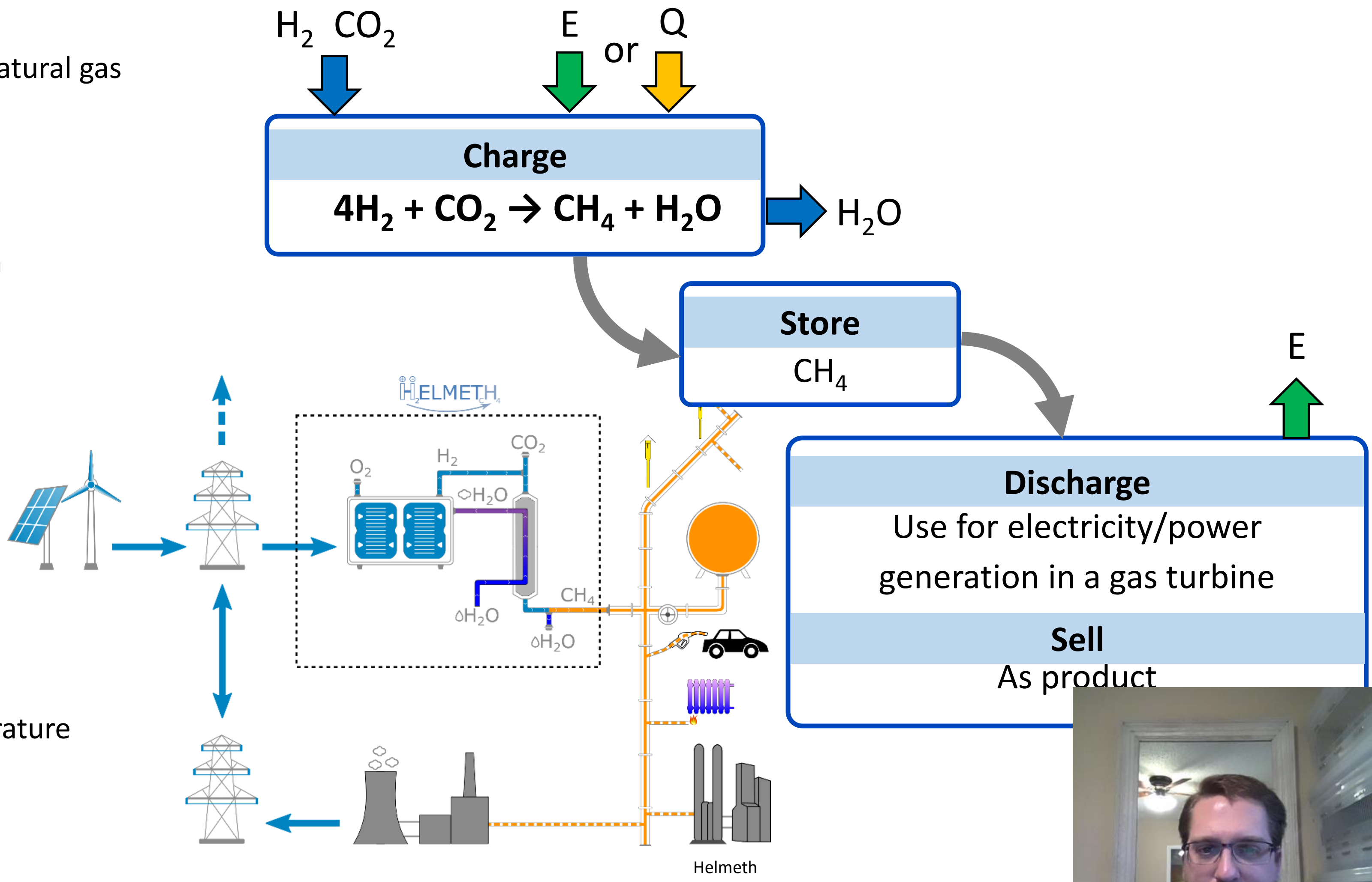
Thermochemical ES: Synthetic Natural Gas

