ASTRI Milestone 12 Report - For Public Dissemination

Australian Solar Thermal Research Initiative

Program Number 1-SRI002 (ASTRI)

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Responsibility for the views, information or advice expressed herein is not accepted by the Australian Government

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Table of Contents

Executive Summary

The Australian Solar Thermal Research Initiative (ASTRI) is a research program, involving a consortium of leading Australian Universities and CSIRO, to deliver cost reductions and dispatchability improvements to Concentrating Solar Thermal (CST) Power in Australia and position Australia in CST technologies.

Milestone achievement

This Milestone Report complies with the agreed ARENA requirements of 9 May 2017 which differs from Deed of Variation (2) while details of the future design of ASTRI are being finalised.

The status of the agreed Milestone deliverables is summarised in the table below.

Summary of the status of each Milestone deliverable and its location in the report

MILESTONE DESCRIPTION	COMPLETION
Report demonstrating completion of activities in the Program Plan	Completed as per Section 6 of this report "Technical report of Research Program"
Achievement of the Key Performance Indicators	Completed as per summaries section 6 and section 7 of this report
Preliminary Financial Report	Completed as per Section 8 of this report

1 About ASTRI

The Australian Solar Thermal Research Initiative (ASTRI) is an eight-year, $87 million international research collaboration. In November 2012, the Australian Solar Institute (ASI) entered into a funding agreement with the Commonwealth Scientific and Industrial Research Organisation (CSIRO) to establish and deliver the Australian Solar Thermal Research Initiative (ASTRI). The ASTRI Program merged under the Australian Renewable Energy (ARENA) investment portfolio in December 2012 when ASI ceased operation.

ASTRI was designed to provide an institutional framework for a coordinated, national approach to CST research in Australia, and also encouraged international collaboration with the USA. As a consortium, ASTRI incorporates researchers from the following seven institutions:

- CSIRO (ASTRI's lead institution)
- Australian National University
- Flinders University
- Queensland University of Technology
- University of Adelaide
- University of Queensland
- University of South Australia

With the combined efforts of the above institutions, ASTRI is delivering the next wave of cost reductions for CST technologies to ensure solar thermal is competitive with other renewable and traditional energy sources, and to develop the Australian capability required to deliver this technology locally and globally. Since its inception, ASTRI has delivered a more than nine-fold increase in the number of CST technology specialists working in collaboration with industry to achieve that aim. There are now more than 140 experts across four states and territories working to unlock CST's potential and identify niche market applications for the technology.

2 Concentrating Solar Thermal

Concentrating solar thermal (CST) power systems utilise the sun's energy to generate electricity. CST uses lenses and reflectors to collect the solar radiation and concentrate it on a receiver with a much smaller area, affording a concentration effect.

CST power technologies are expected to play an important role in the future energy mix because of their capacity to easily incorporate thermal storage within plant design and for CST systems to be hybridized with other sources of energy. The addition of dispatchable CST power plants with thermal storage into the electrical network will provide a low cost solution to improve the overall operation and reliability of the electricity grid and allow increased penetration of non-dispatchable renewable sources (i.e. PV and Wind).

MARKET FOR CST

According to the IEA, CST is a re-emerging market, with costs expected to continue to decrease as more suppliers enter the market, and R&D efforts continue to bring deployment costs down. By 2050, CST is expected to be the main source of electricity in large regions of the world and, with rapid development of CST projects across nations such as Chile, China, India, Morocco, South Africa, and the USA, this technology is coming of age. Few countries in the world are as well positioned as Australia to capitalise on that global growth and contribute to the technologies that will shape the future of this industry.

Currently, the business case for concentrating solar power deployment in Australia is attractive for a limited number of specific market niches, especially at edge of grid and remote locations. Exploiting these niches in the short term will assist in demonstrating the value of CST while increasing market recognition and, ultimately, stimulating market pull in the medium to long term. It should also be noted that production of electricity is just one of the energy applications of CST technologies. Other process heat applications and solar chemistry are much more than niche markets for these technologies.

CST IN AUSTRALIA

CST energy generation in Australia is still in its early stages of deployment. This is primarily due to the lack of market signals for storage in Australia (and most other countries) and thus the technology has not had the opportunity to come down the cost reduction curve to the same extent as variable renewables, which have benefitted from early adoption and market share. Australia's climate makes it an ideal candidate for large-scale CST generation, and declining costs will make the technology increasingly attractive.

It is important to note that while Australian companies are not manufacturers of the main components of PV or wind technology, Australia does stand a good chance to play a leading role in concentrating solar power systems , providing a valuable market entry opportunity.

Australia has the required skill set, human capacity, R&D platform, potential internal market, solar resourceand strategic location in the world to grow a CST industry that can be competitive internationally and capture an important share of the future energy market.

CST GLOBALLY

Around the world in countries such as Spain, Germany and the USA, approximately 5GW of CST plant have been installed, and large-scale CST projects of up to 500 MW are being planned and constructed. New markets are now emerging at a rapid rate in China, Chile and the MENA regions (particularly UAE and Morocco) with China in particular planning to install 5GW by 2021, equivalent to the capacity installed over the last decade.

Previous studies have estimated that a global installed capacity of 10GW of CSP would be sufficient for the technology to generate its own self-sustaining momentum. This level of deployment could be reached by 2019. New Energy predicts that 22GW could be installed by 2025.

In addition, as the level of variable renewables rises in most markets, the case for CSP with storage becomes even stronger.

3 Market Applications

ASTRI's technologies have a range of applications, including electricity production, industrial heating, and with ASTRI's Solar Fuel technologies these applications can also extend to the many greenhouse gas-intensive applications where gas is reformed now, such as fertiliser production or distributed generation of liquid fuels for road transport, mine site use or rail transport fuels. The integration of thermal storage into the process increases the ability of solar thermal technologies to provide output in a reliable manner, so that they can be coupled with processes that have traditionally used fossil fuels.

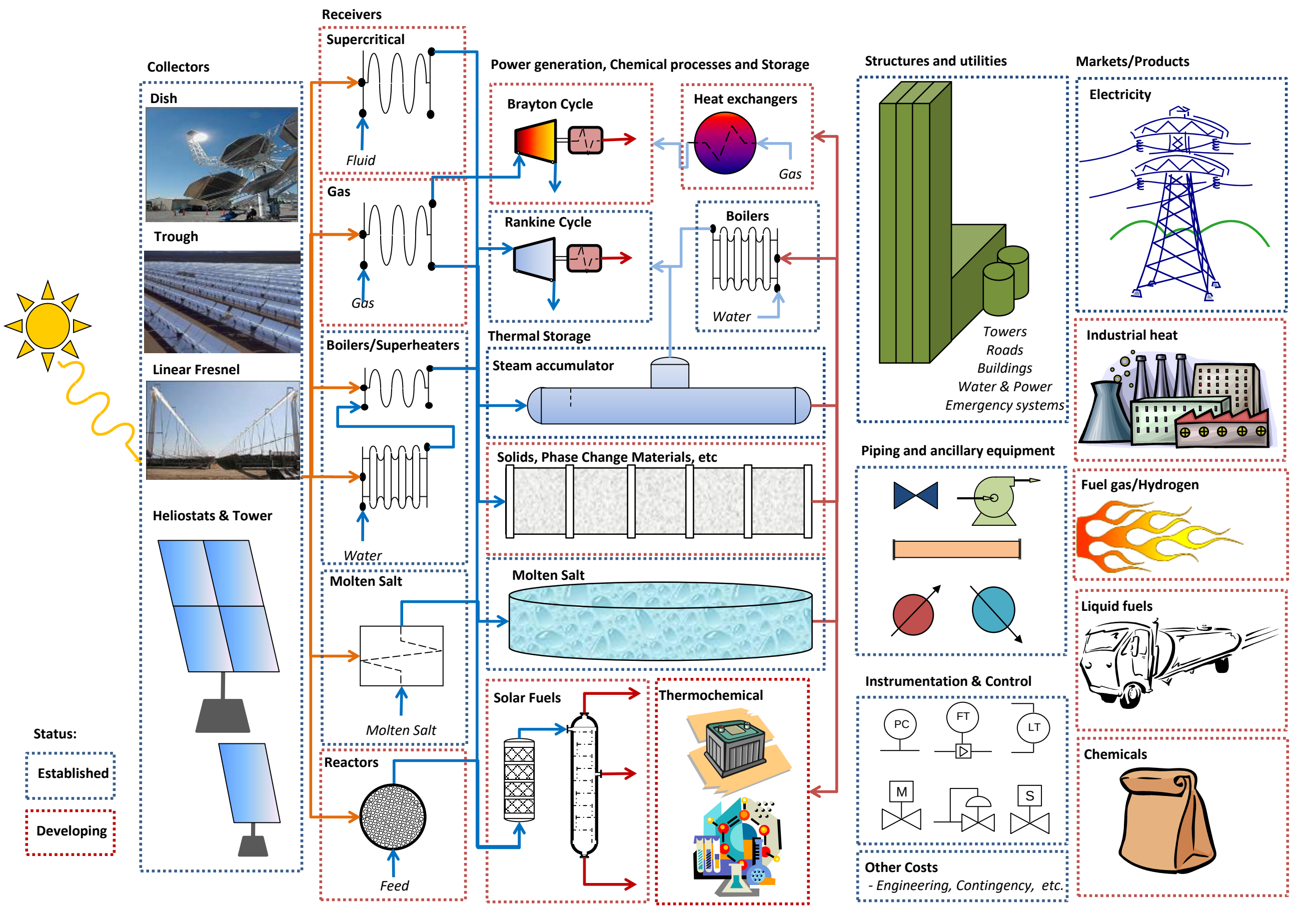


Figure 3.1: Established and Developing Solar Thermal Technologies and Market Applications

ASTRI is working towards improving the bankability of concentrated solar thermal (CST) central receiver technology, from proving current technologies, modelling the economic benefits, through to developing higher efficiency cycles.

