Thermal Storage for Increasing Capacity Factor and Value of CST

ASTRI Symposium on The Future of Concentrating Solar Thermal Technology

Wes Stein | Wasim Saman

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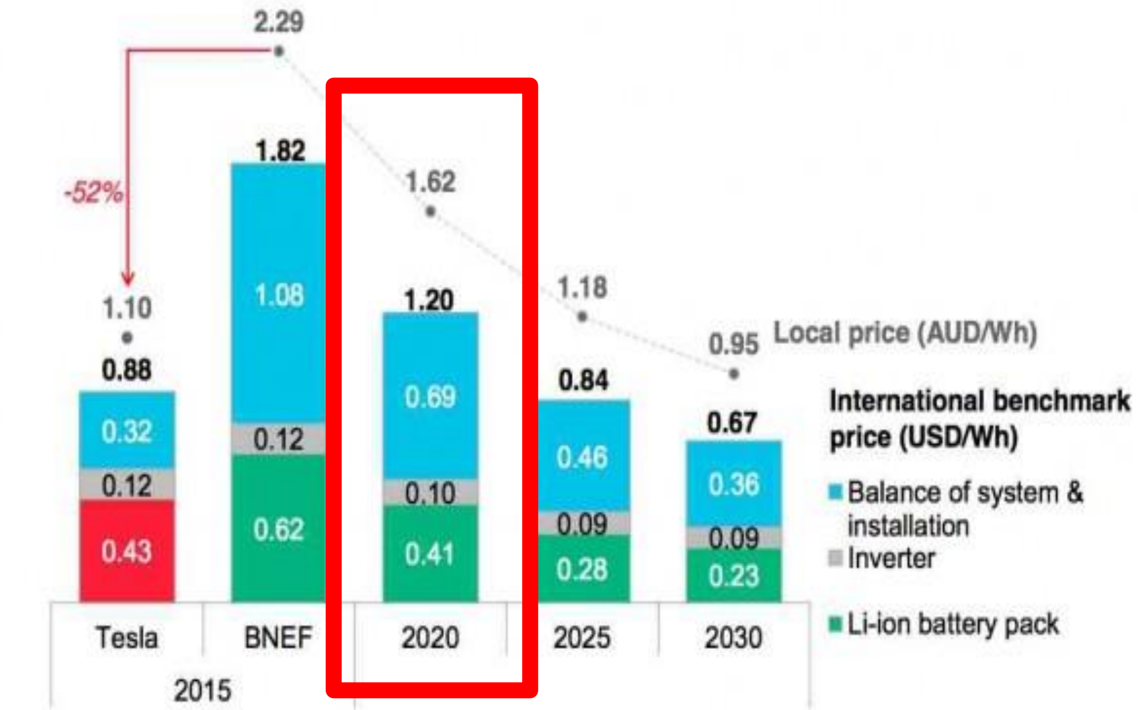
Cost Comparison: Electrical vs. Thermal Storage

Electrical Storage A$/Wh Electrical



Thermal Storage A$/kWh Thermal

Current 2 tank system	37
SunShot Program	15
ASTRI Program	20

Node Overview

Why Storage?

- ✓ Dispatchability
- ✓ High capacity factor
- ✓ Improved internal rate of return

Node Projects:

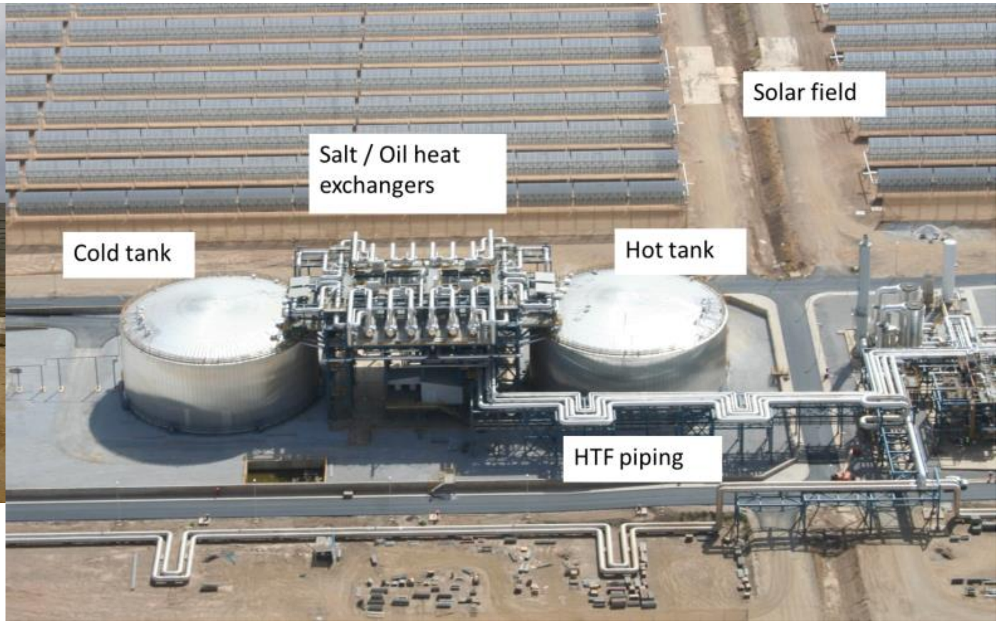
- P21: **High-temperature thermal storage**
- P22: **Low Cost, Reliable PCM Storage**

- ➢ Undertake targeted experimental evaluation of materials and heat transfer processes to support system-level storage concept development
- ➢ Develop a common-basis modelling platform to support annual performance and techno-economic analysis of a range of candidate storage technologies, together with alternative power-cycle options, including optimisation of design and operation strategy
- ➢ Design, analyse, build and test low cost storage systems using phase change materials at high temperatures

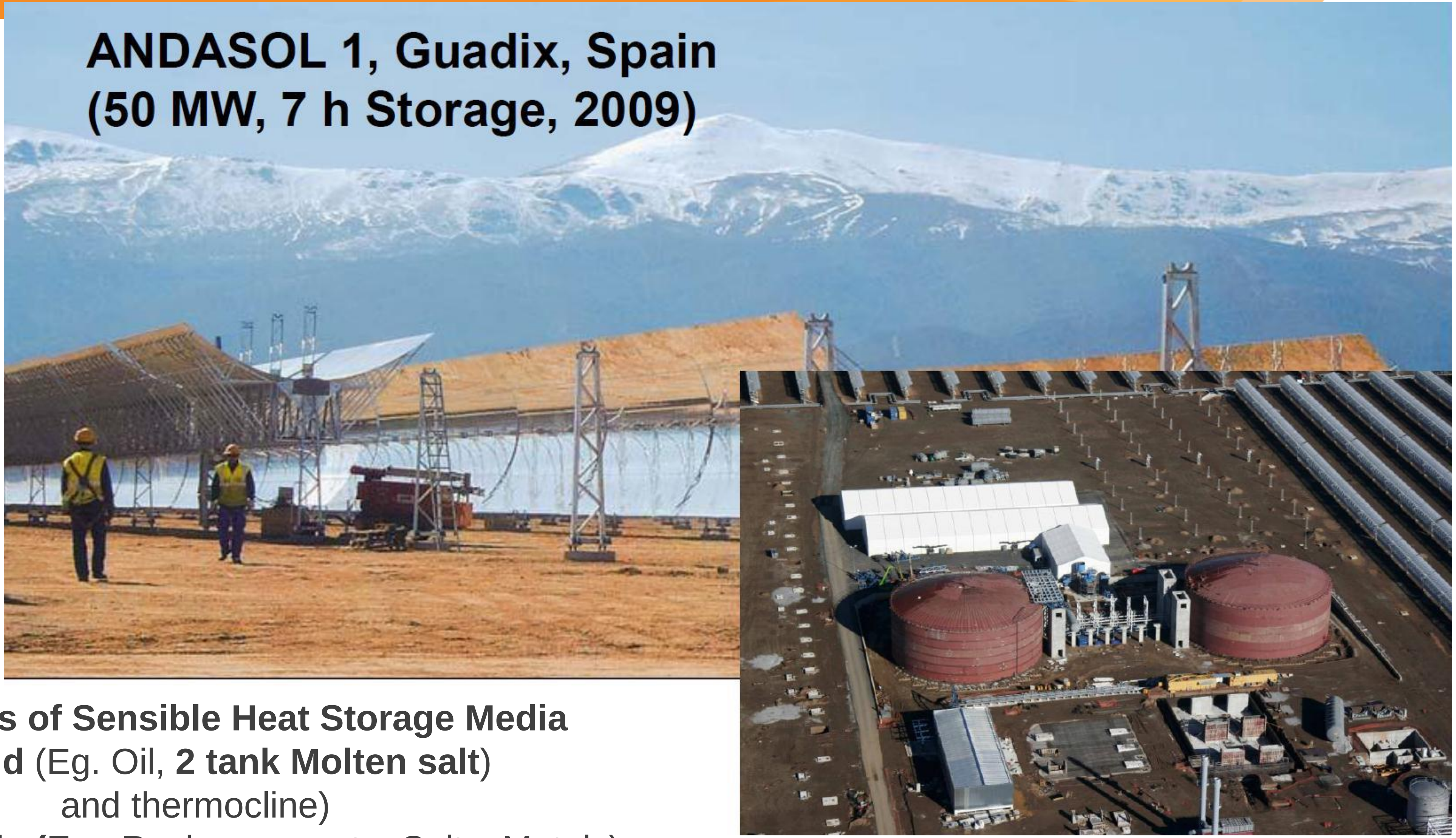
Classification

Three options based on the way energy stored in the material

1. **Sensible heat Energy storage:** Heat stored by raising the temperature of the storage medium at a single phase.
2. **Latent heat energy storage:** Utilising latent heat through solid-solid, liquid-gas, and solid-liquid phase transformations of the storage media.
3. **Thermochemical energy storage:** Energy can be stored during a thermochemical reaction (reversible Endothermic and exothermic reactions)