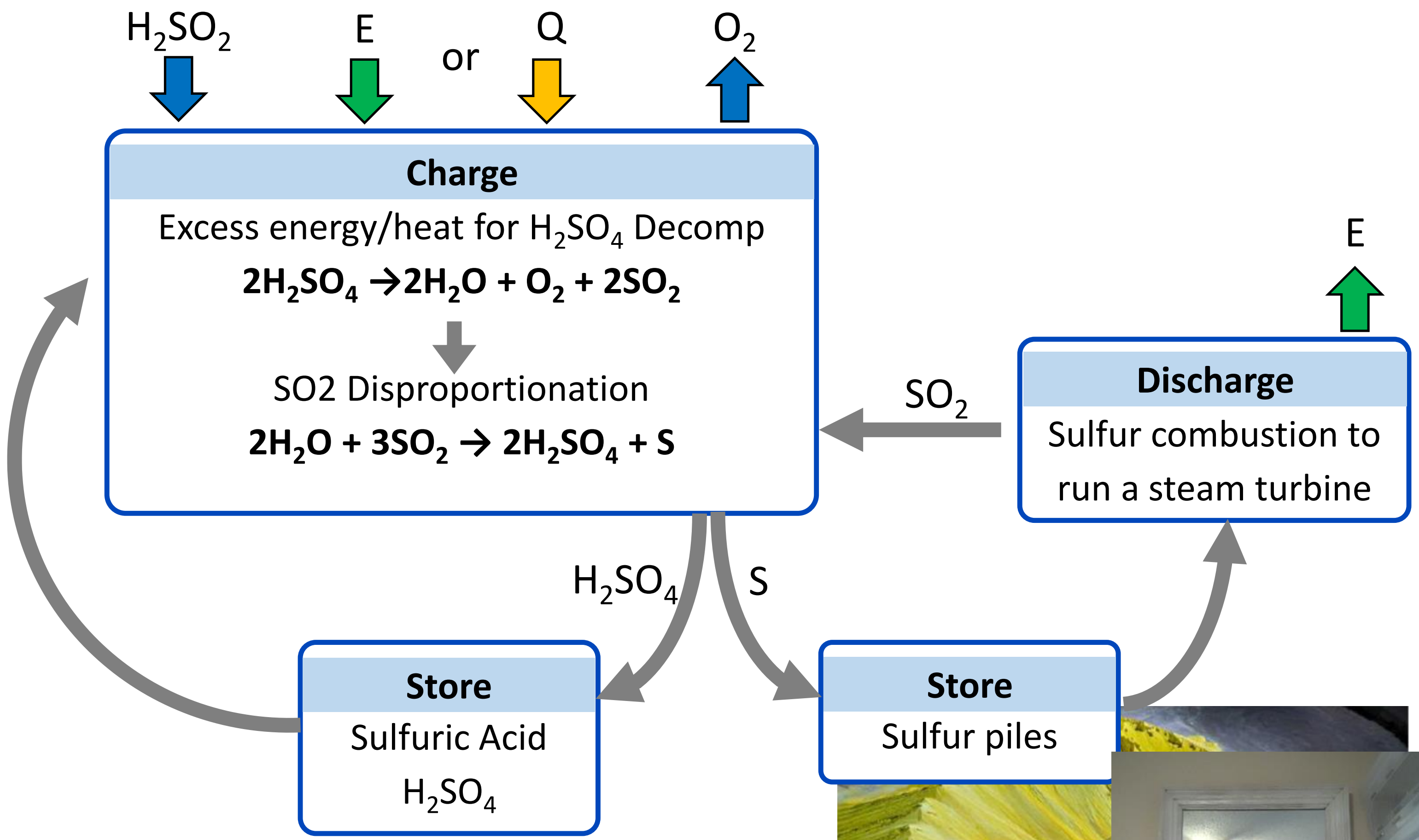
("CO_2 to Fuel" or "power to gas")

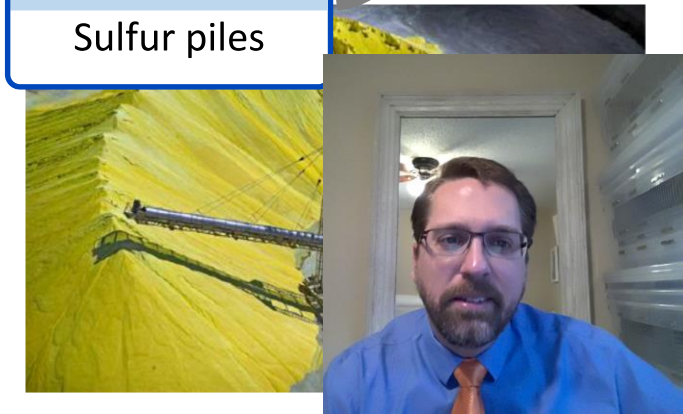
- Principle
  - Use excess energy or heat to generate natural gas from CO_2 and H_2
- Turbomachinery Integration
  - Heat exchangers
  - Materials and structural integrity at high temperatures
  - Carbon capture technologies
- Current TRL
  - Production Demonstration
- Technology Gaps
  - Needs high purity CO2 supply
  - Requires hydrogen production
- R&D Activities
  - HELMETH demonstrator for high temperature electrolysis and methanation
  - TKI Gas