The research ASTRI is conducting is aiming to:

- Reduce cost and improve performance of CST central receiver power plants
- Demonstrate near term technologies for power generation
- Design, develop and test next generation receiver technologies to increase efficiency
- Foster research, development and demonstration through industry collaboration
- Develop scalable technology covering the range 1-25MWe.
-

Value proposition of CST technologies

The value proposition of CST technologies is relevant and attractive. CST technologies have the attributes of a solution that can become part of the backbone of a highly decarbonised energy system of the future.

In application, its benefits are varied and cross a number of priority sectors – for example:

- Electricity sector:
    - CST integrates naturally with storage, and actually becomes cheaper on a $/kWh basis as storage size is increased, which is a unique competitive advantage compared to other storage renewables
    - CST doesn't need any conventional backup, but can be hybridised
    - It can perform different roles as needed, from base-load to peaking plants
    - It can provide critical grid stability to increase penetration of non-dispatchable renewable technologies
    - It allows a higher penetration of variable renewables without clipping

- Industrial and transport sectors:
    - CST can provide process heat, fuel and solar chemistry solutions needed to successfully decarbonise these sectors
    - "Drop-in" fuels can be produced during a transition to EV or HFC vehicles.

The intermediate transformation of solar radiation into heat allows CST technologies to:

- Provide a very large range of energy service options of varying temperature and technological complexity to allow:
    - Heating and cooling;
    - Process heat at high temperatures;
    - Electricity generation; and
    - Solar fuels and other chemistry or metallurgy applications.

- CST technology can facilitate the integration of hybridisation and thermal storage solutions for a range of industries currently under scrutiny for their carbon emissions or called to question on their strategies to reduce emissions and transition to renewable energy sources and practices. For example:
    - If hybridised with biomass, a CST system can provide continuous 24/7 clean and renewable heat process or electricity production operation.
    - If combined with a thermal storage system, CST can provide the heat for the heat process application or for the delivery of electricity when it is needed most or is economically profitable.

When deployed with conventional power block technology, CST delivers dispatchable clean and renewable electricity and ancillary services to the grid.

The capacity of CST to utilise expertise already available in many countries translates to:

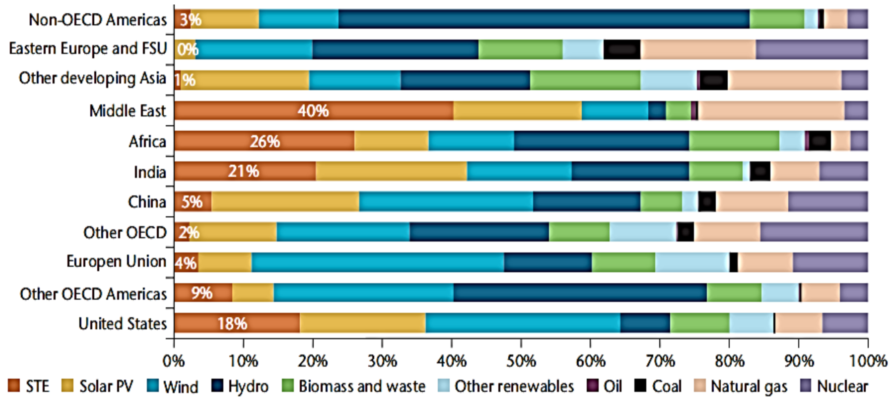
- High potential for conversion or expansion of existing manufacturing capabilities in a country to serve the CST sector;
- Local content of CST projects – i.e. built, manufactured and deployed by local companies; and
- Positive impact on employment, tax revenues and GDP.

Australia currently has more than 1.2GW of installed diesel generation capacity in off-grid and fringe-of-grid systems generating electricity for mine sites and communities at a cost of 24-45 cents/kWh (excluding sunk costs of capital)(AECOM Australia 2014, p16)[1]. This market provides the low-hanging fruit for the scalable CST technology being developed by ASTRI and offers a quick path to commercialisation and rapid cost reduction through experience while serving commercial customers at minimum public subsidies.

The operations and maintenance program offers a range of market applications that can immediately assist CSP systems and operators. These applications are currently focused on the efficient and sustainable mirror cleaning processes utilising Condition-Based Cleaning (CBC) methodology for the optimisation of mirror cleaning schedules coupled to low-cost heliostat reflectivity monitoring using already-installed calibration cameras (e.g. CCD cameras) and a physical dust soiling model for heliostats. These applications can reduce significantly the effort currently dedicated to the evaluation of a mirrors reflectivity and the associated requirement for cleaning to maintain reflectivity of the mirrors surface. This process is optimised and based on the location, soil/dust conditions, schedule optimisation and produces a robust and cost-saving methodology to maintaining a clean heliostat field.

Global opportunities

Because of its excellent value proposition, CST technologies are expected to play a very important role in the transition to a decarbonised world energy system. According to the 2014 version of the International Energy Agency (IEA) roadmap[2], CST plants will be the dominant technology in the future for Middle East and African countries and they will play a significant role across other regions.



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In the future, CST plants will be the dominant technology for electricity generation in Middle East and African countries. They will play a significate role in other regions

The IEA also predicts that together PV (16%) and CST (11%) could become the largest source of electricity worldwide before 2050.

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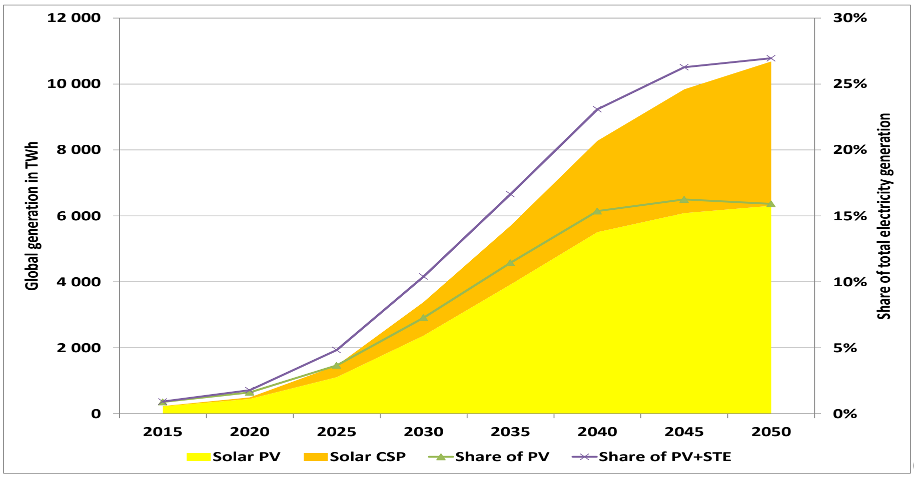
[1] AECOM Australia Pty Ltd (2014). Australia's Off-Grid Clean Energy Market Research Paper (prepared for ARENA). Sydney.

References[2]

IEA (2014a) "Technology Roadmap: Solar Thermal Electricity", 2014 edition, OECD/IEA, Paris; available from http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapSolarThermalElectricity_2014edition.pdf

IEA (2014b), "IEA Technology Roadmaps for Solar Electricity 2014 Editions", OECD/IEA, Paris; available from https://www.iea.org/media/freepublications/technologyroadmaps/solar/Launchsolarroadmaps2014_WEB.pdf



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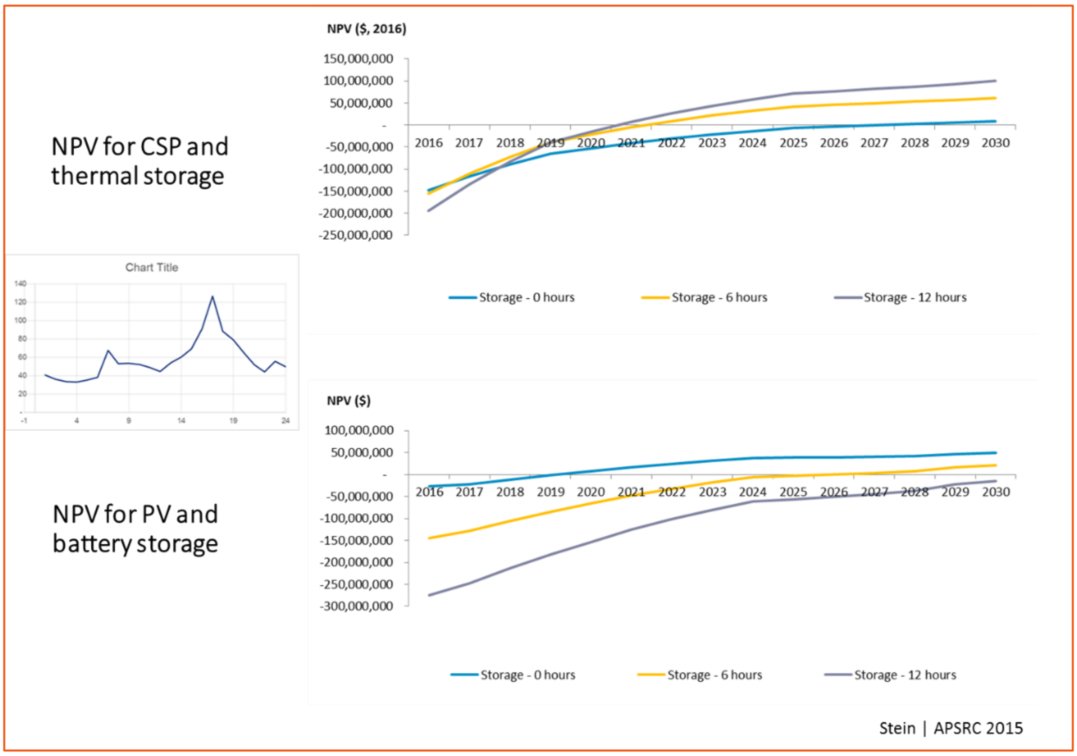
Together CST (11%) and PV (16%) could become the largest source of electricity worldwide before 2050

In fact, PV and CST technologies are beginning to be combined by renewable energy project developers to take advantage of their complementary characteristics, with CST providing the critical thermal storage system to deliver electricity when the sun is not shining.