Current technology: Molten Salt sensible storage:

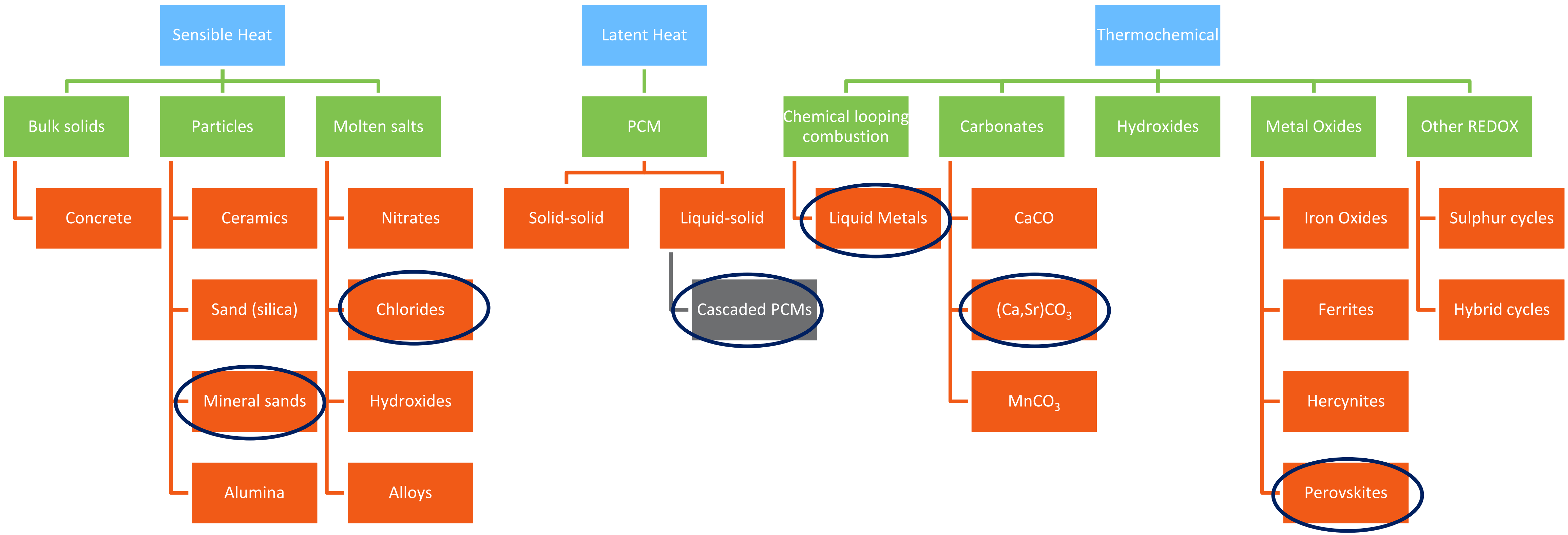


Types of Sensible Heat Storage Media

Liquid (Eg. Oil, **2 tank Molten salt**) and thermocline)

Solid **(**Eg. Rocks, concrete, Salts, Metals)

Thermal energy storage options & selected technologies

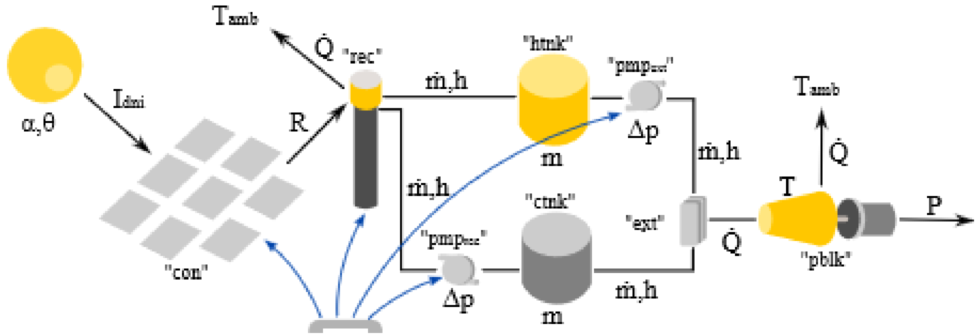


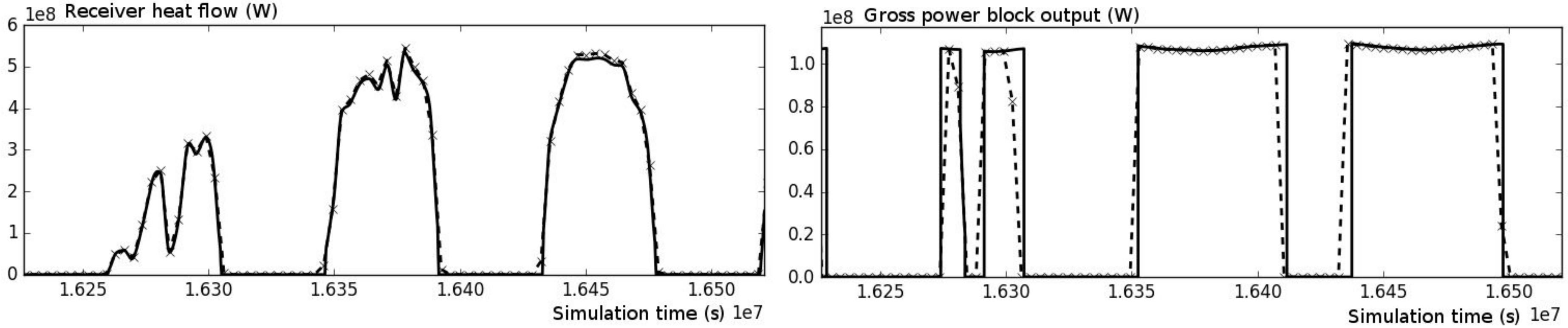
Project P21: High temperature energy storage

- Aim: to advance the state of the art in high-temperature energy storage for CST through development of several specific technology concepts, together with parallel activities in common-basis performance assessment and materials development.
- Scope:
  1. Modelling activity: develop an open source modelling tool to evaluate annual performance of novel CSP technologies at the overall plant scale in terms of both cost/value of electricity (**broader capability than existing models like SAM**)
  2. Storage concepts:
     A. Sensible particle storage for towers (**Australian material opportunity**)
     B. Sensible heat storage compatible with Na receivers (**new molten salt compositions**)
     C. Latent heat storage (**novel solid-solid PCM**)
     D. Thermochemical storage (**theoretical & applied materials discovery, novel chemical looping – patent pending**)

Modelling activity

- Implemented in Modelica: open source software
- Advances state-of-art by enabling novel storage technologies (PCM, TCS etc.) to be evaluated on a statistically valid basis
  - Annual performance and techno-economic analysis of a range of candidate storage technologies, together with novel collection and power-cycle options
- optimisation of design and operational strategies





Comparison of time series output for SolarTherm (lines) and SAM simulation (crosses).

Sensible particle storage

Aim: Develop low cost high capacity and temperature particle thermal storage solution that is scalable

Preliminary cost estimation - \$16/kWh$_{th}$ to \$20/kWh$_{th}$ (natural mineral sand)

Current concept addresses limitations of large scale vertical storage approach (e.g. Sandia concept) and allows scalable solutions with reduced cost (structural, foundation, safety)

De-risk overall technology scale up via adaptation of conventional technology while enabling early deployment

Leverages existing technology:

- Thermochemical (P21); Particle receivers (P12), Power block (P31/P32) and Solar fuels (P42)

