**Supercritical CO_2-Based Long-Duration Electrical Energy Storage
Technical Overview**

Summary

- Long duration (>4-6 hours) energy storage is becoming increasingly important
- Echogen is introducing an "Electro Thermal Energy Storage" (ETES) system based on its ground-breaking development of commercial supercritical CO_2 power cycles
- ETES stores electrical energy as thermal energy, and recovers back to electrical energy
- Materials are low-cost, safe, and environmentally-benign
- ETES does not require lakes on mountains or giant holes in the ground to install
- Economics for long-duration storage at utility scale (10+ MWe) are excellent
- Echogen is looking for partners for a commercial-scale demonstration plant

ECHOGEN
power systems

WHAT IS ETES?
Electro Thermal Energy Storage

ETES in a Nutshell (Simplified View)

## Thermodynamic cycles transform energy between electricity and heat

Charging cycle

- Heat pump cycle
- Uses electrical power to move heat from a cold reservoir to a hot reservoir
- Creates stored energy as both "heat" and "cold"

Generating cycle

- Heat engine cycle
- Uses heat stored in hot reservoir to generate electrical power
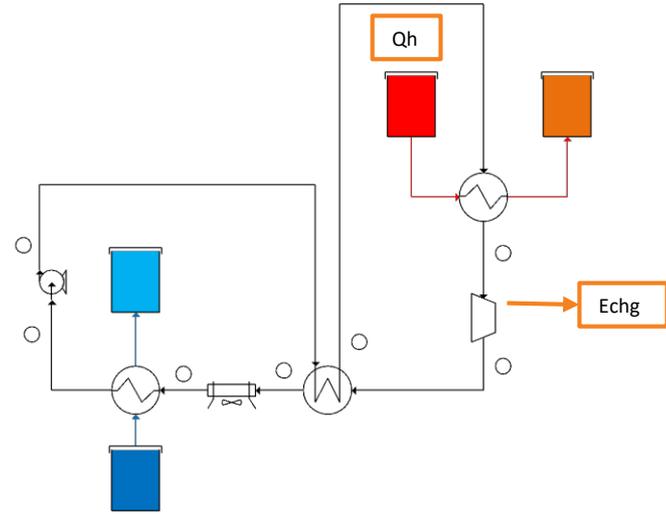- "Cold" energy improves performance of heat engine

ECHOGEN
power systems
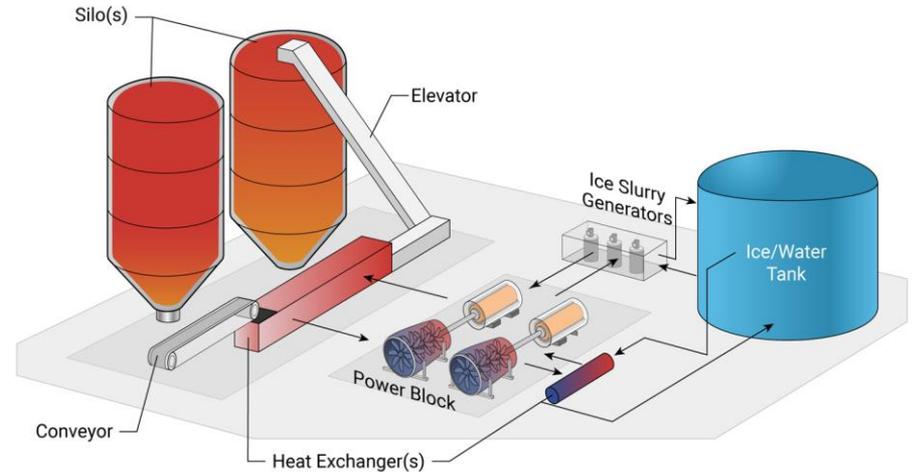
ETES for Thermo Geeks
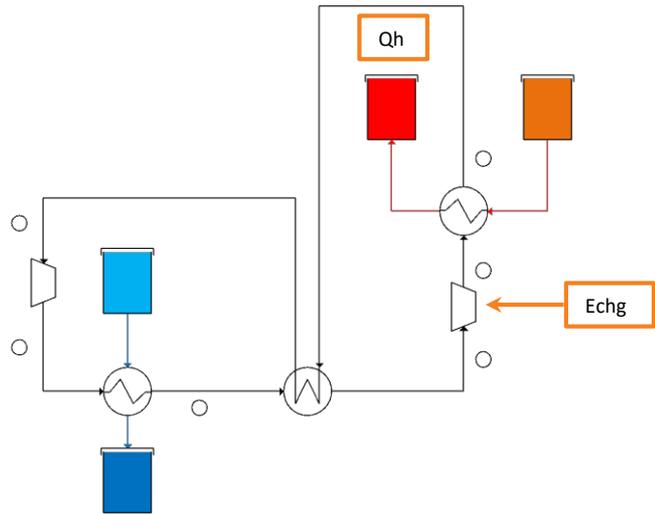
Heat Pump Cycle
COP = Qh/Echg

