Technologies for Deep Decarbonization Using High Temperature Liquid Metal

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Energy storage is the key to decarbonizing electricity and transportation.


Five thermal energy grand challenges for decarbonization

Roughly 90% of the world’s energy use today involves generation or manipulation of heat over a wide range of temperatures. Here, we note five key applications of research in thermal energy that could help make significant progress towards mitigating climate change at the necessary scale and urgency.

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Thermal storage systems

As solar and wind electricity generation has increased, its intermittency has hastened the need for heat storage over a wide range of time scales, from seconds to days, and even seasonal storage. Current technologies, such as pumped hydroelectricity, are geographically limited and lithium-ion batteries (~US$100–1000/kWh, capital cost) are too expensive for the multi-day storage targets (~US$3–30/kWh) needed to fully decarbonize the grid. Solving this problem could enable full decarbonization of the grid, thereby reducing global GHG emissions by ~25%. Thus, the storage problem is one of the most impactful problems to be solved.

Several new thermal energy storage (TES) concepts have been proposed. While it is relatively easy to convert electricity to heat for batteries, non-storage, since the specific heat of virtually all materials is the same on a molar basis, at high temperatures, TES can make use of extremely abundant and low-cost materials that are of importance to the environmental cost. Although several embodiments of TES have been put forth, they are still early stage and have not yet reached commercial deployment. Thus, there is a need to continue developing more complete embodiments that exploit other thermal storage materials and mechanisms. In particular, it is of utmost importance to develop full-system concepts that carefully consider all of the practical issues (for example, materials degradation and compatibility over time, safety, system integration, and so on) that might arise or prevent commercial deployment. For example, systems that utilize a liquid as its energy carrier, by ensuring time-shifted matching of internal thermal demand with the diurnal temperature swings of the external natural environment. Second, TES has the ability to use heat to generate electricity by storing it in the form most conducive to its final usage — namely as thermal energy for space heating/cooling, instead of electricity. Our fundamental challenge in TES adoption is that there is limited tunability in the usage temperature. For example, if the required temperature is 25°C and the ambient temperature swings above and below 25°C, two different TES materials and systems are needed, which dramatically reduces the utilisation of each system, leading to a higher cost. Since the levelized cost of storage (LCOE) is inversely proportional to its utilisation.
The Storage Problem

What is Thermal Energy Grid Storage (TEGS)?

Electricity $\rightarrow$ Heat (storage) $\rightarrow$ Electricity

Electricity in
Electricity out
Like a battery

System with thermal storage and conversion
A Thermodynamic Crime!

Electricity $\rightarrow$ Heat (storage) $\rightarrow$ Electricity

Why would anyone ever do this?
Storing heat can be 10-100X cheaper than storing electricity!

System with thermal storage and conversion

Can be 100% efficient going from lower to higher entropy

Can never be 100% efficient going from higher to lower entropy
Low concentration of active species
Large energy per active atom
Special, pure, organized materials
Impurities and byproducts are bad

100% concentration of active species
Low energy per active atom
Disordered, simple scrap material
Impurity tolerant

Why is it so cheap? – Atomistic Insight

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Large energy per active atom
Special, pure, organized materials
Impurities and byproducts are bad

100% concentration of active species
Low energy per active atom
Disordered, simple scrap material
Impurity tolerant

250-695 kWh/m$^3$ $\$150-400$/kWh

300-600 kWh/m$^3$ $\$4-77$/kWh
Liquid silicon storage
Cp = 950 J kg\(^{-1}\) K\(^{-1}\)
Cost = $1.5/kg
\(\Delta T = 500^\circ\text{C}\)
Cost/Energy = $1.5/kg ÷ (Cp*\(\Delta T\)) = $11.4/kWh-\(t\)
At 50% efficiency
Cost/Energy = $11.4/kWh ÷ 0.5 = $22.8/kWh-\(e\)

Liquid iron storage
Cp = 444 J kg\(^{-1}\) K\(^{-1}\)
Cost = $0.11/kg
\(\Delta T = 500^\circ\text{C}\)
Cost/Energy = $0.11/kg ÷ (Cp*\(\Delta T\)) = $1.8/kWh-\(t\)
At 50% efficiency
Cost/Energy = $1.8/kWh ÷ 0.5 = $3.6/kWh-\(e\)
Volume to surface area ratio
\[ \tau = \frac{m \cdot C_p \cdot R}{\rho \cdot V \cdot C_p \cdot L / kA} \]
For tanks of order 10 m
\[ \tau \] on the order of months
Lose \( \leq 1\% \) of energy stored per day
What Materials? - Atomistic Insight

What about corrosion? The hotter the faster/worse!

Si melts at 1414°C
Fe melts at 1538°C

Molten metal dissolves metal
Like
Sugar water dissolves sugar

Key New Idea = Liquid Metal + Ceramics
“Sun in a Box” TEGS-MPV

Electricity → Heat → Electricity

Water Cooled MPV with Integrated Mirror

Electricity From Any Source Powers Heaters

Multi-Junction Photovoltaic (MPV) Power Block

MPV Module Unit Cell

MPV Can Be Retracted

Dry Cooling Unit
How Are You Going To Pump It?

Pumping at 1350°C

Why Use MPV Instead of a Turbine?

- **Turbine**
  - Doesn’t currently exist
  - **Large barrier to new turbine deployment**
  - $>100M$ of R&D
  - New materials + New HXs
  - Min-Hour response time to full load

- **MPV**
  - **Much lower barrier to deployment**
  - **Lower cost** $<0.5/W-e$
  - Similar efficiency (50-55%)
  - Fast response time (seconds)
  - Fundamentally new cost/learning curve
  - Lower maintenance
Why Multi-Junction Photovoltaics?