Fig 1. Conceptual storage design of Sandia National Laboratories

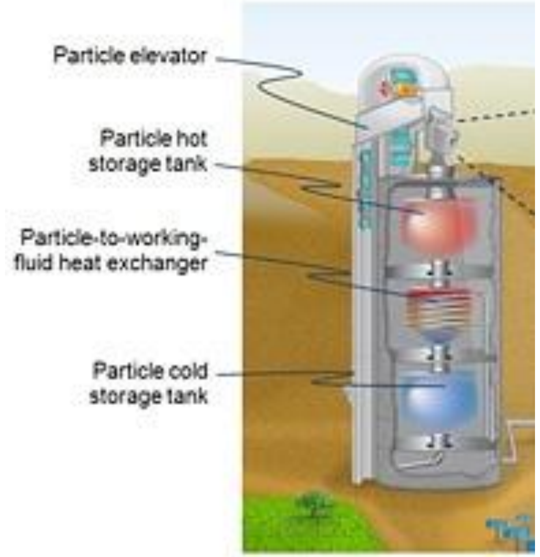
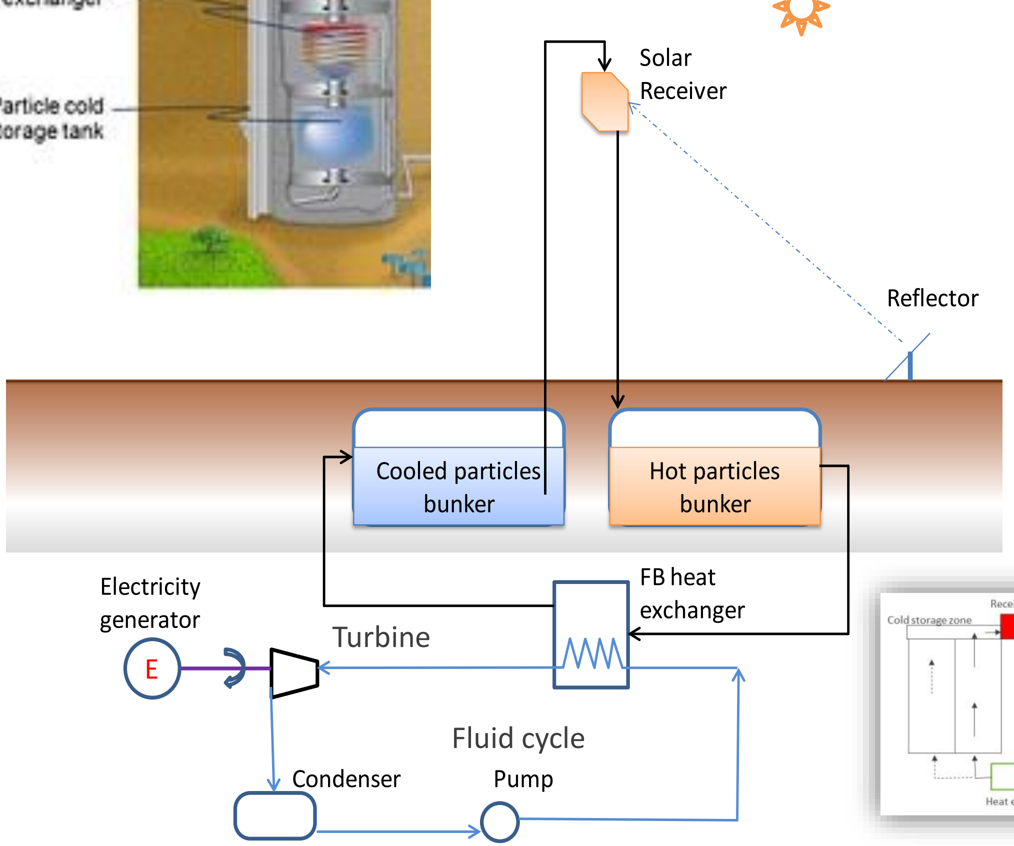
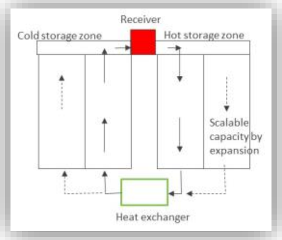


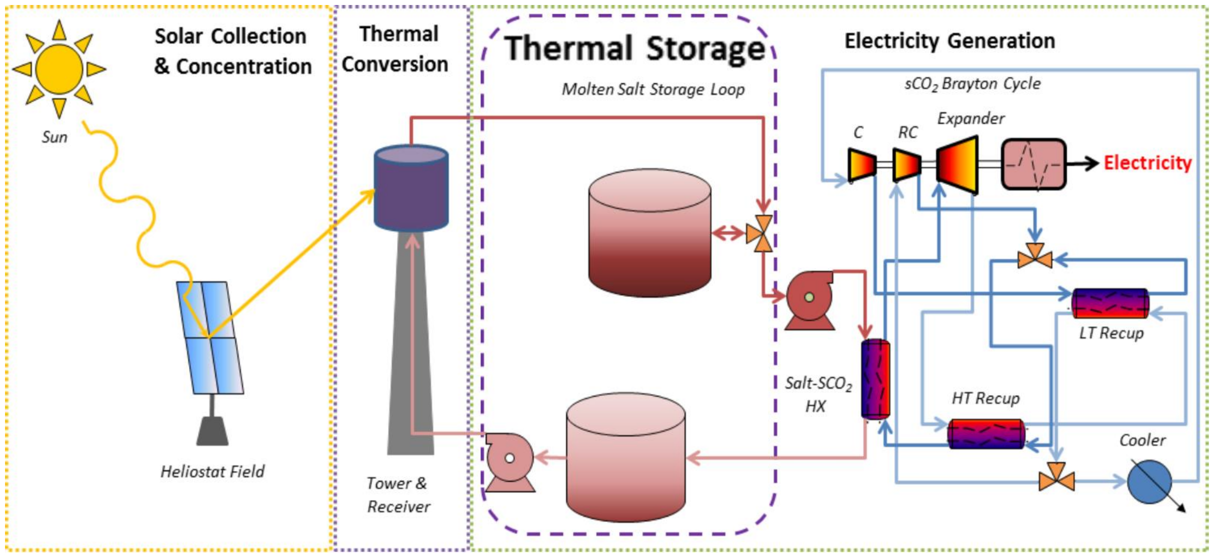
Figure 2. Conceptual cascading, compartmentalised particle storage design of ASTRI

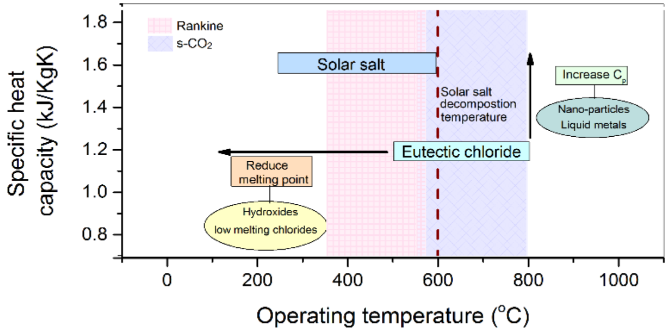


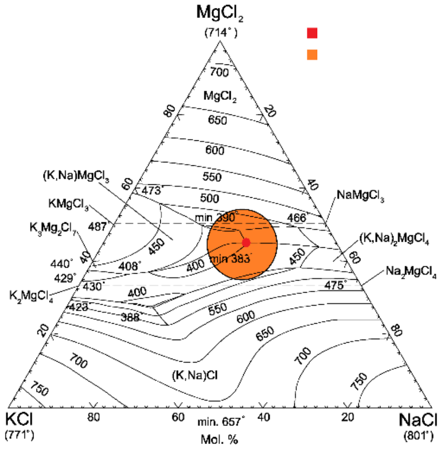


Sensible heat storage compatible with Na receivers

- Aim: identify new low cost salt compositions that are stable at temperatures > 600°C
- Evaluated (and discarded) completely novel direct contact $Na_{(l)}$ with immiscible salt
- Have identified unexplored chloride mixtures (off eutectic as phase change irrelevant)
- Builds on work of US laboratories e.g. Sandia, NREL

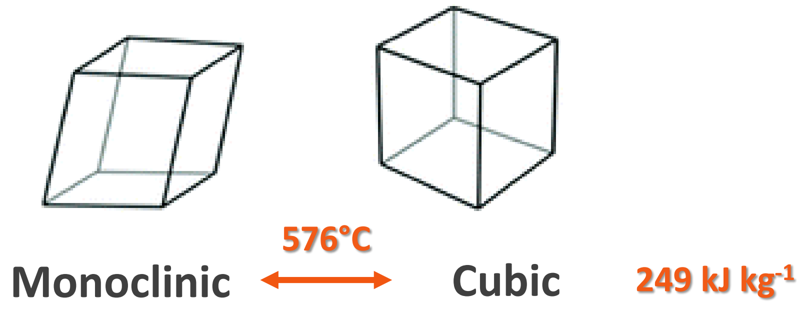


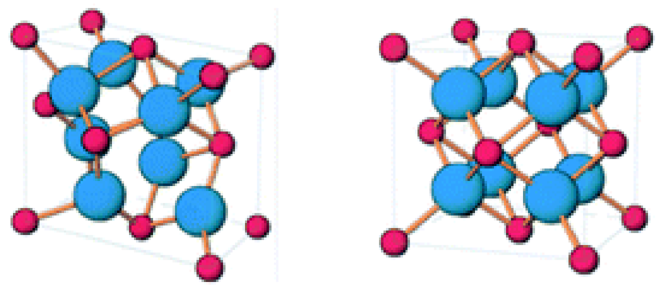


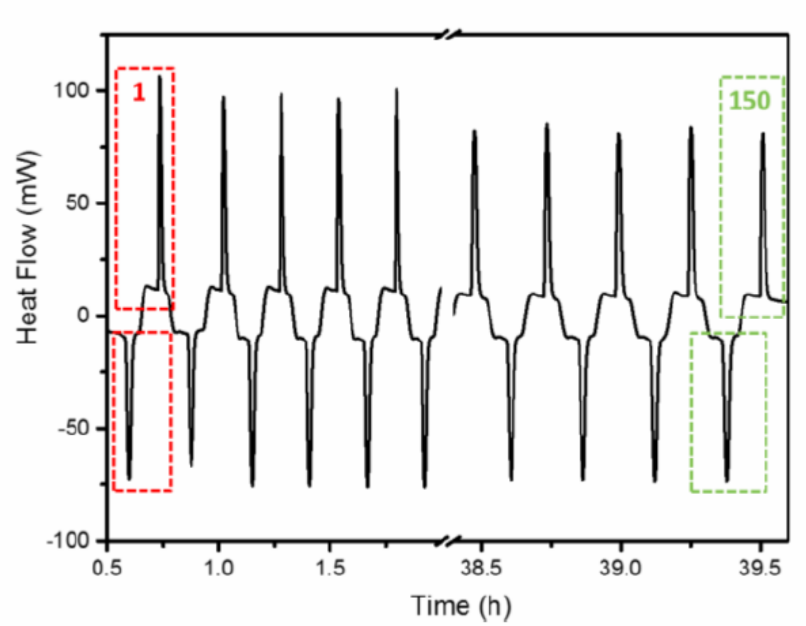


High capacity heat storage using solid-solid PCMs

- Aim: evaluate low cost storage option using Li_2SO_4
- Phase change at 574°C = both sensible and latent heat can be used
- High energy storage density – 2x to 4x that of molten salts
- Preliminary cost evaluation - $21/kWh$_{th}$