Thermochemical ES: Sulfur

- Principle
  - Closed sulfur cycle include SO_2 Disproportionation, Sulfur combustion, and sulfuric acid decomposition
- Turbomachinery Integration
  - GT and heat exchangers for sulfur
- Current TRL: 3-5
- Technology Gaps
  - Overall system complexity and integration
- R&D Activities
  - General Atomics development with CSP
  - Form Energy with ARPA-E DAYS

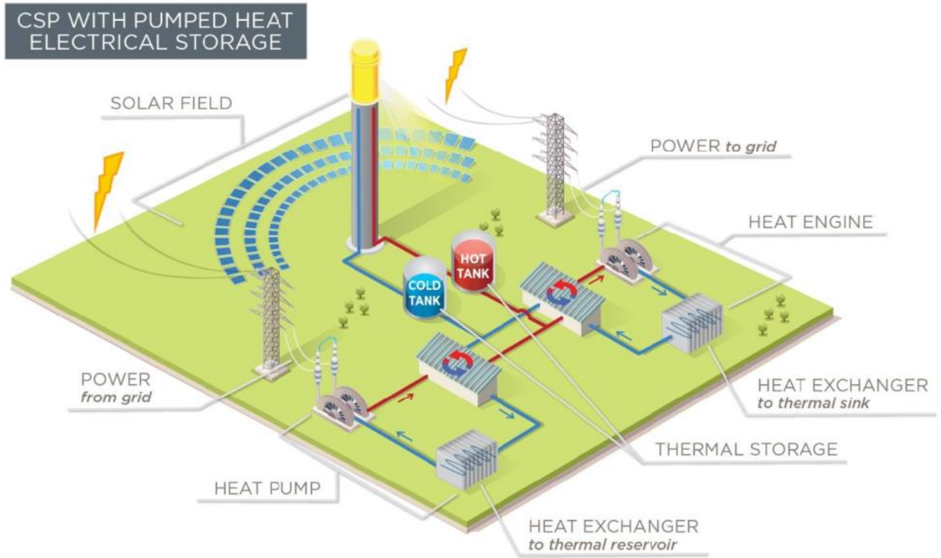




Integrated ES: CSP + Pumped Heat Hybridization

- R&D efforts to combine PHES with existing heat engine, sharing one or both:
  - Power block for discharge mode
  - Thermal storage hardware

- Example CSP system concept
  - Supercritical CO2 power block and PHES fluid
  - Shares both power block and salt tanks
  - Potential for cold-side storage on heat pump to supplement power block precooler



