Thermochemical Storage with Anhydrous Ammonia

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Value Proposition and Problem Statement

• Ammonia-based thermochemical energy storage is a well-developed technology that has the potential to meet the CSP:ELEMENTS performance and cost goals.
  • Target performance: Heat steam to 650°C for supercritical steam power block.
  • Plant context: 220 MW_t plant with 6 hours of storage.
  • Target cost: $15/kWh_t.
• At start of project, two key challenges identified:
  • Ammonia synthesis had never been used to heat steam to 650°C. Is it possible?
  • Can physical storage of high pressure nitrogen/hydrogen mixture be done cost-effectively?
System Overview

Heliostat Field

Ammonia Dissociation (Endothermic Reactor/Receiver)

Ammonia Synthesis (Exothermic Reactor)

Heat Exchangers

Power Generation (Steam Cycle)

Liquid NH₃

Ambient Temperature Storage

N₂/H₂ gas

NH₃ + 66.6 kJ/mol ⇌ \( \frac{1}{2} \) N₂ + \( \frac{3}{2} \) H₂
Objectives

• **Phase 1 Main Objectives:**
  - Demonstrate heating supercritical steam to 650°C.
  - Perform techno-economic evaluation to show cost-effective gas storage.
  - Perform initial design of endothermic reactor/receiver to demonstrate feasibility. (Won’t be discussed in this talk.)

• **Phase 2 Main Objective:** Predict performance and cost of utility-scale synthesis system for ammonia-based thermochemical energy storage.
Selected Milestones and Results

- Gas storage
- Steam heating
  - Experimental
  - Modeling
- Optimizing the synthesis reactor system for low cost
Gas Storage
Gas Storage Milestone

- Need to store ambient temperature, high pressure N$_2$+3H$_2$.
- 220 MW$_t$ plant, 6 hrs storage, needs ~24,000 m$^3$ at 20 MPa.
  - Comparable to two-tank molten salt.
- Underground storage concept:
  - Surrounding geology provides bulk of pressure containment.
  - Underground gas storage already widely used.
- Approaches considered:
  - depleted oil or gas wells
  - aquifers
  - salt caverns
  - rock caverns
  - tunnel drilling
  - shaft drilling
Salt Caverns

• Solution mining of salt caverns is simple, established process:
  • Fresh water pumped into salt dome or bed. Brine extracted.

• Salt caverns widely used for storage:
  • Over 2000 salt caverns in North America alone for hydrocarbon storage.
  • Pure hydrogen or hydrogen-rich gas mixtures have been stored.

• Salt cavern conditions are suitable for our application:
  • Volumes up to 500,000 m³
  • Pressures up to ~50 MPa
  • Rock salt chemically inert to hydrogen
  • Permeability low enough to contain hydrogen gas

• Roughly $1/kWh_t to create storage space (for large projects).
Salt Caverns, cont.

- Suitable salt deposits are present on every continent, good coincidence with high DNI areas.
- Despite this, siting CSP plants for suitable salt deposits is a significant constraint.
Large Diameter Drilled Shafts

• Removes site choice constraint.
• Shaft drilling routinely carried out at up to 7.5 m diameter and depths of 1000 m.
• In consultation with drilling company:
  • Cost roughly $5/kWh_t.
• Conceptual design developed.
• Details of hydrogen impermeable lining and endcaps required.
Steam Heating
Steam Heating Milestone, Modeling

Model shows supercritical steam can be heated from 350 to 650 °C.

\[ m_g = 0.3 \, \text{g/s} \quad P_g = 30 \, \text{MPa} \]
\[ m_s = 0.33 \, \text{g/s} \quad P_s = 26 \, \text{MPa} \]
\[ D_o = 2 \, \text{cm} \]
\[ D_i = 0.5 \, \text{cm} \]
Steam Heating Milestone, Experimental

- Experiments show steam heated from 305°C to 650°C at ~100 W scale.
- Work ongoing toward heating steam at 5 kW scale.
Cost Optimization
Optimized Cost Milestone

- Consider entire synthesis system:
  - Synthesis reactor
  - Recuperating heat exchanger
  - Additional preconditioning subsystems
- Modular system with different reactor designs for different temperature regions.
- Multi-parameter optimization problem with tens of parameters.
- Largest cost is wall material, including high nickel alloy in high temperature regions.
- Minimize wall material volume per unit power.
Optimizing Inner and Outer Diameters

- Optimization is driving to smaller scale.
- Not a surprising result.
- How low can we go?
  - Pressure drop will increase – and pumping power.
  - Manufacturing costs must be considered.
Path-to-Market
Path to Market

1. Identification of partners – current to next 12 months
   - Continuation of experiments, modeling, and design to support solar-driven closed-loop experiment.

   - On sun, using existing tower-based test facility or single dish.
   - Steam production but no power generation.
   - Budget around $4 million.

3. Pilot 1 MWₑ system – 2018-2021, followed by continuous operation
   - Gas storage fabricated above ground using pressure pipe.
   - Heat recovery synthesis reactor designed for 650°C supercritical steam, but throttled to lower pressure for small off-the-shelf subcritical steam turbine.
   - Generate revenue sufficient to cover operating costs, operate for extended years as needed.
   - Budget around $15 million.
Path to Market

4. **First utility scale demonstration, 10 MWₑ – 2019-2024, followed by continuous operation**
   - First trial of *underground storage* using shaft drilling technology.
   - Still using small off-the-shelf subcritical steam turbine.
   - Significant financial assistance package required to build the first system, but operation and balance of financial package on fully commercial basis.
   - Budget around $100 million.

5. **First full-sized system, 100 MWₑ, 10+ hrs storage – 2022-2027, followed by continuous operation**
   - Underground storage either salt cavern or shaft drilled.
   - *Synthesis reactor produces supercritical steam at 650°C, potentially for a supercritical steam turbine.*
   - Preferential finance terms probably required, otherwise a fully commercial system.
   - Budget around $700 million.
Conclusions

- Gas storage in salt caverns or drilled shafts appears feasible within the $15/kWh_t$ budget.
- Ammonia synthesis can be used to heat supercritical steam to 650°C, according to experiments and modeling.
- Cost minimization of the synthesis reactor system is underway:
  - Small diameter tubes are desirable.
  - Multi-parameter optimization of modular design has potential to significantly decrease cost.
- A proposed path-to-market could achieve a full-scale system by 2027.
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QUESTIONS?