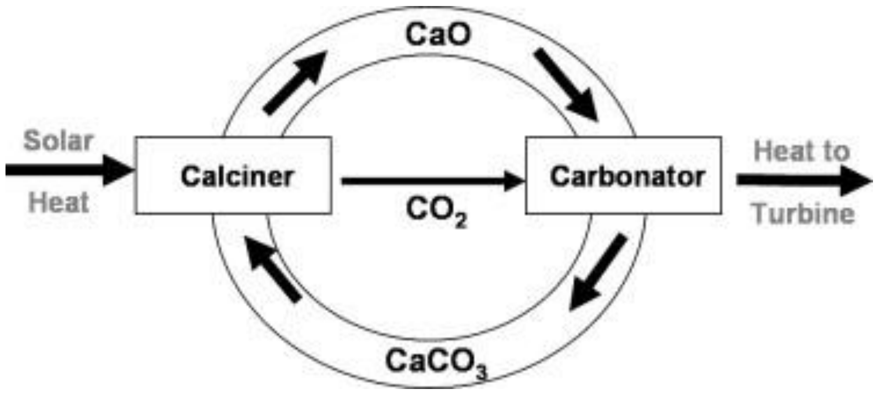




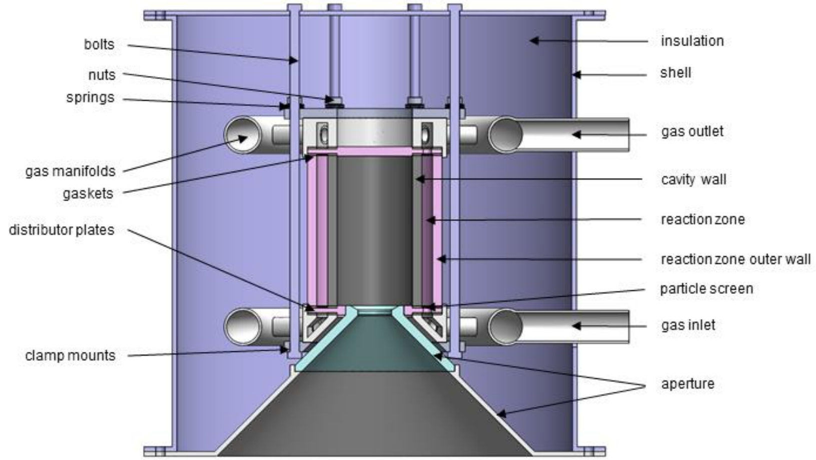
Cycling performance of Li_2SO_4-98.5 in N_2 between 500-655 °C over 150 cycles.

Thermochemical storage – carbonates

- Aim: develop system model for carbonates in high temperature cycles to enable optimisation of system, develop new materials to avoid known issues with sintering in pure $CaCO_3$ systems
- Will build a new reactor using solar simulator
- Collaboration with University of Minnesota



1780 kJ kg^{-1} $CaCO_3$



Novel Reactor Design.

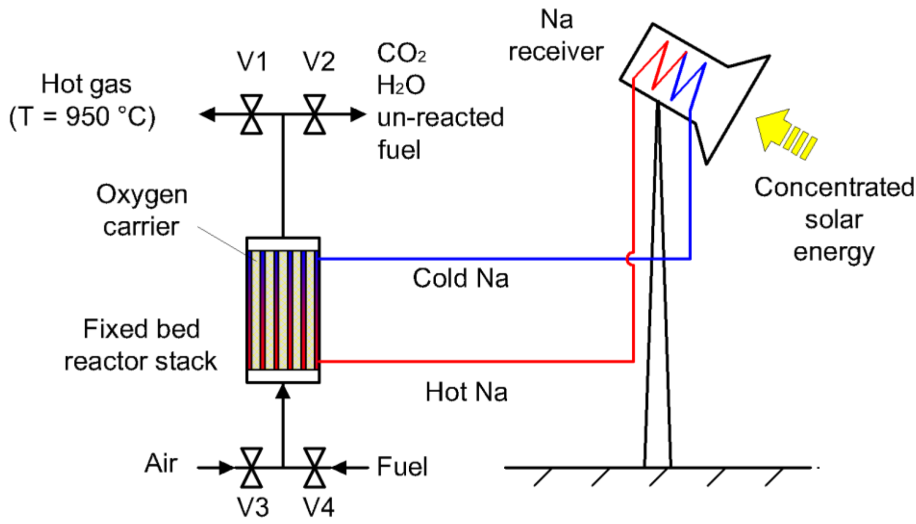
The completed 45kWe high-flux solar simulator at ANU.

Thermochemical storage – Chemical Looping

Aim: To achieve high temperature low cost energy storage of solar thermal energy with minimum exergy destruction.

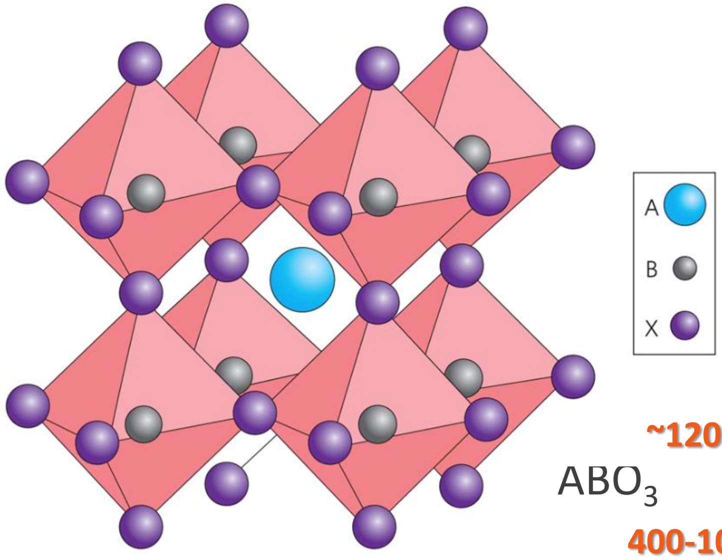
- **Hybrid Solar Chemical Looping Combustion (Hy-Sol-CLC)**
  - High solar share of up **to 60 %** with carbon capture (state-of-the-art is less than 20 %)
  - Release temperature of **~ 950 °C**, while the energy is stored at 750 °C
  - High energy density of up to **7.5 GJ/m³**

- **Liquid Chemical Looping Solar Thermal Energy Storage (LCL-TES) (patent-pending)**
  - Addressing the technical challenges associated with the solid storage medium
  - Combining the benefits of sensible, chemical and latent heat storage
  - High energy density of up to **12.5 GJ/m³**
  - High release temperatures of **> 1000 °C** (suitable for combined cycles)
  - potential collaboration with ETH Zurich



P21.2C Thermochemical storage – perovskites

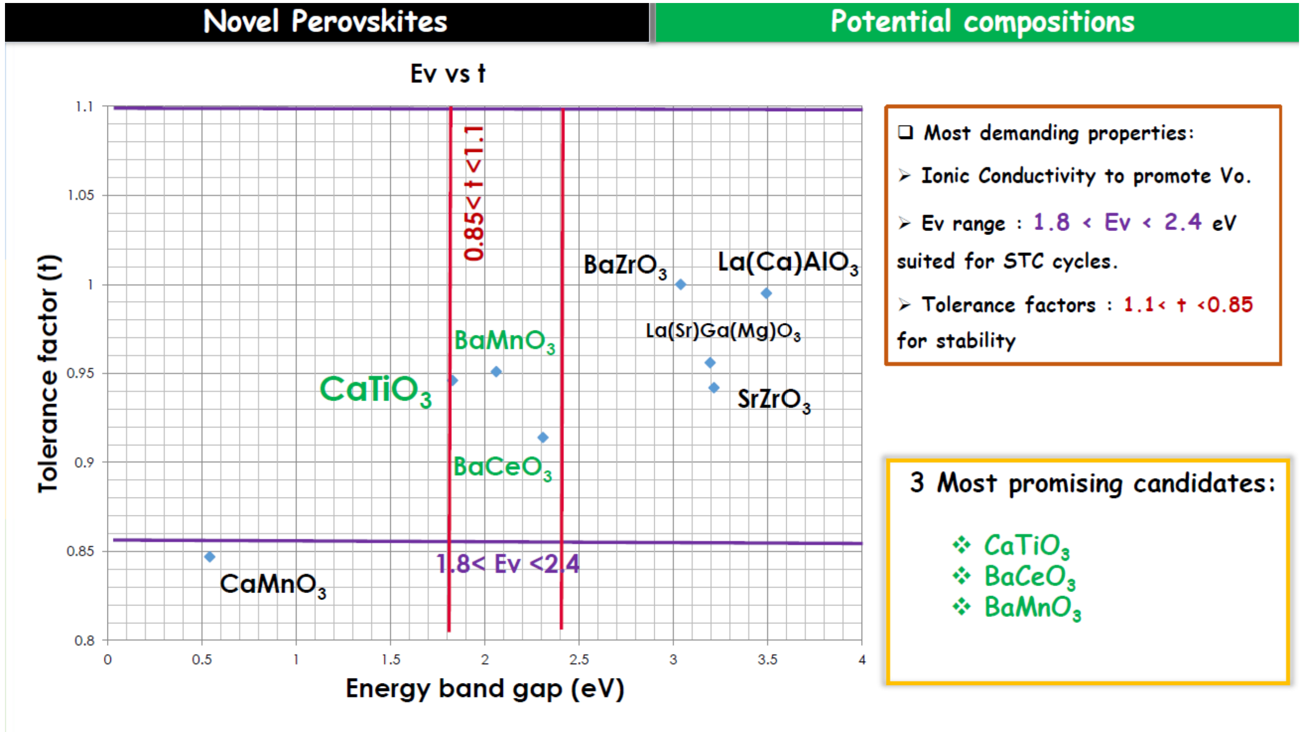
- Aim: materials discovery using ab initio modelling (DFT – molecular orbital theory)
- Perovskites are the new "wonder material" for many applications – PV, fuel cells, high temperature electrolysers, thermochemical energy storage (high temp dissociation)
- World leading capability at University of Newcastle + new PhD student
  - Seeking low cost, high reactivity – through simulation of key thermodynamic properties