A net present value analysis commissioned by CSIRO and undertaken by Deloitte Access Economics shows a strong proposition for CSP with thermal storage over PV and batteries for levels of storage greater than three full load hrs.



One should not forget that the production of electricity is just one of the energy applications of CST technologies. Other process heat applications and solar chemistry are much more than niche markets for these technologies.

4 Specialist Capabilities

4.1 Overview

The broad objective of ASTRI is to deliver cost reductions and dispatchability improvements to concentrating solar thermal power (CSP) and position Australia in CST. ASTRI has coordinated a focussed collaborative programme with rigorously prioritised efforts informed by an overarching economic model.

Focus areas for ASTRI collaborative CST research have been:

- Reduced project capital cost;
- Increased utilisation of equipment (capacity factor);
- Improved efficiency; and
- Minimised operation and maintenance costs.

The following sections provide an overview of the specialist capabilities developed by ASTRI in the above focus areas.

4.2 Economic Modelling

4.2.1 OVERVIEW

The Overarching Economic Model project (P01) is a central activity that combines cost and performance data from other ASTRI projects and literature sources to evaluate the economic performance of CSP plants utilising ASTRI and conventional technologies.

A key objective of the project is to evaluate progress in ASTRI against the Technical KPIs by assessing the performance and cost of concentrating solar thermal (CST) power plants containing combinations of ASTRI and conventional technologies. This requires an overall process simulation to be performed that typically requires simplified representation of the plant components compared to the detailed modelling performed in the specialised ASTRI projects developing individual components, but allows the performance of an entire plant design to be simulated over a year of operation, specifically a 100MWe plant located at Alice Springs. Plant characteristics including capital expenditure (CapEx), operating & maintenance costs (OpEx), annual efficiency, capacity factor (CF) and levelised cost of electricity (LCOE) are estimated and compared to the Technical KPIs at annual milestones.

Additionally, the project has been progressively developing tools for improving the assessment of uncertainty in CST plant viability that include consideration of variations in plant capacity, storage size, equipment costs, location and solar & weather conditions over the plant life. The approach taken has been in broad agreement with the guidelines recently released from the IEA SolarPACES guiSmo task for the development of bankability assessments for planned CST plants.

4.2.2 SIGNIFICANCE AND RESEARCH QUESTIONS

A major driver in ASTRI is the development of new technology options for major components in CST plants, with the intent to both improve the performance and reduce the cost of power plants. However, this can only be achieved if these components can be combined into a complete plant that functions correctly. A major task has been to integrate components developed, either within ASTRI or externally, into a plant that can be used in an annual evaluation of the progress being made within ASTRI towards achieving the Technical KPIs. In addition, alternative plant configurations that incorporate prospective technologies have been developed and modelled to encourage new research goals within ASTRI expected to provide further improvements in plant performance against the Technical KPIs. Another issue that has been addressed is to undertake demonstrations of how applications of the currently available CST technologies can be optimised to provide better financial performance at varying scales for different applications. This has been undertaken through a series of analyses considering power plant size and storage capacity at multiple sites in Australia and published these in a peer-reviewed format to highlight the opportunities that exist for the current technology. Recent project activity has included extension of this to consider the impact of solar variability over the plant lifetime and the financial analysis of potential industrial heat provision at varying scale. Each of these analyses requires that a suitable a plant design be developed and modelled, so that estimates of the capital cost, capacity factor, efficiency and operating costs can use in the financial analysis.

4.2.3 METHODOLOGY

A key contractual challenge within ASTRI has been to combine the output from various ASTRI projects to provide an assessment of performance against the Technical KPIs. Initially a performance assessment was made for a conventional plant design to determine a set of baseline parameters for performance and cost, against which subsequent improvements in technology could be compared. This baseline plant utilised the most common commercial CST technology of that time, namely a plant using parabolic trough collectors, molten salt storage and a Rankine steam power block, located at Alice Springs. Despite the relatively short timeframe, commercial technology has advanced since then through increased uptake of central receiver tower systems with heliostat fields and a rapid decline in the costs for new plant installations worldwide. As ASTRI research projects primarily targeted development of technologies that are more appropriately applied to central receiver tower systems, an additional plant utilising a molten salt receiver and two-tank storage with a Rankine steam power block was designed and modelled to provide a more appropriate reference for comparison with the ASTRI developments.

These initial baseline and reference plant designs were modelled using the System Advisor Model (SAM) software provided by NREL, linked to a costing spreadsheet reflecting current commercial costs. The SAM modelling software was nominated as the preferred tool for determining the overall technical progress of ASTRI against the Technical KPIs due to the software being freely available and in common use worldwide. The representation of the CST plant components within it have been progressively modified through the life of ASTRI in order to represent the changes in size, cost and performance of components due to technology improvements. In addition, more complex models representing the uncertainty in the costs and solar data have been developed in parallel, so that a more realistic probability distribution of the overall performance of the plants can be produced as a precursor to bankability assessments for prospective CST plants. An extension to the original Technical KPIs, which only envisaged that the plants would be of approximately 100MWe scale, has been to also consider the performance of a smaller plant of approximately 25-30MWe scale.

An example of the processes developed in order to assess progress against the Technical KPIs is shown in figure 4.1. This configuration was modelled using a combination of costing data from literature and ASTRI projects, a custom heliostat field design, a sodium receiver, a PCM storage system and a sCO_2 power block, with these components being developed within a range of ASTRI projects. While SAM is used as the central modelling tool for the overall plant analysis, it is beyond the capability of the software to accurately model some of the custom components and it is therefore necessary to make modifications that ensure that the component performance matches that of specialised models from the other ASTRI projects. The output from assessment of this process configuration included a Monte Carlo assessment of the probability that the design met the target LCOE over the lifetime operation under variable solar conditions. This has resulted in the development of an additional modelling tool based on the Modelica language that is more flexible in capability than SAM and is expected to be the primary modelling tool for ongoing development of the overall ASTRI plant design in the future.

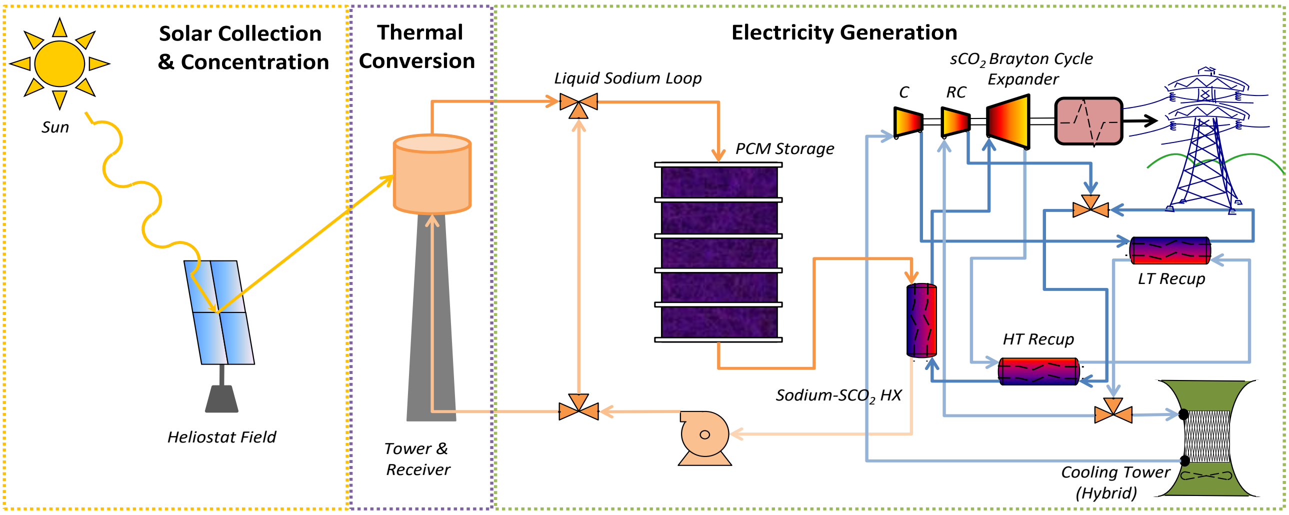


Figure 4.1 - Plant design incorporating a range of ASTRI technologies

4.2.4 RESULTS

The key deliverable from the Overarching Economic Modelling within ASTRI is an annual assessment of the performance of CST plant configurations incorporating ASTRI technologies against the Technical KPIs. In Figure 4.2 the LCOE determined in progressive development of the ASTRI plant configuration as new components were added for milestones is shown for two different plant sizes. For comparison the LCOE cost reduction learning curves from the Australian Energy Technology Assessment (AETA) for CSP and estimates of the LCOE for commercial plants at the same site are shown, along with the ASTRI Technical KPIs for LCOE. It is apparent that the rate of decrease in the cost of commercial CST has been considerably faster than was anticipated in the AETA studies and that ASTRI technological developments are comfortably achieving the Technical KPIs. ASTRI KPIs should be reassessed towards improving confidence in the technologies with the ultimate aim of commercial adopted.

