High Temperature
Solar Thermochemical Energy Storage

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Solar Thermal History at ANU

- Solar thermal at ANU since 1970/71
- White Cliffs power station, first solar power plant in Australia, 1984
- ANU SG3 Dish, largest solar dish concentrator in the world, 1994
- Ammonia thermochemical energy storage, 1998
- ANU SG4 Big Dish, largest solar dish concentrator in the world, 2009
- Solar chemistry and basic research expansion, 2013
- Craig Building, ANU high-flux solar simulator, materials labs, 2015
Solar Thermal Research at ANU

- Solar fuels
- Solar materials
- Solar power
- Solar concentrators
- Thermal storage
- Solar heating and cooling

Fundamentals:
- Thermal science
- Physics & optics
- Chemistry & materials
- Control & dynamics
- System integration
Solar Reserve’s Crescent Dunes

- 110MW_e, 10 hours storage
- 670MW_th receiver 20.4m x 17.7m diameter
- 200m high tower
- ~ 3,000m diameter heliostat field
RND005 ARENA Project: High temperature solar thermal energy storage via manganese-oxide based redox cycling

Overall project goals

• Demonstrate the potential of CSP with integrated thermochemical energy storage
  → High temperatures >1000°C → combined gas/steam turbine power cycle → power block efficiencies up to 60%.
  → Need for high-temperature thermal energy storage

• ASTRI LCOE target: 0.12 AUD(2012)/kWh<sub>e</sub>
  US Sunshot targets: LCOE: 0.06 USD/kWh<sub>e</sub>, storage: 15 $/kWh<sub>th</sub>
Project Overview

Task 1: Active Material Development (CU, ANU)

Task 2: Solar Reactor Development (ANU)

Task 3: Optical Field Design (ANU)

Task 4: Techno-Economic Analyses (CU, ANU, IT Power)
Manganese oxide thermodynamics

\[ \text{MnO}_2 \leftrightarrow \text{Mn}_2\text{O}_3 \leftrightarrow \alpha\text{-Mn}_3\text{O}_4 \leftrightarrow \beta\text{-Mn}_3\text{O}_4 \leftrightarrow \text{MnO} \leftrightarrow \text{Slag} \]

**Reduction in N\(_2\)**

- Starting point: 2 mol MnO, 100 mol N\(_2\)
- Enthalpies of reaction:
  - \(\text{MnO}_2 / \text{Mn}_2\text{O}_3\):
    - Transition: 280-350 °C
    - \(\Delta h\): 481 kJ kg\(^{-1}\) [1]
  - \(\text{Mn}_2\text{O}_3/\alpha\text{-Mn}_3\text{O}_4\):
    - Transition: 700 °C
    - \(\Delta h\): 214 kJ kg\(^{-1}\)
  - \(\alpha\text{-Mn}_3\text{O}_4/\beta\text{-Mn}_3\text{O}_4\):
    - Transition: 1173 °C
    - \(\Delta h\): 80 kJ kg\(^{-1}\)
  - \(\beta\text{-Mn}_3\text{O}_4/\text{MnO}\):
    - Transition: 1450 °C
    - \(\Delta h\): 897 kJ kg\(^{-1}\)
  - Slagging:
    - Transition: 1625 °C
    - \(\Delta h\): 1580 kJ kg\(^{-1}\)

**Oxidation in air**

- Starting point: 2 mol MnO, 79 mol N\(_2\), 21 mol O\(_2\)
- Enthalpies of reaction:
  - \(\text{MnO}_2 (\text{tetragonal})\):
    - Transition: 280-350 °C
    - \(\Delta h\): 481 kJ kg\(^{-1}\) [1]
  - \(\text{Mn}_2\text{O}_3 (\text{cubic})\):
    - Transition: 467 °C
    - \(\Delta h\): 214 kJ kg\(^{-1}\)
  - \(\alpha\text{-Mn}_3\text{O}_4 (\text{tetragonal spinel})\):
    - Transition: 1173 °C
    - \(\Delta h\): 80 kJ kg\(^{-1}\)
  - \(\beta\text{-Mn}_3\text{O}_4 (\text{cubic spinel})\):
    - Transition: 1450 °C
    - \(\Delta h\): 897 kJ kg\(^{-1}\)

**Sensible heat:**
\(c_p \sim 1\) kJ/kg/K (800–1500°C)

Manganese oxide kinetics

\[ \text{Mn}_2\text{O}_3 \rightarrow \text{MnO} \text{ conversion in N}_2 \text{ carrier gas} \]

\[ \text{MnO} \rightarrow \text{Mn}_3\text{O}_4 \text{ conversion in N}_2 \text{ carrier gas with 0.25-1\% O}_2 \]

Enhancement of \( \text{Mn}_3\text{O}_4 \rightarrow \text{Mn}_2\text{O}_3 \) re-oxidation kinetics

- 44 \( \mu \)m particles
- Residence times: \( \sim 1-3 \) s

Particle fabrication

Büchi spray-dryer

SEM of synthesized particles

Synthesis route

Before calcining

After 8 hours of calcining at 1200°C
Table 4. Comparison of modelling parameters for default molten salt tower system and MnO$_x$ system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value in updated Molten Salt tower model</th>
<th>Change for MnO$_x$ system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heliostat mirror area</td>
<td>1,289,123 m$^2$</td>
<td>Unchanged</td>
</tr>
<tr>
<td>Tower height</td>
<td>203.3m</td>
<td>Unchanged</td>
</tr>
<tr>
<td>Power cycle output</td>
<td>100 MW$_e$ Steam</td>
<td>Similar or higher</td>
</tr>
<tr>
<td>Power cycle conversion efficiency</td>
<td>41.2%</td>
<td>Increases to 57%</td>
</tr>
<tr>
<td>Thermal Energy storage</td>
<td>10 Hours at full load</td>
<td>Unchanged</td>
</tr>
<tr>
<td>Costs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site improvements</td>
<td>$21.6m</td>
<td>Unchanged</td>
</tr>
<tr>
<td>Heliostat field</td>
<td>$238.2m</td>
<td>Unchanged</td>
</tr>
<tr>
<td>Power block</td>
<td>$76.3m</td>
<td>Lower tbc</td>
</tr>
<tr>
<td>Balance of plant</td>
<td>$45.4m</td>
<td>Lower tbc</td>
</tr>
<tr>
<td>Storage</td>
<td>$94.9m</td>
<td>Similar tbc</td>
</tr>
<tr>
<td>Tower</td>
<td>$28.7m</td>
<td>Unchanged</td>
</tr>
<tr>
<td>Receiver</td>
<td>$84.9m</td>
<td>This will increase due to added complexity. A system with secondary concentrators to boost concentration and maintain thermal efficiency is assumed.</td>
</tr>
<tr>
<td>Indirect costs @25%</td>
<td>$147.5m</td>
<td>Unchanged</td>
</tr>
<tr>
<td>Variable O&amp;M costs</td>
<td>$15/MWh</td>
<td>Unchanged</td>
</tr>
<tr>
<td>Annual generation at Longreach Qld</td>
<td>528.3 6GWh</td>
<td>Increases to 594 GWh</td>
</tr>
<tr>
<td>Real LCOE</td>
<td>$150/MWh</td>
<td>Approx. $130/MWh, tbc</td>
</tr>
</tbody>
</table>