~1200 °C

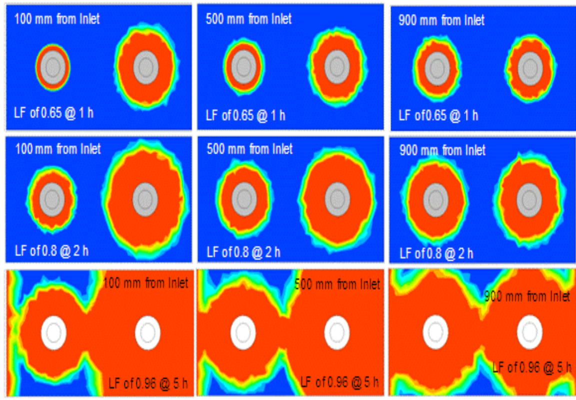
$$ABO_3 \longleftrightarrow ABO_{3-\delta} + \delta/2\ O_2$$

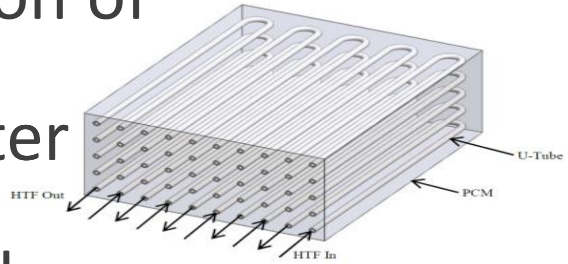
400-1000 kJ kg^{-1}

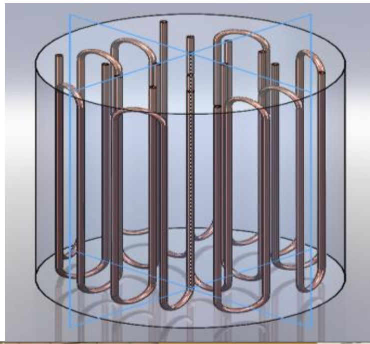


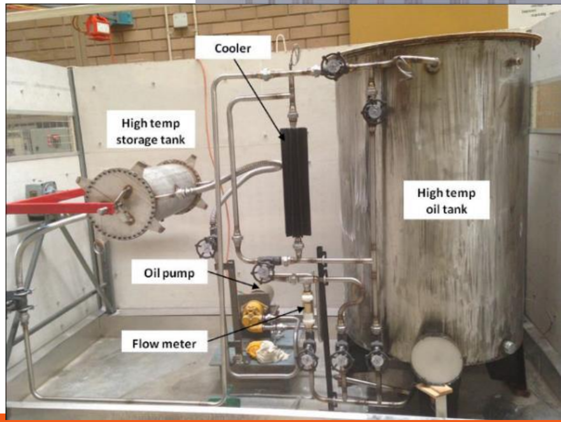
P22: Low Cost, Reliable PCM Storage

- Developing new methods for evaluating material properties due to uncertainty in available data
- Identified and testing properties of potential candidates from 400-700 degrees C.
- Stability evaluation of candidates through Cycling testing
- Compatibility testing for PCM/container materials
- Examined options for enhancing heat transmission of PCM systems, incorporating best combination
- Developed a number of designs through computer modelling/ prototype testing
- Techno-economic analysis revealed that some alloys as well as salts should be considered as PCM
- Utilising a large scale test facility for intermediate prototype testing









Low Cost, Reliable PCM Storage, improving shortcomings

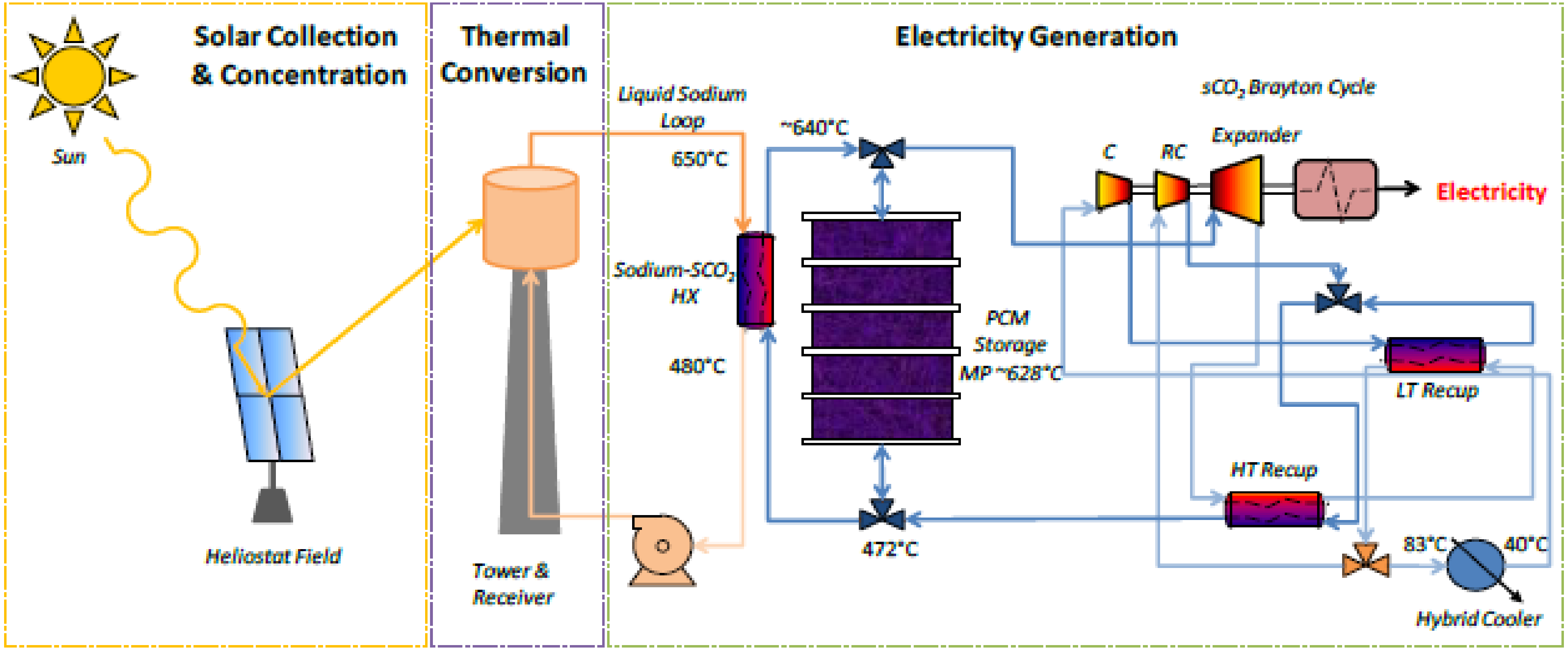
Low thermal conductivity and heat transfer rate

- Increasing heat exchanger surface (Eg. Using finned tubes, heat pipes, encapsulated PCM, optimising shell and tube arrangements)
- Dispersing high conductivity particles into a PCM (Eg. PCM-graphite composites, impregnation of metal matrix or nanoparticles into the PCM)
- Dynamic PCM system : using recirculation of the PCM during the melting process
- Direct Contact heat exchanger: direct contact between the storage material and the heat transfer medium.

Insufficient long term stability

- Find compatible containers for PCM
- At least 1000–2000 cycles are recommended in laboratory measurements.