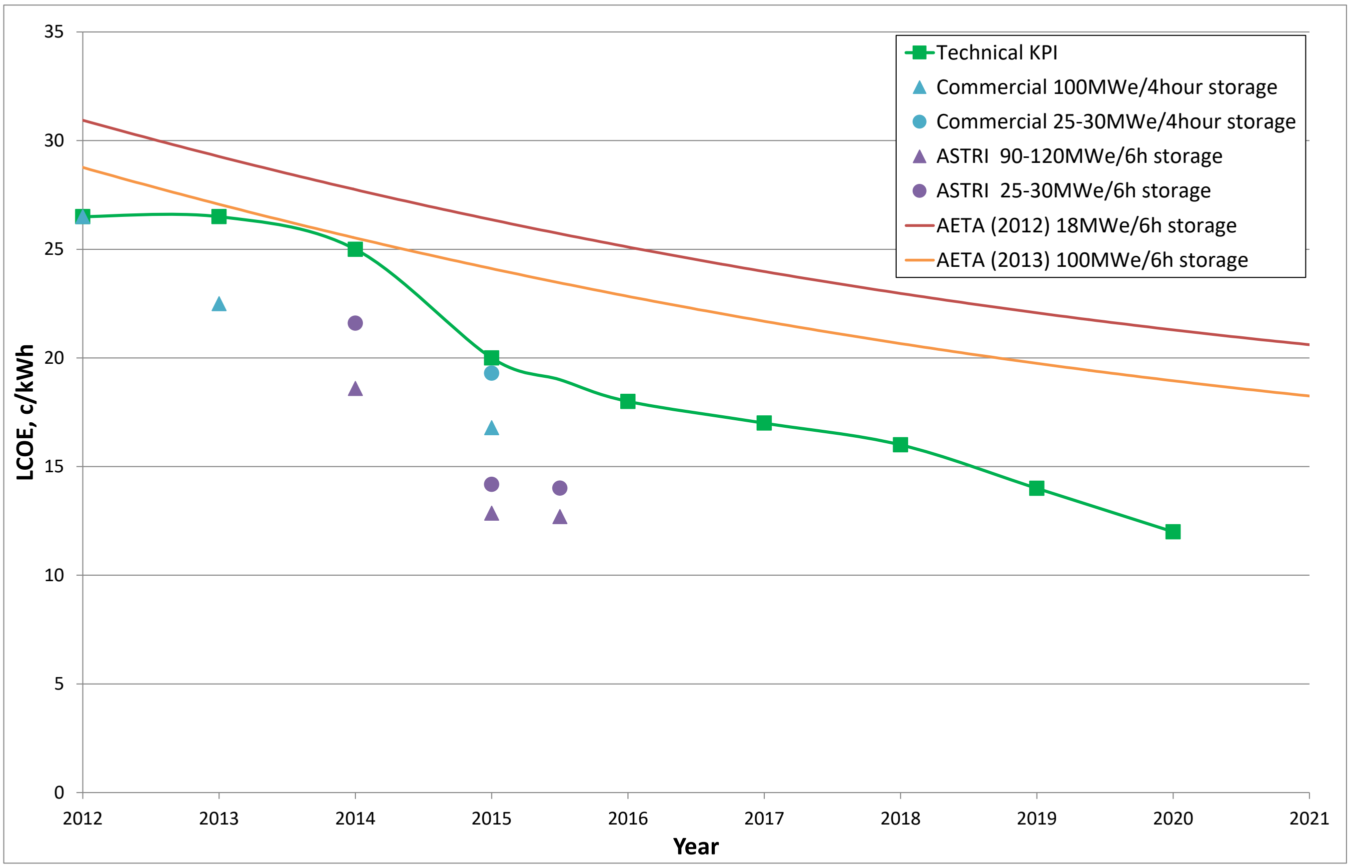


Figure 4.2 - Comparison of ASTRI plant financial performance with Technical KPI and data from other sources

The modelling methods developed in the project have also been applied to the analysis of optimal storage capacities for different size solar plants at a range of Australian sites. An example of this analysis is given in figure 4.3 for Kalgoorlie, where the LCOE for a range of storage sizes is shown for the design year and multiple years of real solar data. A general finding of the analysis is that large plants with large storage tend towards lower LCOE, but also that the performance in any individual year is extremely susceptible to climate variability. This could lead to exposure to significant financial risks, so studies on the impact of solar variability on predictions and the influence of the time-resolution of the solar data in order to determine appropriate analysis methods for bankability assessments have also been undertaken. In figure 4.4 it is indicated that significant variation in predictions occurs with different time steps in the solar input being used into a dynamic model of a parabolic trough system, rather than the commonly used 60 minute steps. Solar data for this study was generated using a probabilistic approach where approximately 20 real years were used to produce 100 synthetic years of data. This is considered to be an appropriate method for producing more realistic assessments of likely plant performance over the entire plant lifetime.

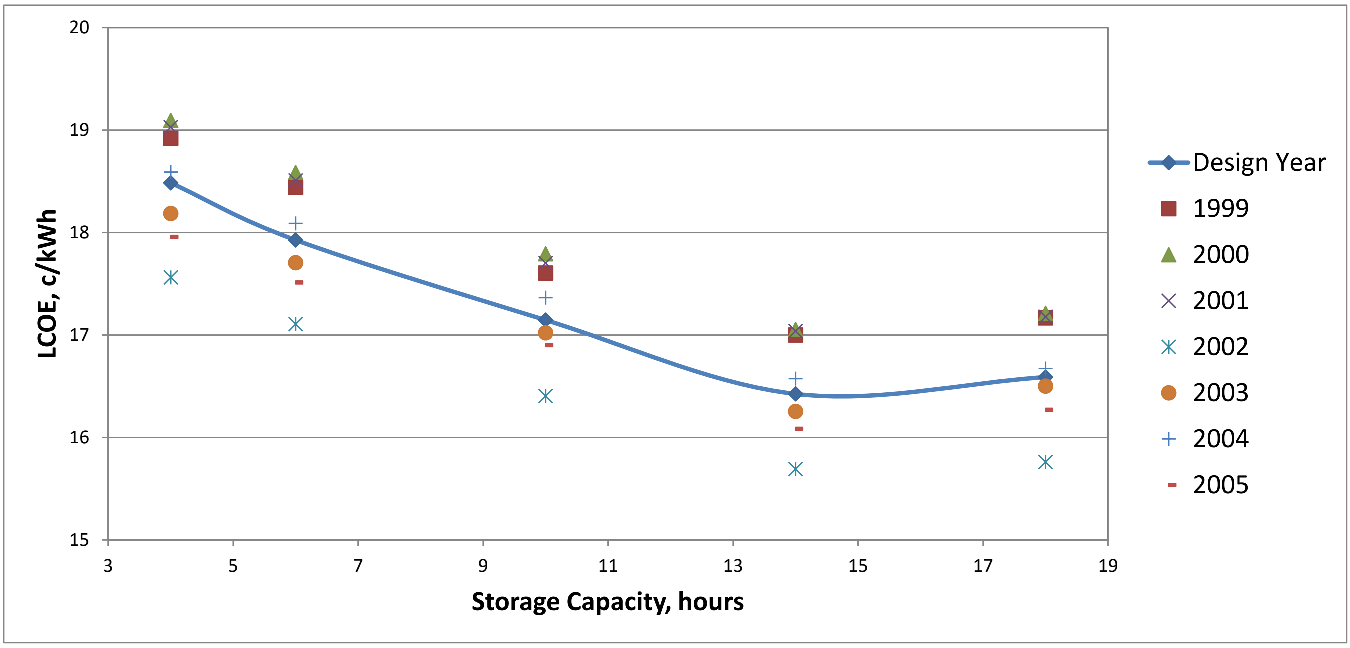


Figure 4.3 - Variation in LCOE for varying plant sizes and storage capacities at Mildura for individual years of operation using historical solar data