Ideal COP = 1/(1-Tc/Th)

Overall Process
RTE = Egen/Echg
= COP x Efficiency

Ideal RTE = 100%

Power Cycle
Efficiency = Egen/Qh

Ideal efficiency = 1-Tc/Th

Non-ideal processes result in RTE ~60%, even at modest temperature ratio

WHY USE CO$_2$ FOR ETES?

High Efficiency, Low Cost, Safe Materials

Working Fluid and Reservoir Choices…

Main Metrics Are:

- Efficiency
- Cost
- Safety

Remember Three Things…

- Round-trip efficiency is not a strong function of the reservoir temperatures
- Two main types of reservoirs—phase-change and "sensible"
- "Glide-matching" is vital

ECHOGEN
power systems

If RTE Isn't a Strong Function of ΔT…

… then we can choose the reservoir temperatures to suit the working fluid (and vice versa)

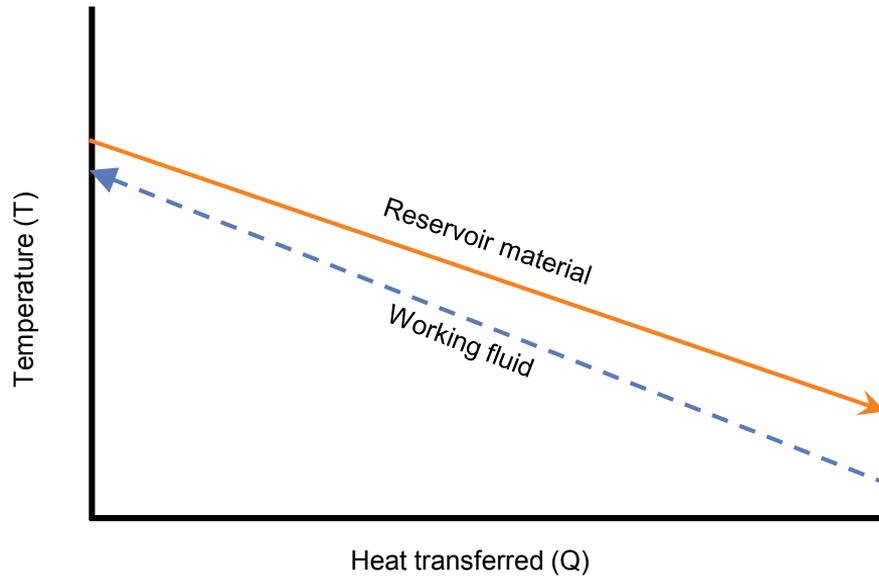Since efficiency is only modestly driven by ΔT, then cost and safety become the main drivers in selecting reservoirs

ECHOGEN
power systems

Charging process – hot working fluid heats up cold reservoir
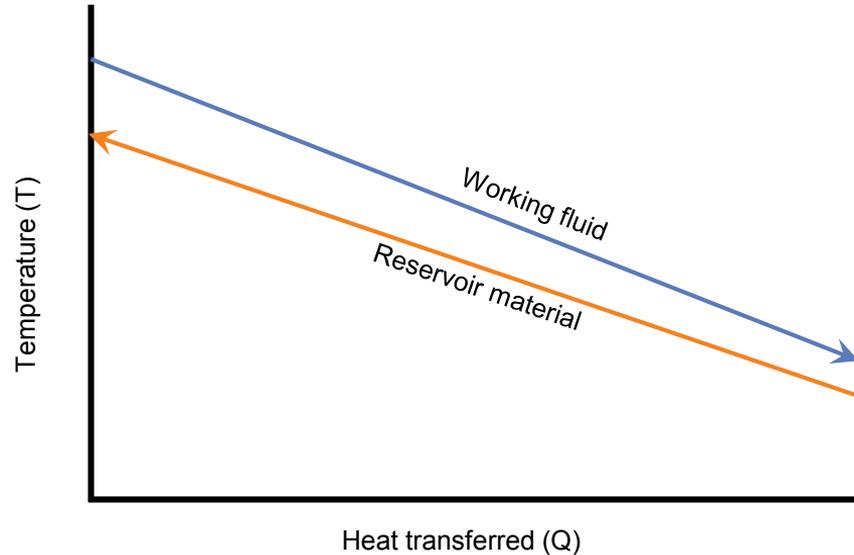
Reservoir Type and "Glide Matching"