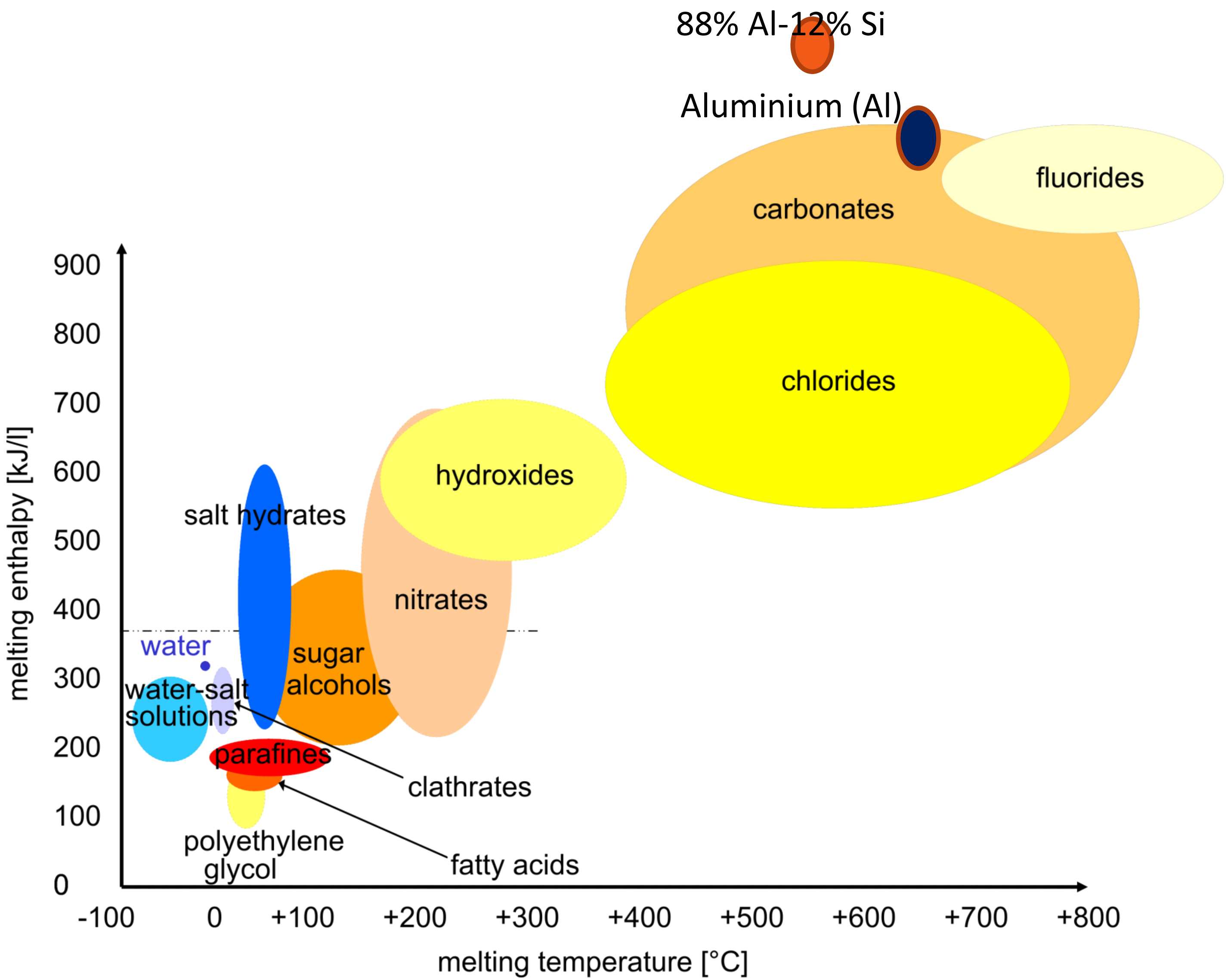
Proposed CSP Configuration: Australian Solar Thermal Research Initiative



Uses liquid Sodium for energy collection and supercritical CO_2 for storage and generation

Selected Materials

Material	MELTING POINT (ºC)	LATENT HEAT (KJ/KG)
53% BaCl, 28%KCl - 19% NaCl	540	211
52.2% Na2CO3-47.8% K2CO3	710	140
59.45% Na2CO3-40.55%NaCl	638	278
88% Al-12% Si	576	567
Aluminium (Al)	660	397



Melting temperature vs. melting enthalpy for organic PCMs and inorganic salt PCMs

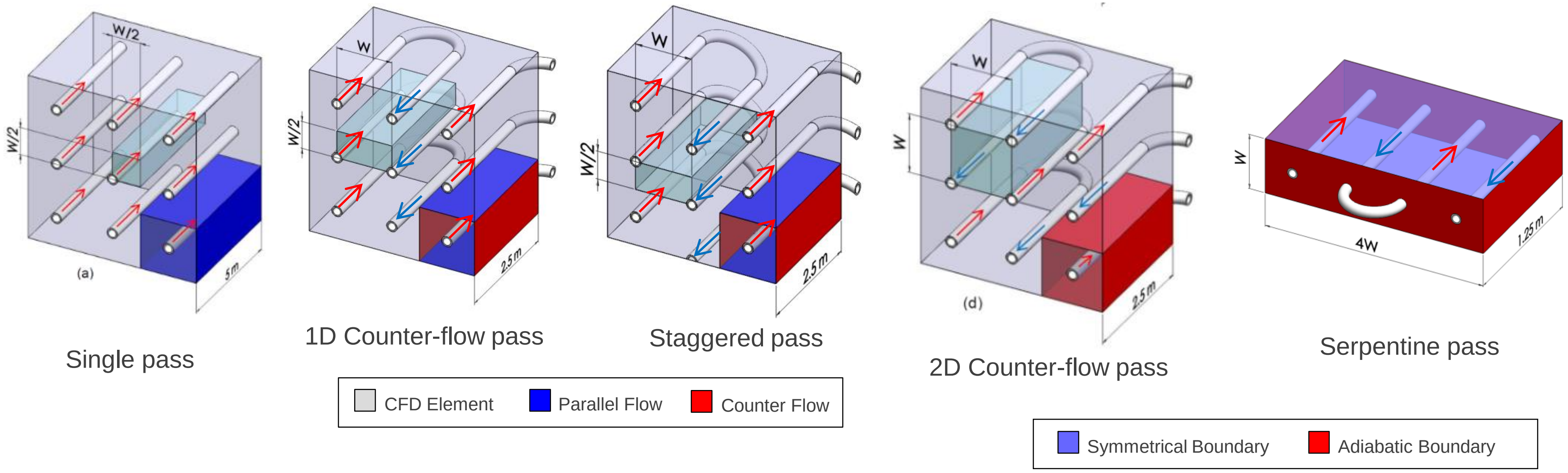
Low Cost, Reliable PCM Storage

Eutectic Na_2CO_3–NaCl salt: A new phase change material for high temperature thermal storage

- Thermophysical properties were investigated using a Simultaneous Thermal Analyzer (STA) and X-Ray Diffraction (XRD).
- From experiment, melting point of eutectic salt is 637.0 °C and heat of fusion is 283.3J/g, which agree with theoretical values determined by FactSage software.
- The thermal stability analysis indicates that the eutectic molten salt has good thermal stability without weight loss in a CO_2 environment at temperatures below 700 °C, compared with 0.51% weight loss in a N_2 atmosphere. The weight loss observed in the latter, is most likely to be due to the salt's decomposition at high temperature.
- Melting temperature, latent heat of fusion and solidification varied marginally after 1000 thermal cycles.
- This demonstrates that the eutectic Na_2CO_3–NaCl salt is a promising high temperature phase change material.

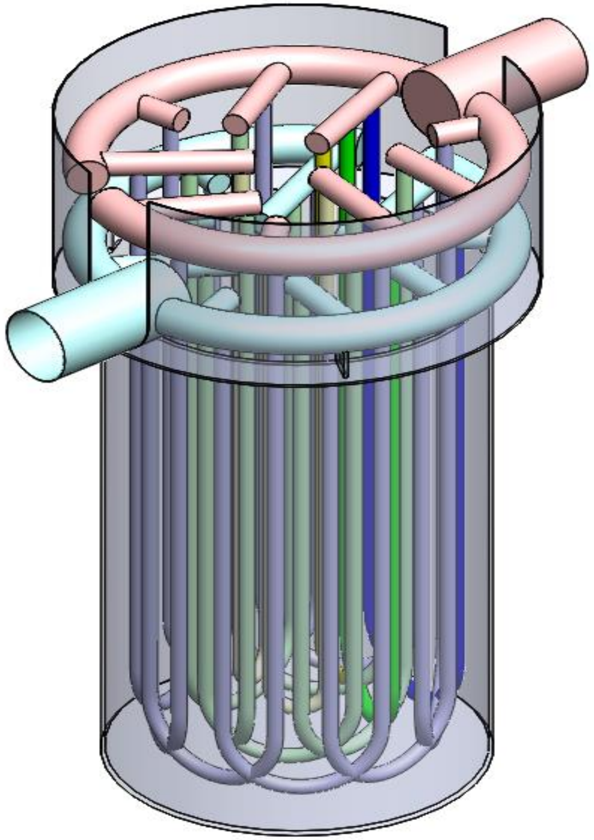
CFD Analysis

- **Effective Tube-in-Tank PCM thermal storage for CSP applications**
  - **Several configurations of tubes for a tube-in-tank PCM storage system were investigated and parametric study conducted**
  - **Results showed improved effectiveness with counter flow arrangement**

