Sulfur Thermal Energy Storage for Industrial Decarbonization

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The Problem

1900 Terawatt-hours of industrial process heat are consumed every year below 300 Celsius.

90% of industrial process heat is from fossil fuels.

Cumulative energy used for process heat in US Manufacturing industries

Chemical processing, plastics, mineral mining, etc.

Dairy and food processing, ethyl alcohol, breweries, etc.

6,500 TBtu/yr

(Adapted from McMillan et al., 2023, NREL/TP-7A40-83020)
The Opportunity

For the first time, heat from renewables can be cheaper than fossil fuels.

1. Lazard's Levelized Cost of Energy and Levelized Cost of Storage 2019
2. Adapted from EIA California Natural Gas Industrial Price: https://www.eia.gov/dnav/ng/hist/n3035ca3m.htm
3. Adapted from EIA U.S. natural gas consumption by sector

- **01** Renewable Levelized Cost of Energy (LCOE)
  - $0.03 per kilowatt-hour

- **02** California NG Industrial Price
  - $0.04 per kilowatt-hour

- **03** Annual Industrial Natural Gas in US:
  - $36 Billion
Process heat demand is constant. Renewable energy is not.

Thermal energy storage (TES) is necessary to match energy supply with heat demand.

Breakthrough material repurpose dramatically reduces storage cost.

Our Innovation

Sulfur replaces 60%+ of the thermal energy storage (TES) cost with an ultra low-cost fluid.

*In the comparison chart, bottoming temperature for molten salts and sulfur are set to be 20 °C above their freezing point.
Technological Breakthrough

**Sulfur Thermal Energy Storage (TES) Design**

- Single tank design that involves HTF tubes located within molten sulfur bath.
- Natural convection currents enable efficient storage and retrieval of heat from sulfur thermal storage.
- Sulfur has low freezing point (~105 °C) compared to SOA solar salt (~220 °C) that ensures low parasitic load and low O&M cost.
The First Prototype

Market Readiness:

- Sulfur heat storage pilot: 350 kilowatt-hours & 300 °C.
- Over 85% thermal efficiency, 3rd party verified by Exponent.
- Three US patents awarded.
Ongoing Renewable Energy Pilot Projects

To demonstrate with solar thermal and electricity

- $3m California Energy Commission
- Demonstrates charging from electricity
- Generate pressurized hot water for industrial process heat

- $1.4m Department of Energy
- Prepare for integration with solar thermal
- Will demonstrate 24-hour renewable process heat

Solar PV + storage < fossil fuels

Solar thermal + storage < fossil fuels
Client Projects

- Started $500k Engineering for $6M+ Pilot project
  - Design, install, and test a pilot sulfur TES integrated
  - Integrate with Miraah Solar Field (300 MW-thermal)
  - Verify system performance at 50 tons per day of steam
- Full-scale system over 500 MWh

**Searles Valley Minerals**

- Preparing a 1.5+MWh sulfur TES pilot project integrated with renewable electricity
- Client requires 700 MWh TES to meet their process heat requirement
HPC4EI Project: High-Fidelity and High-Performance Computational Simulations for Rapid Design Optimization of Sulfur TES

NREL PI: Zhiwen Ma and Michael Martin

CHALLENGE

- Prototypes are expensive and optimizing the product design through simulations will minimize design iterations.
- Complex multiscale physics and non-linear properties.

APPROACH

- Apply NREL center experience in complex fluids (sCO2, cryogenic helium) to model heat transfer in the system.
- High-fidelity computational tools to simulate, and machine learning (ML) tools to optimize designs.

IMPACT

- Accelerate development of this technology while building NREL expertise in thermal energy storage.
- Valuable experience for student interns who contributed to the field through journal publications and conference presentations.
Modeling Tool Development

CFD Model Development & Validation

- Robust modeling tool with short-run time to optimize sulfur TES design for different applications.
- Reduce product-to-market time.
- Critical for system design (ex. solar + sulfur TES) optimization based on annual technoeconomic simulations.

ROM Verification

Machine learning for reduced order model (ROM)

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Oliver et al., ASME J. Energy Resour. Technol., 2023

Menear et al., AAAI 2022 Fall Symposium
Renewable industrial electrification

- Run in-house economic model for entire year
- Determines when heat would come directly from the solar PV field, from the solar energy stored in Element 16’s system, or from fossil fuels
- Optimize for solar multiple (capacity of solar PV field vs. heat load/demand)
- Key result: Levelized Cost of Heat (LCOH), or how much the heat costs amortized over project lifetime
- LCOH allows renewable energy projects to be directly compared with fossil fuel boilers

- Solar multiple of 3 and sulfur TES storage capacity of 14-to-16-hour duration provides the least LCOH.
- \( \text{CO}_2 \) emission reduction of 2 million metric tons for the 150 MMBTU/h heat demand over 30-year system lifetime.
Thank You

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Startup Program and Financial Backers:

[Logos of various entities]