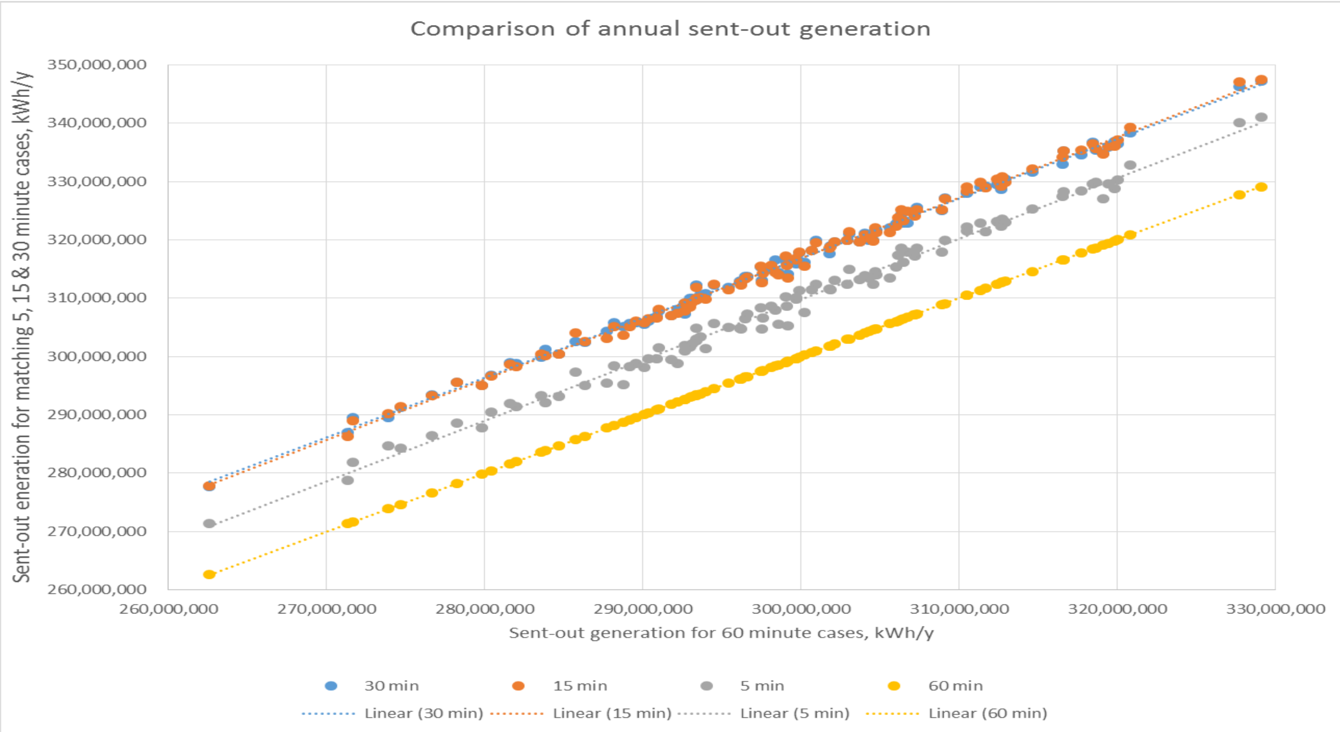


Figure 4.4 - Influence of time resolution of solar data and annual variability on predicted plant output

A recent extension to the project has been to undertake analyses of the potential for increased financial viability through optimisation of plant designs with storage to meet time of day variations in power demand. This is a complex optimisation that needs to vary the storage, field and power block sizes to match the requirements of the network, with those often being influenced by weather conditions at the same time. An example of the output for a series of plant designs aiming to achieve optimised revenue from the sale of electricity is shown for an individual day at Mildura in figure 4.5. The plant output profile varies depending on the size of storage used, but typically the optimisation attempts to meet the minor price peak in the morning and the higher early evening peak. Network electricity prices vary considerably throughout the year and, based on these 2003 prices, no CST plant would be competitive in the market. However, the analysis indicates that the most competitive case would be a plant with approximately 16 hours of storage. This is for a conventional CST plant design and the Rankine steam power blocks benefit from the near continuous operation possible with large storage capacity. The methods used in this analysis are under continuing development and are yet to be applied to alternative plant designs.

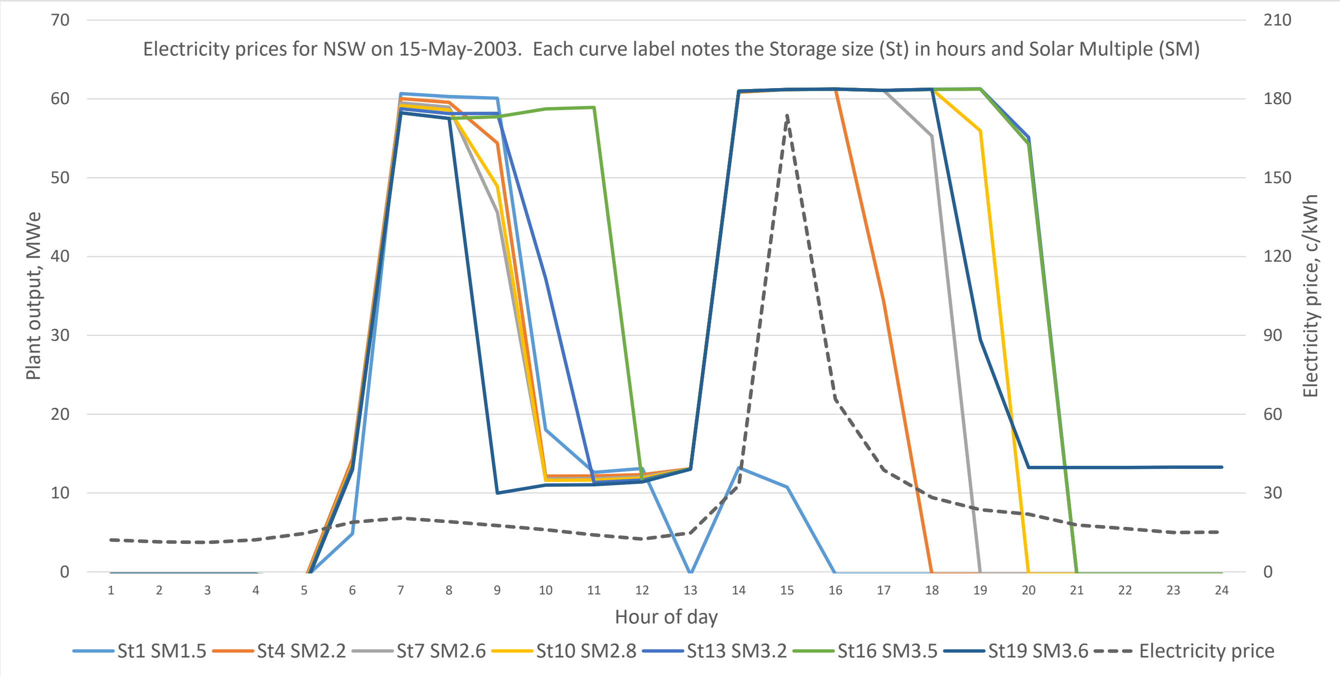


Figure 4.5 - Example results of optimisation of plant design to match network electricity prices

Another extension to the modelling activity has been to modify conventional CST plant designs to provide heat input into industrial applications, with an assessment of the financial viability at locations around Australia. An example from this analysis is shown in figure 4.6 representing the likely levelised cost of heat (LCOH) for a large scale industrial heat supply in Kalgoorlie (WA), using a molten salt tower and storage system for steam generation on demand. This system has a considerably larger thermal storage (13 hours) than the electricity generation applications generally studies in ASTRI. The LCOH indicated for this case is around $17.5/GJ, which may be of interest to industrial operations in the event of natural gas prices increasing. Supplying industrial heat can be more complex than electricity generation due to the need to integrate appropriately into existing processes at appropriate temperatures, and can have more stringent capacity factor requirements.

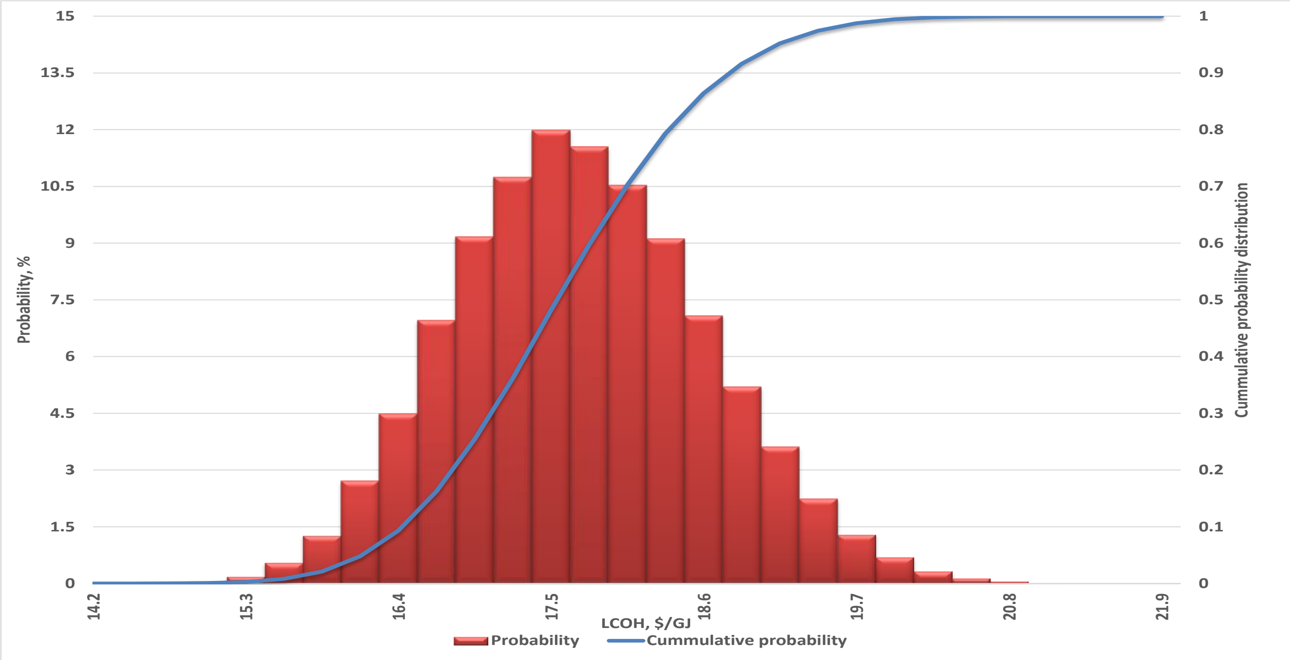


Figure 4.6 - Probability distribution for the cost of high capacity factor industrial heat provision at 250MW$_t$ scale in Kalgoorlie

4.2.5 INDUSTRY APPLICATIONS

The modelling methods developed in the project were specifically aimed at establishing that the CST technologies being developed within ASTRI were capable of achieving the Technical KPIs for each annual milestone. This was a very specific task limited to one plant design at one site, however, the methods can be used to investigate the financial viability of a range of electricity generation and industrial heat provision at other Australian sites. The methods have been progressively developed towards establishing a capability for pre-feasibility analyses that are suitable for commercial clients who are considering CST as a technology option.