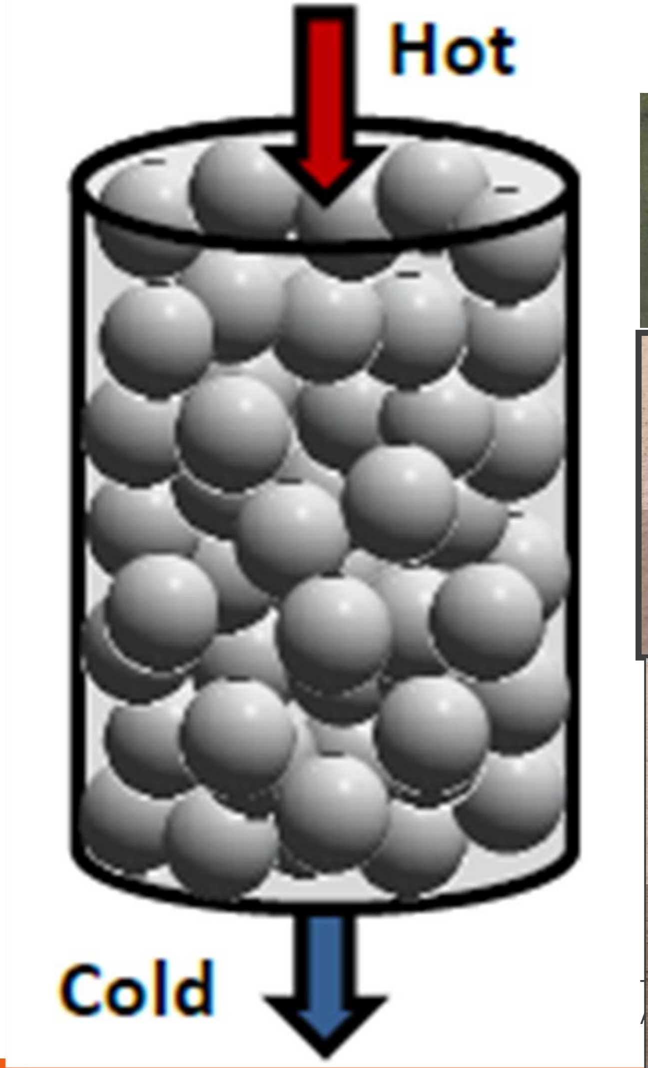


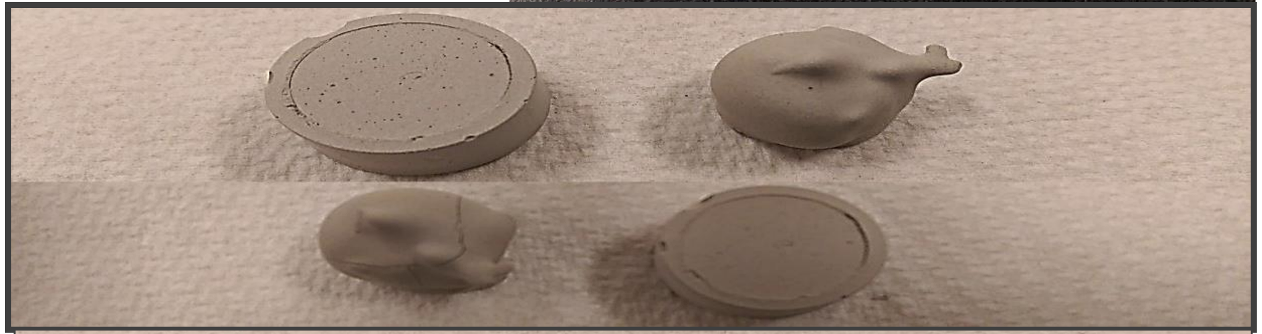
Tube in Tank Prototype Designs

- **2 prototypes have been designed and built for testing in the high temperature test facilities**
- **Both rigs are identical but built with different materials to cater for different PCMs**



PCM Encapsulation: Packed Bed





Corrosion tests

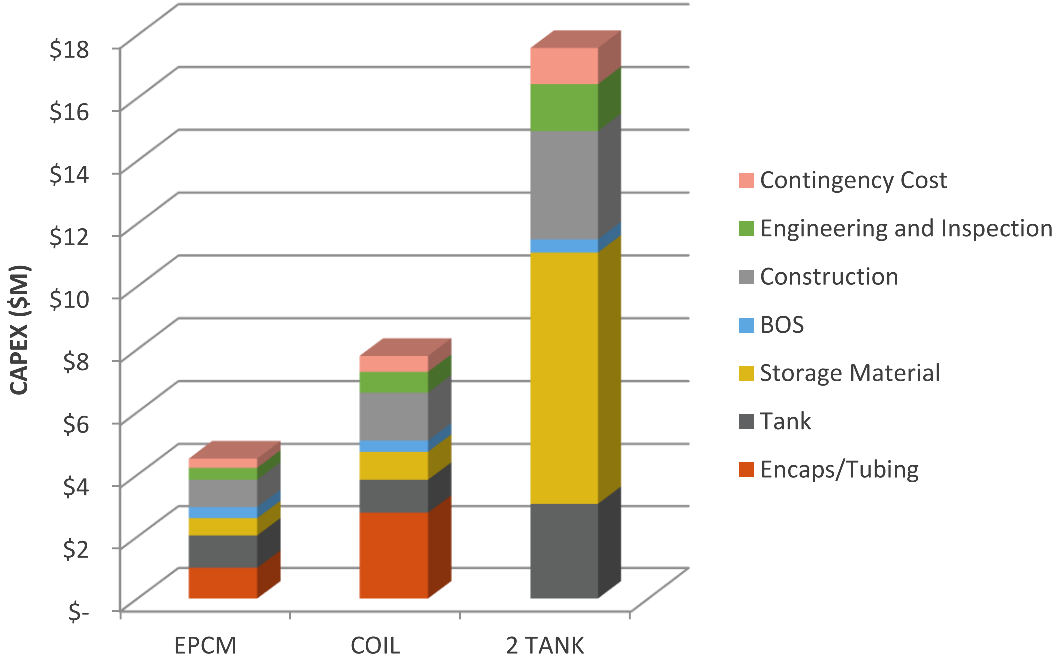
- Eutectic carbonate salts, Tm ≈ 400 °C
- Corrosion tests on SS 316 @ 600 °C

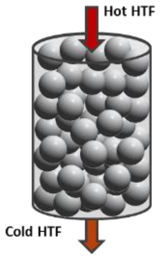
molten salts

Techno-economic analysis PCM and tube material

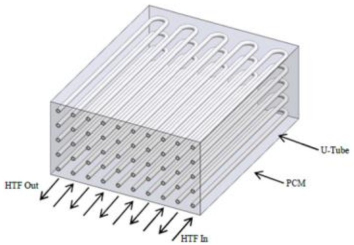
PCM WITH MELTING POINT	COIL MATERIAL	$/kWhr	kWhr/m3	Ratio of coil to PCM mass	Tube to Total Cost	PCM cost, $/kg	Tube cost, $/kg
450 PCM 40% $MgCl_2$/60% NaCl	Incolloy 800	19.7	220	0.15	0.94	0.17	15
623 PCM 60% Na_2CO_3/40% NaCl	Incolloy 800	19.1	242	0.15	0.93	0.20	15
508 PCM, 35% $LiCO_3$, 65% K_2CO_3	SS 316	22.9	345	0.15	0.25	3.48	6.63
560 PCM, 35% NaCl, 65% LiCl	Incolloy 800	48.3	299	0.15	0.31	5.77	15
aluminium-silicon eutectic alloy	Titanium alloy	12.1	511	0.005	0.05	2.20	25
710 PCM, 51% K_2CO_3, 49% Na_2CO_3	SS 316	10.2	315	0.15	0.61	0.74	6.63