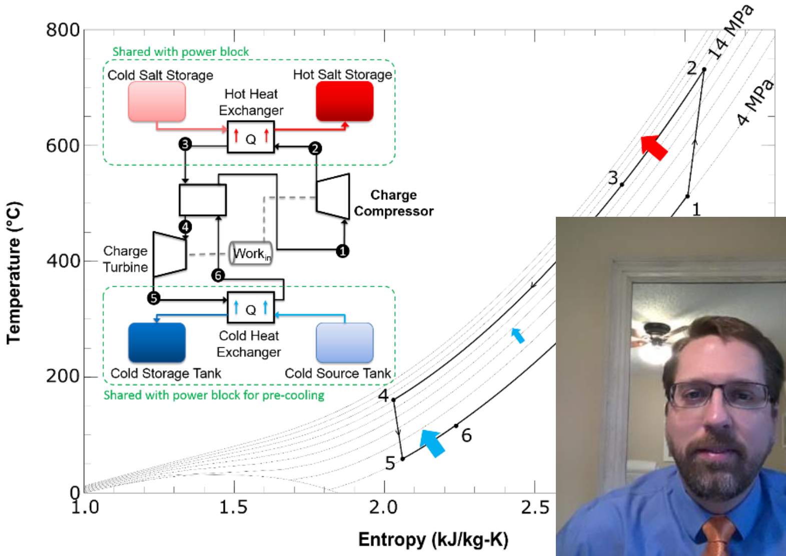
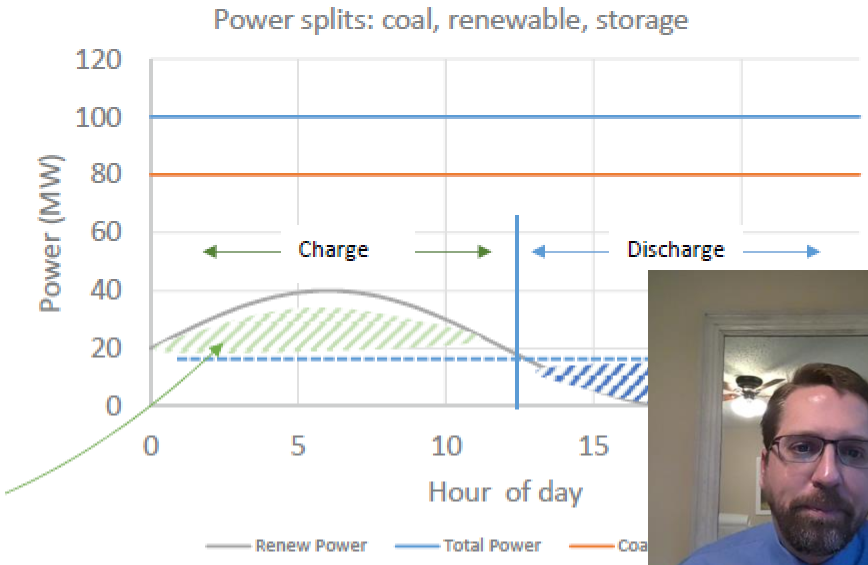
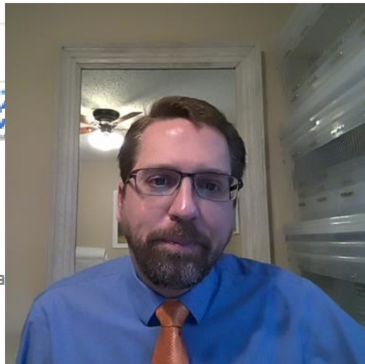


Image and Data Sources: DOE (2019), Smith *et al* (2019), Aga *et al* (2016)

Integrated ES: Fossil + Energy Storage

- Fossil without CCS
  - Improve turndown and peaking capability of gas/coal/nuclear plants
  - Alternative to plant cycling
  - Sharing of infrastructure and heat stream optimization
  - Enhance baseload plant ramp rate
  - Dispatchable bottoming cycles
- Side topic: Fossil with CCS
  - CO_2 solvent storage (post-combustion CCS)
  - Oxygen storage (IGCC and Oxy-Combustion)
  - Hydrogen storage (IGCC)