4.2.6 PUBLICATIONS

Meybodi M.A, Beath A.C. (2016) Impact of Cost Uncertainties and Solar Data Variations on the Economics of Central Receiver Solar Power Plants: An Australian Perspective, Renewable Energy 93, 510-524

Hinkley J.T., Hayward J.A., Beath A.C., Brinsmead T.S., Meybodi M.A, Lovegrove K.M. (2016) Current and Future Status of Concentrating Solar Power in Australia, J. Japan Institute of Energy, 95, 227-234.

Meybodi M.A., Santigosa L.R., Beath A.C. (2017) A Study on the Impact of Time Resolution in Solar Data on the Performance CSP Plants, Renewable Energy, Volume 109, August, Pages 551–563.

Meybodi M.A., Beath A.C. (In preparation) Economic Viability of Concentrating Solar Thermal Systems for Process Heat Applications: An Australian Case Study.

4.4 Reducing Capital Expenditure

The key technologies to reduce CapEx are the solar field, receiver and balance of system. Proving the reliability of CSP component and systems technologies will reduce technical and investment risk, which will improve bankability and effectively reduce CapEx.

ASTRI has developed world leading capabilities to progress reduction in capital expenditure of key CSP components. Specifically ASTRI has developed advanced capabilities in the following key areas:

1. Low costs heliostats:
    - For companies interested in furthering the development of heliostats, or heliostat sub-components, ASTRI offers expertise across the full domain of **heliostat design**. R&D services span the areas of optical design and mirror technologies, structural design and optimisation, determination of wind loads and improved aerodynamic performance, optimisation of field layout, and integration of smart sensors.
    - **Heliostat field design** is strongly linked to the intended solar receiver concept, and ASTRI has the capability to tailor heliostat design to match downstream requirements, and to integrate heliostat field performance characteristics into full system models.
2. High temperature solar receivers:
    - **Sodium receivers.** Capabilities in ASTRI include simulation of sodium receiver performance, development of high-efficiency design concepts for a range of operating conditions, geometric optimisation of receiver designs, advice on material selection, stress limits in tubes, testing for materials compatibility, testing of durability of absorber coatings, modelling of receivers as part of an integrated CSP system, and testing of laboratory scale prototypes.
    - **Particle receivers.** Capabilities in ASTRI include coupled hydrodynamic and radiative heat transfer modelling, testing of small scale prototypes, modelling of particle receivers as part of an integrated CSP system, property characterisation and durability testing of particles, and experimental facilities to model impact of wind on particle dynamics.

4.4.1 LOW COST HELIOSTATS

Overview

The goal of the heliostat field cost down project was to demonstrate proof-of-concept for a new, low-cost heliostat design that could be manufactured, installed and operational at a cost of 120 AUD/m^2. Following an in-depth scoping study, the project was initially structured around two main streams of research: a design concept stream and a technology development stream. In future, the project is restructured to focus on technology, tools and techniques, and to make them readily available to industry partners as the basis of specific collaborations, and to encourage the move from exploration to demonstration. The project team has also set itself a stretch goal of $90 AUD/m^2, and will continue to monitor cost reductions using a standardised costing tool developed within the techno-economic analysis stream.

Key Challenges to Achieve Low Cost Heliostats

Heliostat field costs presently comprise around 35-40% of the total capital cost of a CSP central receiver power plant. The need for deep cost reduction is widely acknowledged within the industry. A detailed review of the state-of-the-art of heliostat technology early in the ASTRI project concluded that the key to achieving LCOE targets is not a single 'breakthrough' development, but to bring together all potential concepts resulting in performance improvement or cost reduction as a single package. Some of the key findings from the scoping study were as follows:

- Concurrent engineering processes are essential, with engineers across disciplines working together from the earliest stages of product design, and throughout the design life-cycle.

- Heliostat sizing depends on finding a balance between competing drivers to reduce size (compatibility with volume manufacturing and assembly processes) and increase size (driven by actuation, control and communication system costs).
- Wind-tunnel testing shows that a highly variable wind load is developed across the heliostat field which is a critical contributor to the worsening of heliostat design parameters. Decreasing heliostat wind loads will allow for lighter and lower cost heliostat designs. To achieve reductions in wind loads, heliostat-field perimeter wind fences and other wind reduction strategies should be considered.
- The use of thin glass (~1 mm) for mirrors provides increased reflectivity; however, a supporting substrate is required due to the fragile nature of the thin glass. An attractive option is the sandwich panel, which can be strong and very rigid, and may be designed to contribute significantly to the supporting functions of the heliostat structure.
- Advances to wireless communication technology in conjunction with decreases in the cost of photovoltaics, have made the 'autonomous' heliostat a viable option.
- Heliostats with a primary horizontal axis of rotation allow up to 80% denser spacing without collision, which is useful particularly in regions close to the tower. Furthermore, with this mode of tracking it is feasible to use linear actuators, potentially allowing the use of cheaper components.

ASTRI Research Methodology

Considering the design principles identified in the Scoping Study, as well as the particular research capabilities across the ASTRI team, a heliostat development program was formed with a heliostat design concept development stream, and a number of technology development streams, as described below. Although the subject matter was diverse in discipline, a common thread throughout the heliostat research program has been a focus on prototyping and demonstration, and another feature is the high level of integration and information sharing between streams.

Heliostat Design concepts

Three heliostat design concepts were investigated (Table 4.1), with down-selection to two concepts in 2015 (A&C).

Table 4.1. Overview of key features of ASTRI heliostat concepts

30 m² sandwich panel heliostat (ANU led)	**Mini-facet heliostat (UniSA led)**	**Drop-in heliostat (CSIRO led)**
~30 m² with 4 facets	~20 m² with 80 mini-facets	~10-16 m² with three facets
Thin-glass, sandwich structure	Active adjustment of each facet	Fully pre-fabricated
Minimal support structure	Self-aligning facets	Drop in place
Tilt-roll with linear drives	Coarse tracking of support frame	Self-aligning
Autonomous power/control		Autonomous power/control

Heliostat technology streams

Mirror optics and structure

Sandwich panels make efficient use of materials to achieve strength and rigidity, and can contribute significantly to the overall structure. ANU leads development of a sandwich panel mirror technologies, and is developing methods of characterising mirror panel performance, including consideration of wind-structural-optical interactions.

Aerodynamics and wind loads

Heliostats are subjected to drag and lift forces, overturning moments and structural vibrations. The University of Adelaide leads experimental wind tunnel and analytical CFD investigation of heliostats in both stowed and operating conditions, as well as investigation of wind loads downstream of neighbouring heliostats.

Field design
Optimisation of a heliostat field layout is mainly focused on minimisation of losses associated with the cosine factor, spillage, blocking and shading. CSIRO leads development of methods to better place heliostats to use land area more efficiently, and increase heliostat density, and has developed a software package called HELIOSTAT STUDIO to allow better heliostat design decisions related to factors such as heliostat shape, size, and tracking style.

Smart control
Born from the concept of the “drop in” heliostats with self-calibration, a suite of smart sensors and control systems is under development, led by CSIRO. This includes smart sensing for heliostat position and orientation, optical closed-loop sun tracking and wireless communication.

Techno-economic analysis
Led by CSRIO, a standardised costing tool is being developed to aid heliostat development, including self-fill categories and a high degree of flexibility to suit developers of either full heliostat concepts, or sub-components.