A - Modeled efficiencies of 1- and 2-junction cells as a function of junction bandgap (the bottom junction is used, for the 2-junction cells), for several different emitter temperatures.

B - Optimal top-junction bandgap for the 2-junction cells as a function of the bottom junction band gap.

Efficiency = \frac{\text{Power}_{\text{out}}}{\text{Q}_{\text{total}}} = \frac{123}{(123 + 89.4 + 18.7 + 4.6)} = 52\% \\

- <1% loss in electronics for heater \\
- ~1%/day loss in heat leakage \\
- <1% loss in parasitic load \\
- ~ 50% roundtrip efficiency (RTE)

C. Amy et al., Energy & Environmental Science, 12, 334 (2019)
System Cost

Cost = CPE*Time + CPP

Cost per unit energy = CPE

Cost per unit power = CPP

CPE ($/kWh-e)

CPP ($/W-e)

Medium
Graphite Insulation
Transfer Fluid
Construction
Alumina Insulation
Fiberglass Insulation
Tank Base
Cooling for Base
Inert Containment

MPV Cells
Inverter
Graphite Insulation
Heater
Tungsten Foil
Cooling
Pumps and Piping
Construction
What’s Next?

• ARPA-E Project
• Build a prototype
• Pumping
• 2500°C Heaters
• Emitter evaporation/deposition
• Cell redesign/optimization + fabrication
• High current density
• High reflectivity (> 98%)
• High efficiency (≥ 50%)
• Long term testing
HYDROGEN PRODUCTION FROM METHANE

All Gases

CH₄ + H₂O → CO + 3H₂

CO + H₂O → CO₂ + H₂

Steam Methane Reforming (SMR) + Water-Gas Shift (WGS)

Gas + Solid Products

CH₄ → C + 2H₂

Direct Thermal Pyrolysis

CH₄ → C + H₂

The plugging problem
THE REACTOR CONCEPT

- Lower cost H$_2$ $0.5-1.50$/kg
- No CO$_2$ emissions

CH$_4$ + H$_2$ → C(s) + CB

- Produces carbon black
- No corrosion – No plugging!

- We now know how to make it
- We know how to pump Sn(l)

Protrusions create eddies to prevent CB contact

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• No CO$_2$ emissions
• Produces carbon black
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THE COMPELLING ECONOMICS

- **Graph 1:**
  - **Title:** Current range of CB prices
  - **X-axis:** Carbon Black Price ($/ton)
  - **Y-axis:** H₂ Cost ($/kg)
  - **Graph Lines:**
    - Red: Pyrolysis
    - Blue: DOE Target
    - Black: SMR+WGS

- **Graph 2:**
  - **Y-axis:** Percentage (%)
  - **Graph Sections:**
    - Methane
    - Electricity
    - O&M
    - CAPEX (Other)
    - CAPEX (Tin)

**Notes:**
- Current range of CB prices
- Comparative costs of different processes and components.
Wetzel's Group at KIT in Germany


Prior Work – Laying the Foundation

For $T \leq 500 ^\circ C$
- Union Joints
- Elbows
- Pumps
- Valves

For $T > 500 ^\circ C$
- Union Joints
- Elbows
- Pumps
- Valves

> 2000 ^\circ C$ Heaters
- Ar plasma arcing through insulation
Detailed reactor modeling:

- Predict profiles of temperature, species concentration and bubble size density in reactor
- PDAEs in time, vertical position & bubble size coordinate
- Software: Jacobian (equation-based modeling system) & DAEPACK (numerical engine)
- Incorporate detailed reaction kinetics models for methane pyrolysis via, e.g., CHEMKIN
- Optimization-based experimental design with reactor model for model discrimination and parameter estimation
- Cycle of design, experiments, validation
Task 2: Centrifuge Development

Stationary Reservoir
Spinning Reservoir
Gap for tin extraction
Bearings
Actuators

Platform 1
Platform 2
Before Pumping

While Pumping

\[ P_2 - P_1 = \rho gh \]
Liquid Droplet Heat Exchanger Model

Full System Model for Performance

Yu Qiao (UCSD) Construction Material

Flexural strength (MPa)

Carbon Black (CB)

Hydrogen

Technoeconomics
PROGRESS TO DATE

SiC vs. Graphite Reactor?

- Zirconia-based insulation
- Alumina-based insulation
- Silica-based insulation
- Stainless steel strut channel
- CFC support for column

Mock reactor (water)

Agilent 990 Micro GC
Top 5 Problems in Thermal Science & Engineering

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[Image of a pie chart showing global primary energy usage in 2016 – IEA Energy Outlook]

High Energy Density Thermal Storage


EV’s use 35-40% of the battery capacity for space conditioning.
Global CO2 emissions ~ 37 GtCO$_2$-eq → HFCs could become 10-25% of the problem!

Decarbonizing the Industrial Sector

Future Opportunities
1. Increase thermal efficiency of current processes
2. Zonal heating (e.g., electrical induction)
3. New redox processes
   - Electrochemically
   - Chemically (e.g., H₂)
   - Thermally

Electricity: 25%  Transportation: 14%  **Industry: 15%** → Cement: 5%  Steel: 4%  Aluminum: 1%  Hydrogen: 1%
Zonal Heating and Cooling

Space heating and cooling ~ 13% of US energy usage

T. Hoyt et al., Building and Environment, doi:10.1016/j.buildenv.2014.09.010
Long Distance Transmission of Heat

building energy goes to heating at < 60°C
~ 60% for residential
~ 32% for commercial

Can we use this?
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QUESTIONS?