Generating process – reservoir material heats up working fluid

Temperature (T) vs. Heat transferred (Q) diagram showing Reservoir material (orange solid line) and Working fluid (blue dashed line).
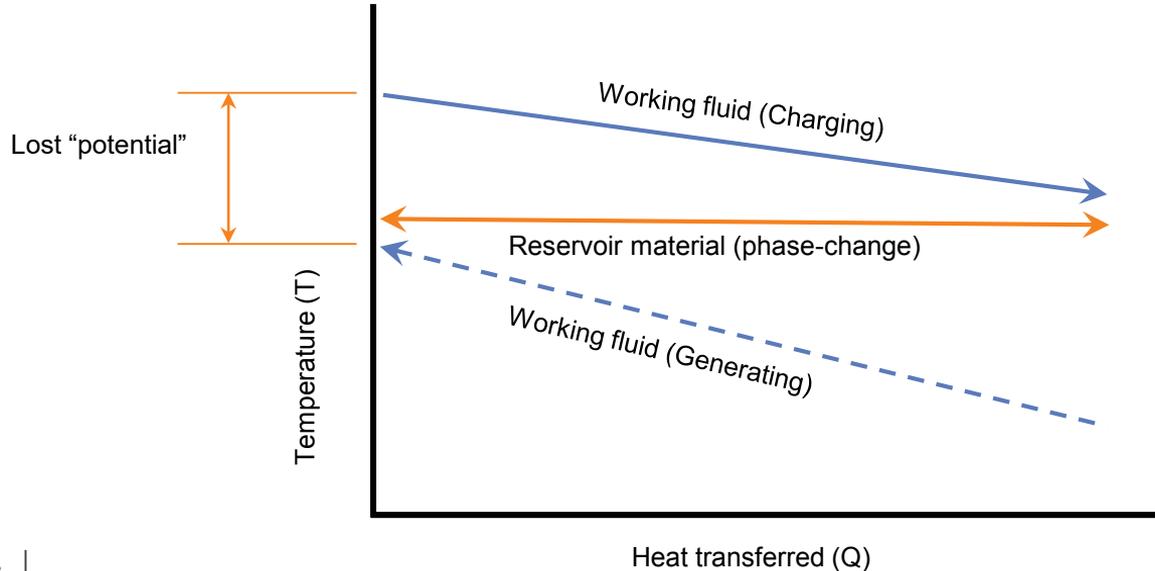
Reservoir Type and "Glide Matching"

Glide match defines the lost thermodynamic "potential" (exergy for the nerds among us) in the round-trip process

ECHOGEN
power systems
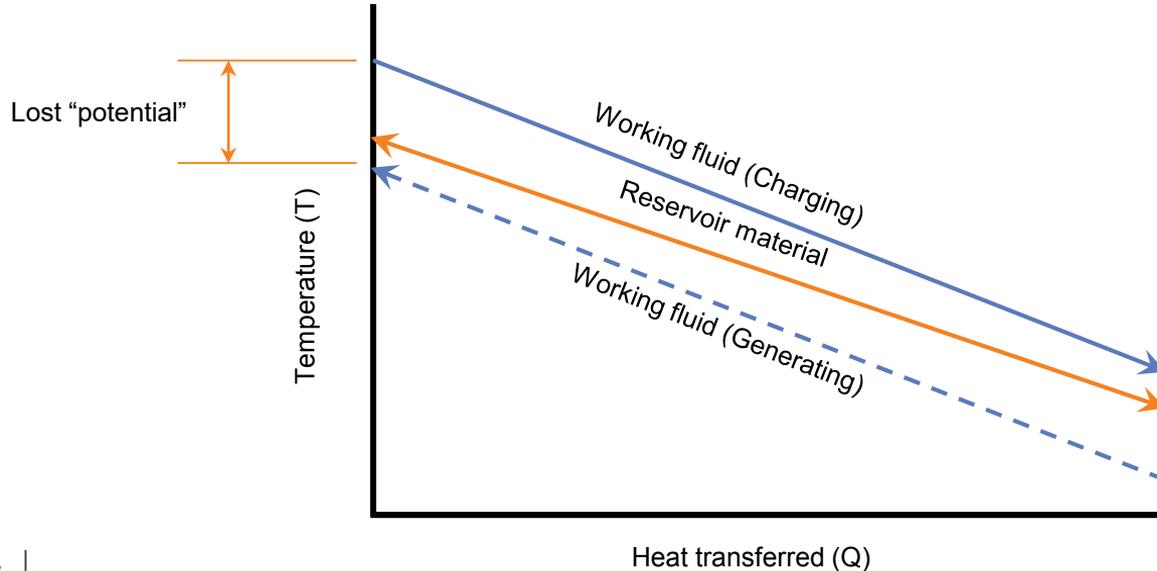
An example of bad glide-matching… sensible fluid with a phase-change reservoir