Cost of Thermal Energy Storage Options

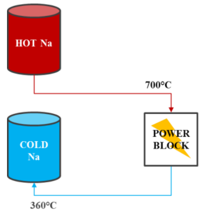




$11.2/kWht



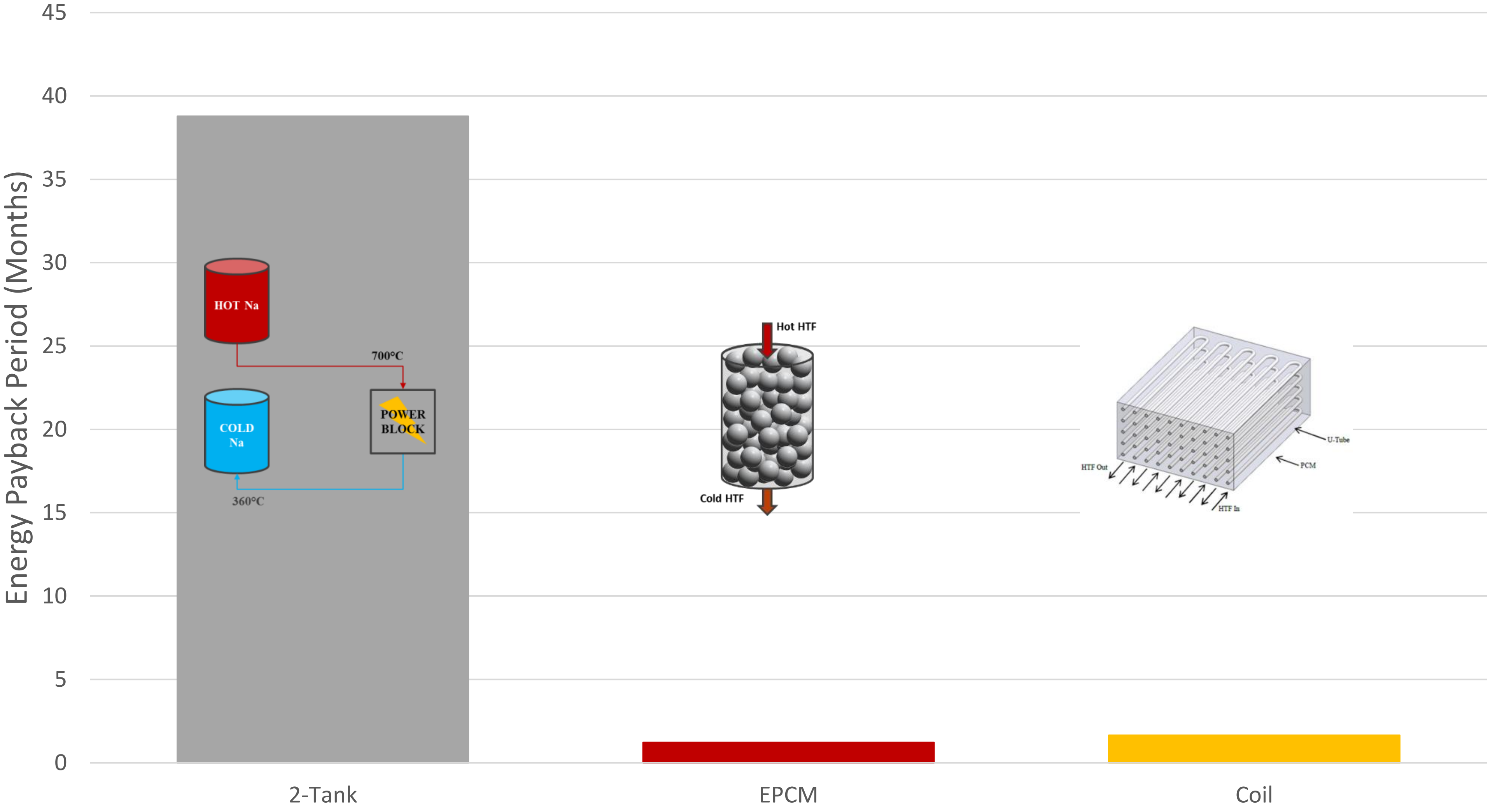
$19.2/kWh$_t$



sodium two-tank $43.4/kWh$_t$ systems

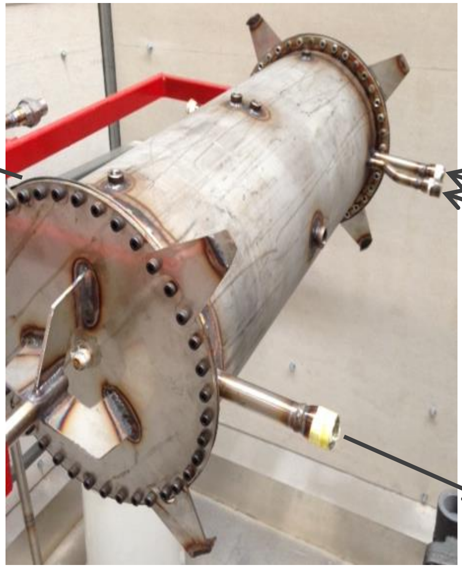
Base case two-tank molten salt system cost : $ 37/kWh$_t$

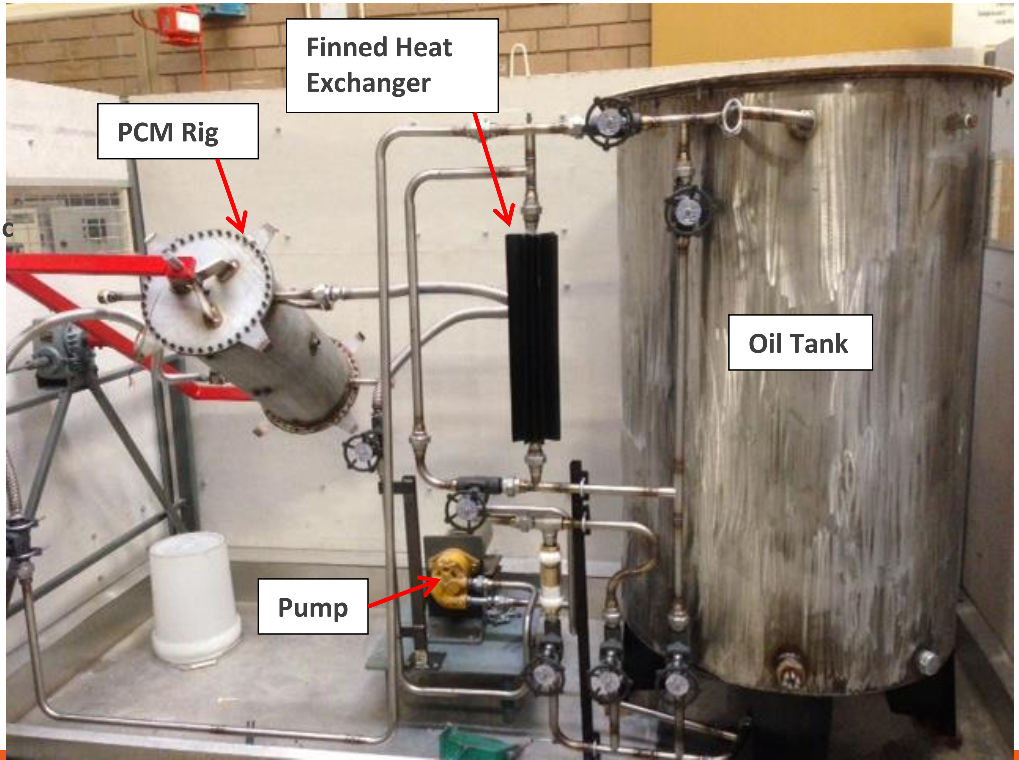
Energy Payback Period of Thermal Energy Storage



Dynamic PCM Systems for High Temperature Thermal Storage

- **Dynamic PCM Test Prototype for high temperature PCM designed and built**





International Collaborators

- Sandia: Modelling particle receiver
- NREL: SAM, Modelica, PCM property evaluation
- CIEMAT/PSA: (Modelica)
- Loughborough University (UK), economic analysis of thermal storage using SAM.

Working with Innostorage (funded by the European Union 7th Framework Programme):

- Universitat de Barcelona (Spain): Corrosion investigation of molten salt PCMs with stainless steel
- Universitat de Lleida (Spain): Life cycle cost and energy analysis of different thermal storage technologies

  Use of nano particles to enhance the specific heat of phase change materials by 20%

  Improving knowledge on dynamic melting

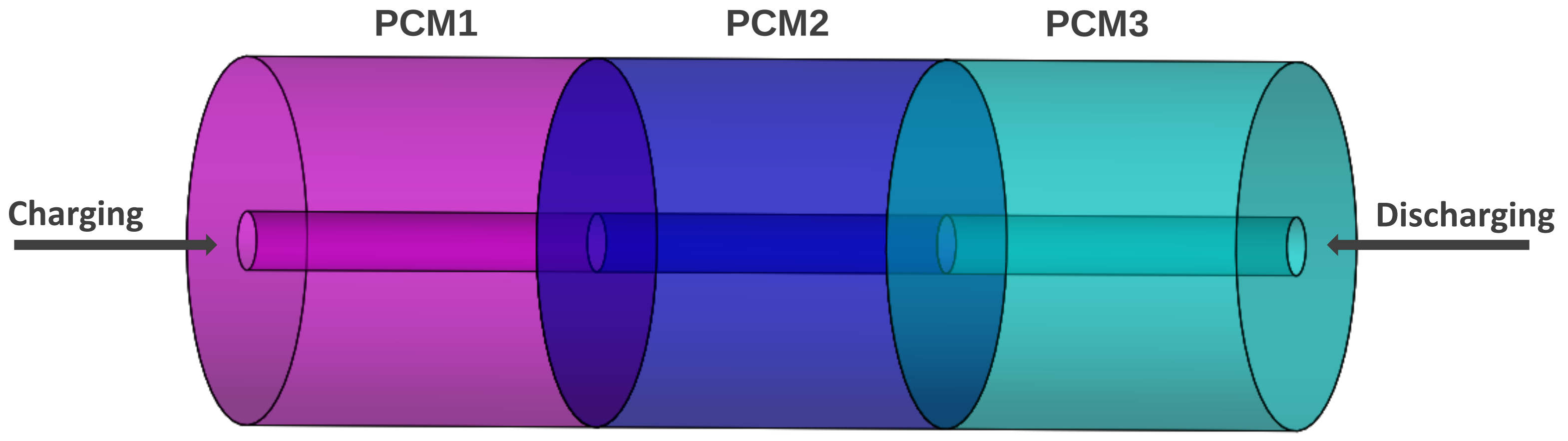
Current Status

- A number of suitable materials are available for use for PCM storage at an extended temperature range
- A number of innovative design options have been investigated through modelling and low temperature testing.
- The estimated $/kWhr costs are below the two tank molten salt base case system over 300-600 °C range with additional savings are achieved as no trace heating element system is needed to avoid freezing, (and no discharge molten salt pump is needed).
- Considerable system savings are likely through increasing the system capacity factor
- Improved value proposition of CSP systems are anticipated with our innovative storage technologies

Future Directions

- As more renewable energy is installed, more CSP plants with longer storage capacities will be necessary and economically attractive
- Higher temperature operation is possible with tower systems and should lead to higher overall thermal efficiency. A number of storage options are being considered with different levels of maturity
- Phase change thermal storage provides an economically and technically viable alternative to the current 2 tank systems in CSP plants. A number of suitable PCM materials and system designs are available to provide practical storage with higher capacity factor and improved rates of return
- More systems development and integration into the CSP plant is necessary to improve confidence.
- More work is necessary on developing and testing system prototypes to reduce technical and economic risks for industry take up.

Cascaded latent heat storage system



Melting temperature:$T_{PCM1}>T_{PCM2}>T_{PCM3}$

<u>Advantages:</u>

- offers a higher utilisation of solar field and phase change material
- a more uniform heat transfer fluid outlet temperature
- second-law efficiency can be improved

High Temperature Test Facility

- **Performance Specifications**
- Heater modules with output power up to 200kW
- Air flow variable up to 500 lt/sec (STP)
- Fan exit pressure up to 600 Pa
- Operating temperature up to 900 C
- Temperature sensor accuracy < 1%

University of South Australia

Industrial Application:
High Temperature Molten Salt in Mineral Processing

Novel technology being developed with industry

Advantages

- Molten salts provide an energy efficient path to selectively extract metals from minerals (avoids breakdown of mineral)
- Solar energy (heating molten salt) is ideal as heat input into mineral processing
- Novel technology will also result in large reduction water and components

Acknowledgements

The Australian Solar Thermal Research Initiative (ASTRI) Program is supported by the Australian Government through the Australian Renewable Energy Agency (ARENA).