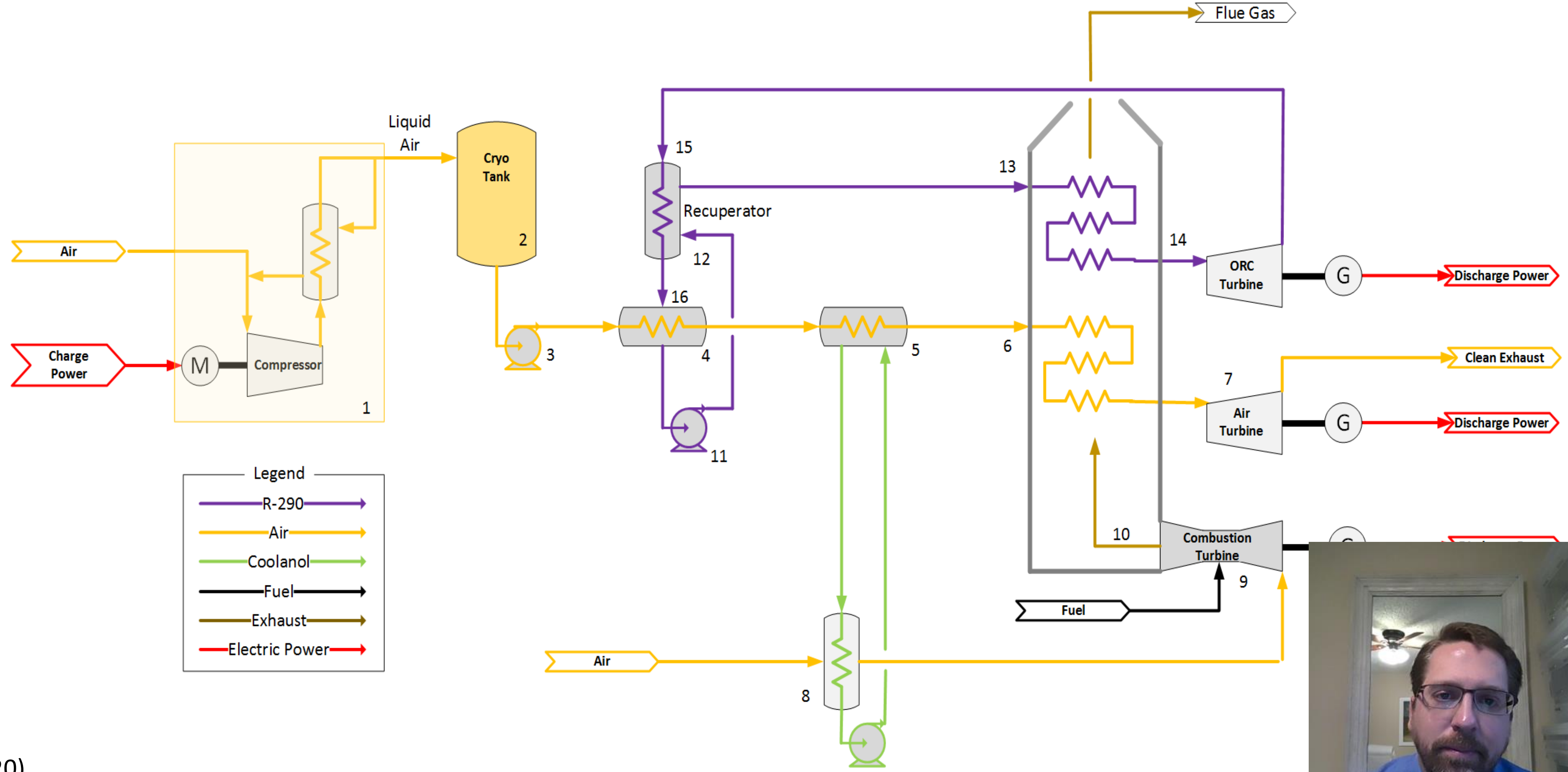


Data and Image Sources: Richards (2019), DE-FOA-0001989, IEAGHG 2012

Integrated ES: Fossil + Energy Storage

Example Concept of Liquid Air Combined Cycle

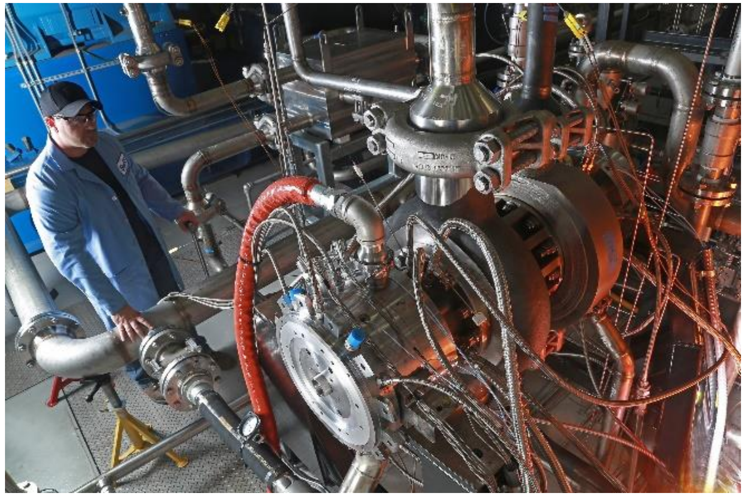
- Hybridizes with existing open cycle gas turbine
- Incorporates liquid air for energy storage
- Requires bottoming cycle component development
- System optimization for different cycles, fuel cost scenarios, hardware/permitting constraints



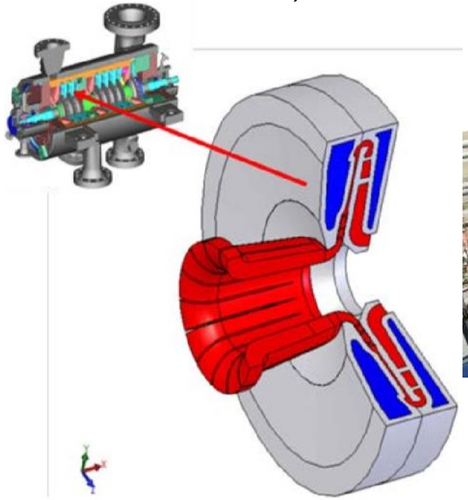
Data and Image Sources: Pintail Power (2020)