ECHOGEN
power systems

CO$_2$ Cooling and Heating Processes

- The low-temperature processes are condensation and evaporation (constant-temperature phase changes)
- So we pair them with another phase change process:

- Conversely, the high-temperature processes are sensible (temperature increases as heat is added)
- So we pair them with another sensible enthalpy material:

ECHOGEN
power systems

The Material(s) World

- By selecting a moderate temperature range, we avoid costly materials of construction for containment and piping:
  - LTR: -10 to -2°C (14 to 28°F) – no cryogenic materials
  - HTR: 300-350°C (572 to 662°F) – no nickel-based alloys

- Storage materials are low-cost and safe:
  - Water + 10% PG: $12/kWhe (water/salt < $1/kWhe)
  - Sand: < $1/kWhe
  - Containment (tanks & silos): $12/kWe

- Reservoirs are not pressurized
  - No need for large pressure vessel containers

- CO_2 itself is low-cost, non-flammable and non-corrosive

ECHOGEN
power systems

Longer Duration = Lower Capex/kWh

2020 Capex Comparison, 50 MWe

2020
50 MWe, 10hrs
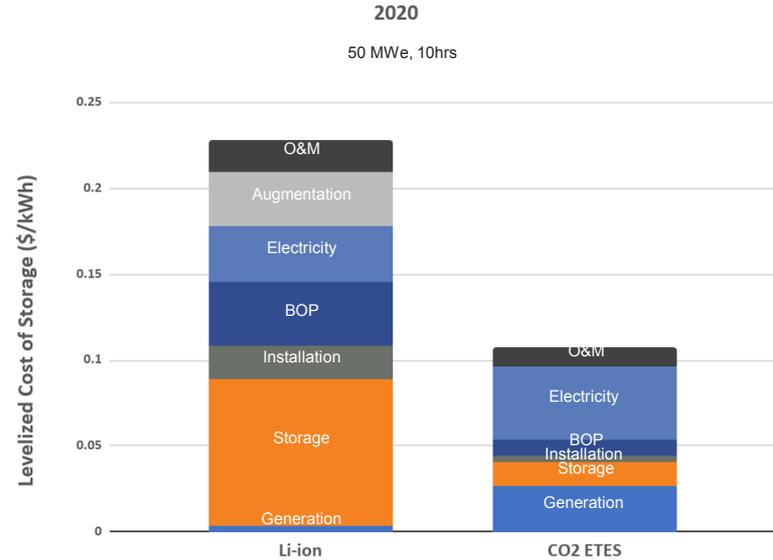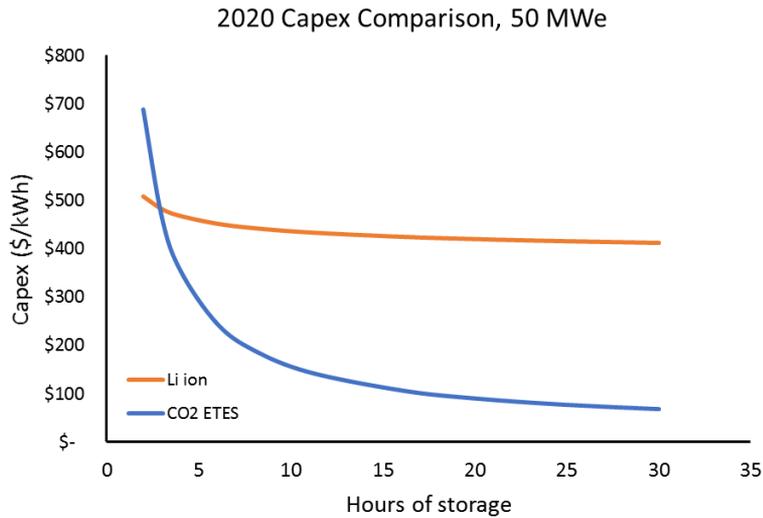
Lower Capex => Lower LCOS

ECHOGEN
power systems

What Does CO$_2$ ETES Offer?