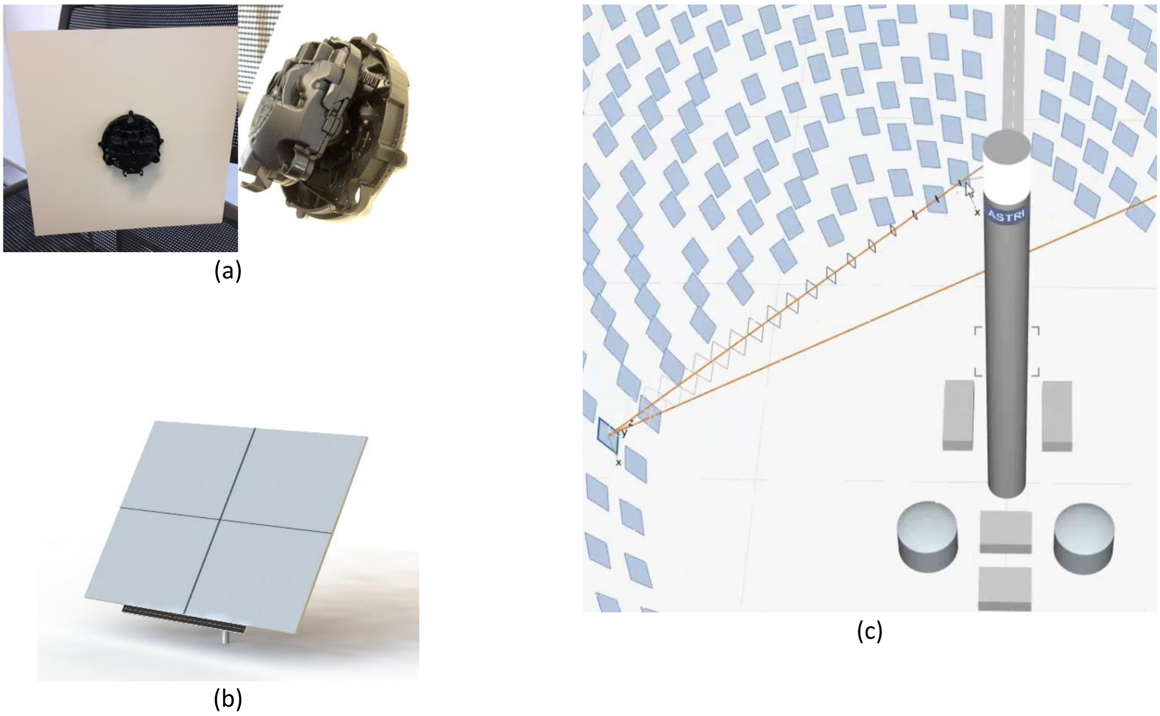


Figure 4.7. (a) Mini-facet concept, with the automotive actuation device (b) the 30m^2 sandwich panel heliostat concept and (c) a snapshot of analysis in HELIOSTAT STUDIO.

Key Findings

Some of the achievements are as follows:

- Development of optical/structural modelling and measurement tools including photogrammetry, FEA, MCRT, flux mapping, all set for upcoming structural optimisation work, particularly on sandwich panels. Results of this work can be directly applied in partnership with industry in the development heliostat mirrors and support structure, or in improving existing designs by minimising materials and improving performance.
- Wind loads and wind tunnel testing. We have significantly advanced the scientific aspects of wind load analysis. Results from this work can be used in the design of heliostats to further optimise the dimensions of the heliostat mirror, pylon and support structure with respect to the approaching turbulence characteristics at a particular field site. Furthermore, the spacing between rows of heliostats in the field can be optimised to minimise the wind loads on in-field heliostats and thus reduce the cost and land area required for the installation of a solar field in a power tower plant.

- Control systems prototyped, making use of low cost sensors potentially enabling on site alignment and continuous calibration at minimal cost. Development of low-cost smart sensors can enable industry to reduce cost in installation and field calibration for new heliostat designs, and could also potentially be retrofitted to existing plants to improve controllability and tracking accuracy.
- Optical analysis tools allowing easy evaluation of field-level performance impact of design decisions e.g. tracking and shape. The HELIOSTAT STUDIO software can be used in partnership with industry to measure the impact of proposed design changes on annual performance, and allow more informed decision.

Notably, ASTRI has formed a well-integrated and functioning multidisciplinary team covering optical, structural and aerodynamic know-how. The high level of interdisciplinary know-how across the team is unusual compared to other heliostat research groups globally.

4.4.2 HIGH TEMPERATURE SOLAR RECEIVER DESIGN

Three high-temperature solar receiver design concepts are being evaluated as part of ASTRI's research: a flux-optimised sodium receiver, a falling particle receiver, and an expanding-vortex particle receiver. The receiver technologies under development form part of a set of integrated plant configurations, with the receiver designed to operate under high-flux (~2 MW/m2) and to achieve high efficiency with outlet temperatures in the range 650–850°C.

Key Research Challenges for High Temperature Receiver Technologies

Receivers play a fundamental role in CSP systems, as the optical focal point in the solar concentrator and the place where difficult high-temperature heat transfer must take place with minimal losses. Within ASTRI (and in other international research programs) there is a strong focus on system configurations that operate at high temperatures, compatible with sCO_2 Brayton cycles. Thermal-to-electrical conversion efficiency above 50% is possible, but requires temperatures exceeding the limits of current molten salt receiver and storage technologies. Therefore, in parallel with the power cycle development, there is a need to develop advanced, high-temperature receiver technologies with different heat transfer media.

High Temperature Receiver Development Activities

A detailed scoping study was carried out as a precursor to the research work in the project. The study included a review of the many high-temperature receiver options (solid particle receivers of various types, tubular receivers, liquid metal receivers, volumetric receivers, falling film receivers), reviewed practical challenges relating to materials, coatings, corrosion, etc, and included an internal ranking process to assess which concepts should be taken forward for further research based on the criteria including potential for high performance, economic feasibility, technical risk, and stage of development. The decision to focus on sodium and particle receivers was a result of the findings of the scoping study.

The project was then structured around the three receiver concepts selected for development - the sodium receiver, falling particle receiver, and solar expanding vortex receiver – let by ANU, CSIRO and University of Adelaide respectively.

Sodium receiver (ANU) The scope of the R&D focussed on key design challenges, particularly flux limits relating to material stresses, and geometric optimisation of receivers starting with a simple cylindrical base case (Figure 4.8) and then using multi-objective optimisation methods to develop more complex but better performing geometries suited to higher solar flux levels. Performance predictions have been made through the development of a fully integrated thermal, optical and hydrodynamic model. In parallel, ANU has designed a sodium test laboratory adjacent to a high-flux solar simulator, which will be used for a range of receiver prototype and materials compatibility tests.

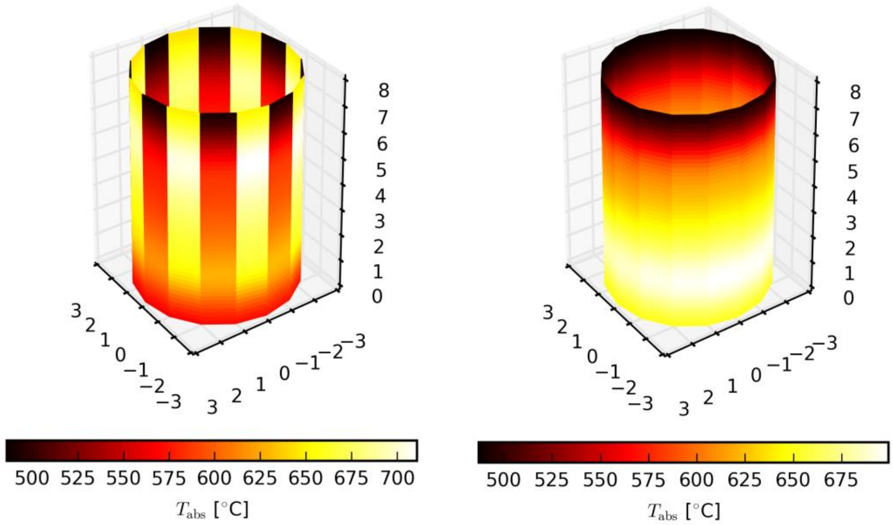


Figure 4.1. Absorber temperature distributions for a sodium receiver with 8 flow-paths, going down then up (left), and 16 flow-paths going down (right).

Falling particle receiver (CSIRO). A model was developed to simulate the complex radiative and hydrodynamic heat transfer that occurs for this receiver concept. The model was validated against experimental data obtained by ASTRI partners Sandia National Laboratories. Based on the findings, a new concept for achieving better control of particle residence time was developed. The concept is presently being patented. An experimental rig for cold-flow testing of this new concept is well developed, with testing to commence in mid-2017.

Solar expanding-vortex receiver (University of Adelaide). The development of the Solar Expanding-Vortex Receiver (SEVR) builds upon previous work on a solar vortex reactor for reacting particles in a controlled gas environment. The ASTRI SEVR concept (Figure 4.9) has several distinctive features: it uses non-reacting particles for energy absorption and transport, and is down-facing, inclined towards the heliostat field. Investigations, both CFD and experimental, have focussed on the aerodynamic mechanisms to control the vortex, and to reduce the prospect of particle deposition on the inlet window as well as increase particle residence time. Performance models are also under development, and further prototyping and testing plans are well advanced.

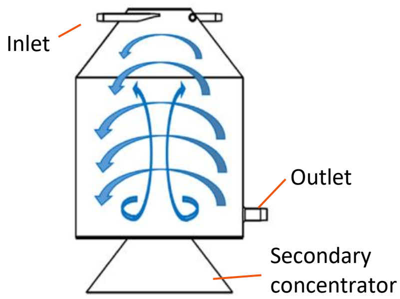


Figure 4.2. Simplified representation of the 3D flow-field within the SEVR

Industry Applications

Sodium receiver

- A thorough scoping study identified the potential performance benefits of sodium receivers when operating at elevated temperatures and at high solar flux.
- High-flux operation is particularly vital for improved performance relative to existing receiver technologies, and therefore it is important to understand how thermal stresses in tubes limit flux. This is

one of the key focusses of research in this project, and has relevance not only to sodium receivers, but to the development of all tubular receiver designs exposed to elevated solar flux.

- Methods for geometric optimisation of receivers have been advanced within ASTRI and applied to the design of sodium receivers. However, the methods have much broader applicability for solar receiver design, and in a recent example, were used for the design of the SG4 dish receiver at ANU, which in 2015 achieved a record 97.1% solar-to-thermal efficiency.