Machinery & HX Development Needs

- Most new thermodynamic systems are closed or semi-closed cycles requiring:
  - Very high machinery efficiency over a variety of temperatures, pressures, and scales (radial axial)
  - Low leakage/makeup requirements; consider hermetic machinery
  - High pressures, densities, possibly temperatures
  - PHES: High-temp compressor; single machinery train for charge/discharge mode
- Integration of compression, expansion, and heat exchange functionality into machinery to improve cost and performance
- Hydrogen combustion, compression
  - Emissions, stability/range
  - High tip speeds or many stages
- Fast ramping and wide operating range
- Low-cost compact HX for gas-liquid and with fast transient capability



High-Efficiency High-Temperature 10 MWe 715 °C Supercritical CO_2 Turbine with Low-Leakage Dry Gas Seals (Moore 2019)



CO2 Compressor for CCS with Internally-Cooled Diaphragms (Moore 2014)

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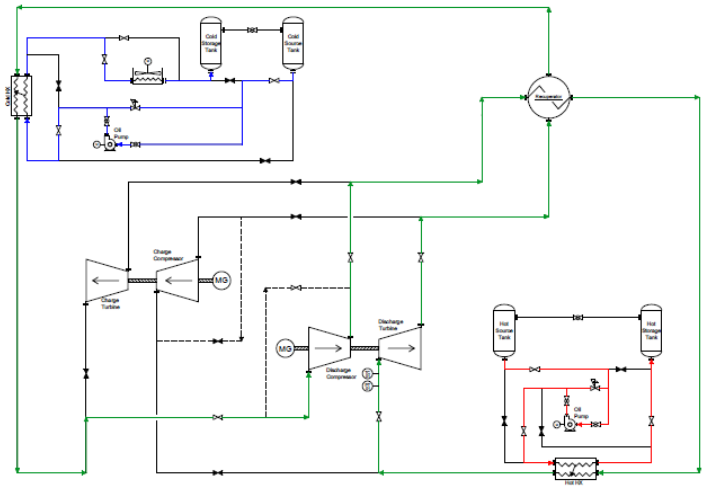
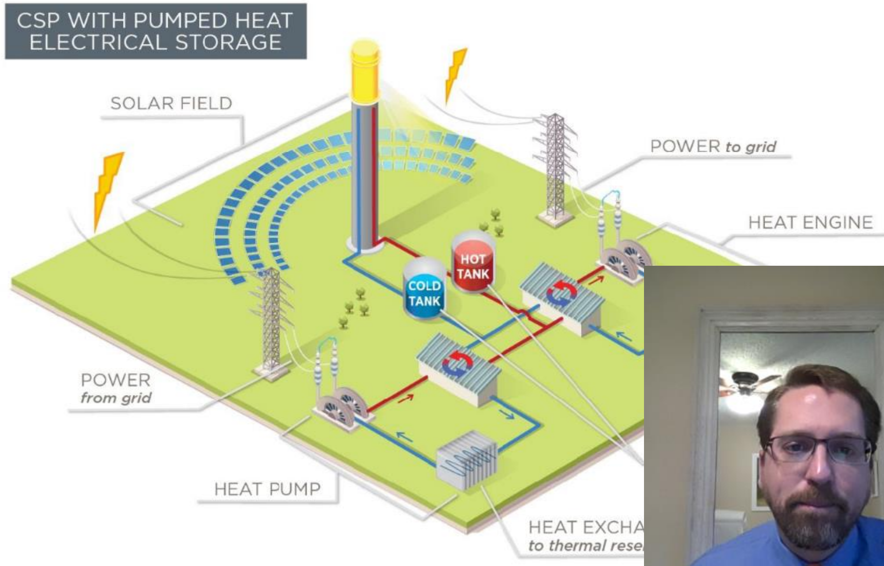
System Development Needs

- Control & operation experience of closed or semi-closed cycles
  - Inventory control for turndown; ambient conditions
  - Leakage management / recovery
  - Trip & settle-out scenarios
  - Charge/discharge mode system balancing
- Detailed plant design & cost optimization
- Integration/optimization with numerous generators and applications
  - Coal, Gas, Nuclear, Concentrating Solar, Waste Heat, Combined Heat & Power, Geothermal
  - Sector coupling with heating, cooling applications
  - Existing Brayton/Rankine cycles, advanced power cycles
  - Storage for time-shifting CCS





CSP Integrated with PHES (Image Source: U

Questions?

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