- Low capex and LCOS for long duration applications
- Safe, low-cost, low-impact storage and construction materials
- A native AC-AC storage solution (no power electronics)
- Conventional generation equipment
- Compact plant footprint free from geographical restrictions
- Significant development risk reduction from existing CO2 power cycle work

ECHOGEN
power systems

EES Team has Done it Before

Schedule, cost, and performance projections are based upon demonstrated experience with comparable systems

- Team has over 10 years designing, building and testing comparable systems for most of the proposed solution
  - Built and operated the largest sCO_2 power systems in the world

- Echogen has devoted hundreds of manhours towards building and validating component cost models

- Previous EPS100 experience on cost, timing, and performance

  - Turbo-machinery first article + NRE within 2.3% of $2.2M budget
  - Total skid cost within 0.15% of $8.2M budget
  - Process skid ship date within +1 day of target
  - Power skid ship date within +6 weeks of target

PCHE model cost vs quote

Predicted Cost (k$)

Quote Cost (k$)

ECHOGEN
power systems
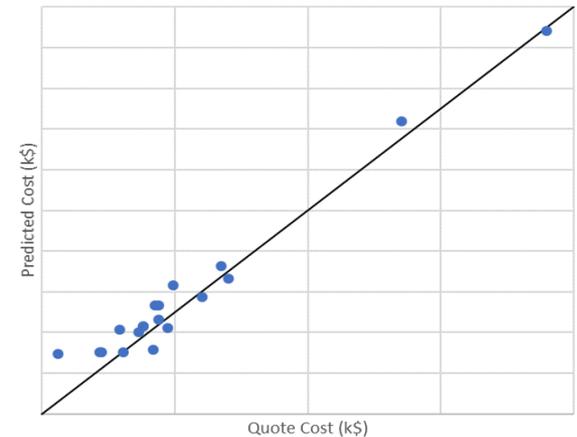
EES Team has Done it Before

From concept...
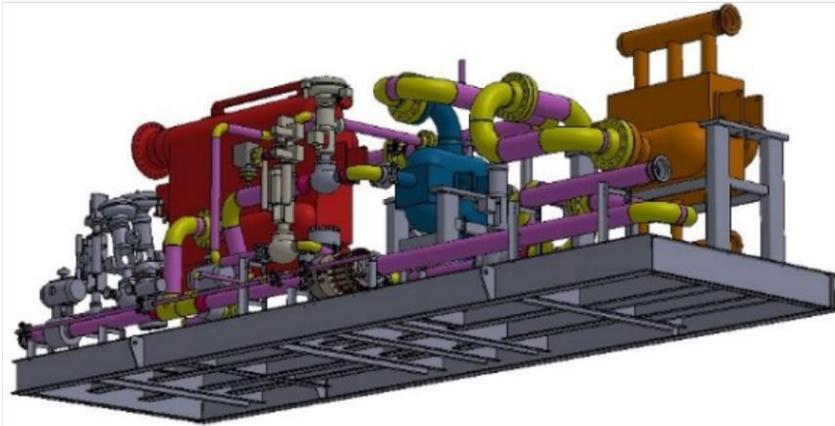
… to reality, on time, on budget

ECHOGEN
power systems

Summary For Those Who Called in Late

- Long duration (>4-6 hours) energy storage is becoming increasingly important
- Echogen is introducing an "Electro Thermal Energy Storage" (ETES) system based on its ground-breaking development of commercial supercritical CO_2 power cycles
    - ETES stores electrical energy as thermal energy, and recovers back to electrical energy
    - Materials are low-cost, safe, and environmentally-benign
    - ETES does not require lakes on mountains or giant holes in the ground to install
    - Economics for long-duration storage at utility scale (10+ MWe) are excellent
- Echogen is looking for partners for a commercial-scale demonstration plant

ECHOGEN
power systems

Contact: Tim Held, Ph.D. (CTO) theld@echogen.com