Falling particle receiver

- Using the heat transfer model for estimating solar energy absorption by the falling particle curtain, the overall solar energy absorptivity of a 6m high falling particle curtain was calculated for different flow rates and particle sizes. Receiver performance was estimated under full load and part load conditions.
- Concepts for a scaled-up receiver employing four cavities were analysed , with preliminary performance predictions for different sun positions (Figure 4.10).

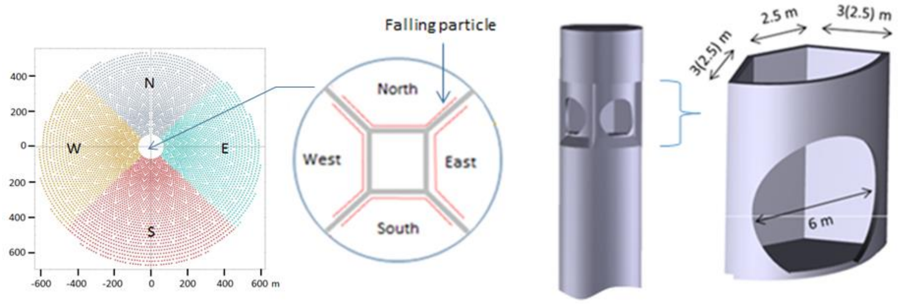


Figure 4.3. Concept geometry of a receiver employing 4 cavities compatible with the ASTRI reference field optimised for a system in Alice Springs, Australia, (assumed heliostat size: 6.1 m x 6.1 m, number of heliostats: 6,177, tower height: 92 m).

- Major development of falling particle receiver technology is proposed as part of the US Sunshot Gen 3 program, including a multi-megawatt demonstration system led by Sandia National Laboratories and involving numerous industry partners. ASTRI has been invited to partner in this proposal.

Solar expanding-vortex receiver

- The SEVR has been shown to overcome several issues associated with previous vortex receiver designs, in particular relating to the propensity for particles to egress through the aperture and deposit onto the cavity window. Particle deposition has been reduced to the extent that there is the potential for the receiver to be operated without the need for a window.
- A residence time distribution dependent on particle size can be achieved such that larger particles, requiring longer residence times to heat-up to a given temperature, are preferentially retained within the receiver relative to smaller particles. Therefore, a more uniform temperature distribution of the directly irradiated particles can be achieved.
- In addition to the current non-reacting particle receiver case, the concept is suited to a range of reacting particle applications, including outside the power-generation area, such as in minerals processing applications.

4.5 Increasing Capacity Factor

A critical determinant in the LCOE of weather-dependant generators is the capacity factor, or how many hours of the year the power block or turbine can operate to produce electricity that can be sold into the grid. The capacity factor of a CSP plant can be increased by the inclusion of thermal storage, hybridisation, alternative field designs and adapting overseas technologies to the Australian market.

ASTRI's approach is to develop the materials needed for low cost storage and analyse the system impact benchmark against overseas technologies and create the unique Australian value proposition. The development of cost effective storage technologies is considered a prize that can differentiate CSP from other weather dependent generators. Both thermos-physical and thermochemical storage are major capabilities of research within ASTRI.

ASTRI is able to provide highly skilled engineers, master, PhDs and early career researchers on design, construction and evaluation of thermal energy storage materials and systems. Specifically ASTRI is able to provide the following capabilities:

- Screening and identification of materials properties: including FactSage, HSC Chemistry and a low cost desktop tool to evaluate potential redox materials based on first principles calculations.
- Testing of thermophysical properties of high temperature materials: melting point, specific heat capacity, and enthalpy of phase change, enthalpy of reaction, density, conductivity, corrosion, materials compatibility and thermal stability. The teams also implemented experimental models to obtain kinetic parameters and mechanisms.
- Experimental demonstration at prototype level of high temperature thermal energy storage concepts from molten salt and liquid metals to particulate media. Design of components to provide integration of the storage systems with other components of the plant including sodium/salt heat exchanger.
- High temperature complex receiver/reactors expertise.
- High accurate techno-economic analysis of usual and novel CST systems.
- Design and development of low cost tailor made PCM storage systems to suit particular temperature and operational requirements.
- Testing for materials compatibility, finding suitable material combinations and providing advice on material selection as well as testing for materials compatibility,
- High Temperature Storage System Design: Capabilities include the development of low cost high performance designs for a range of operating conditions
- High temperature Storage System Testing: Using our recently commissioned high temperature test facility, laboratory scale prototypes can be tested under controlled charge and discharge scenarios up to 900°C.

4.5.1 HIGH TEMPERATURE THERMAL STORAGE

The high-temperature storage project was established to advance the state of the art in thermal energy storage (TES) for CST power plants, through the development of several specific technology concepts, together with parallel activities in common-basis performance assessment and materials development. The project has also been developing a sophisticated integrated process and techno-economic model to establish the value proposition of CST with storage as well as investigating potential future thermal storage options.

High Temperature Thermal Storage Technologies

The state of the art in TES is molten nitrate salts, which are limited to an operating temperature of ~580°C and whose temperature decreases with depth of discharge due to the use of sensible storage. There are a wide range of potential options to increase the temperature of TES, whilst also increasing energy density and/or enabling constant temperature discharge, some of which are shown in Figure 4.11. The team has developed a systematic approach to review the state of art and prioritise them, accounting for compatibility with other components in the ASTRI systems. From an initial scoping study, several areas were selected for technology development, as indicated by the ovals in the Figure 4.11.

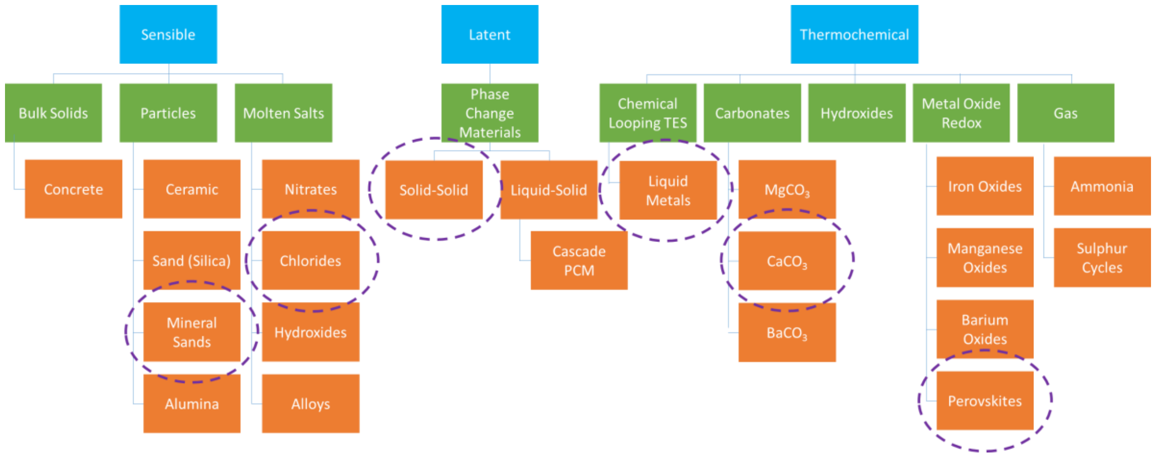


Figure 4.4 Selected high temperature storage options showing those selected for assessment within P21 (circled)

The key technologies being targeted by ASTRI can be summarised as follows:

- **Sensible heat storage in particles:** Particles offer the potential to operate at much higher temperature than molten salts, and are a priority for ASTRI Horizon 3 (H3) for power and Horizon 2 (H2) for fuels. ASTRI is coordinating this work with the Solar Paces Particle Technology Working Group targeting low-cost particles and efficient storage systems that are compatible with both our the power and fuels systems.
- **Sensible compatible with molten salts:** ASTRI is targeting Chloride salts, which offer the potential to reach higher temperatures than the commercial nitrate salts for H2 and H3 systems;
- **Solid-Solid PCM**: ASTRI is targeting specific phase change materials as an option for H3. These offer temperature compatibility with ASTRI cycles and energy storage at constant temperature;
- **Thermochemical (carbonate looping)**: ASTRI is targeting carbonates as an option for H3. These offer increased mechanical strength to cycling, temperature compatibility and high energy density;
- **Thermochemical (chemical looping):** ASTRI is targeting novel liquid metal oxides as another option for H3 technology. These offer potential for very high resistance to cycling and high rates of heat and mass transfer, together with high temperature and energy density;
- **Thermochemical (redox perovskites):** ASTRI is targeting novel perovskite particles as a class of particle for H3 systems that offer potential for a step-change in performance over other solid-phase redox materials being explored internationally.

ASTRI High Temperature Thermal Storage Research Activities

Experimental activity:

While the research encompassed a range of technologies and activities at different institutions, a common approach was employed to move the potential options forward along the TRL scale through a staged development:

1. **Establishment of laboratory scale equipment**: Three new, specialised facilities have been established for each storage program, as shown in the photographs below. The fourth program has, involving perovskite redox storage, is undertaking a desktop design while additional resources are being sought.

2. **Lab-scale testing of materials and reactors** have been completed for five of the six technology programs. Three reactors have been demonstrated at lab-scale using novel thermal storage materials and one system (a solid-solid PCM) is making good progress after an initial delayed due to a late recruitment.
3. **Construction of lab scale demonstration equipment** is planned for mineral sands and novel molten salts, while completion of the reactors for thermochemical looping and chemical looping activities are in progress.
4. **Discontinuation of activities:** Two storage concepts will be discontinued. The work on solid-solid PCM has been dropped from the program, while research on perovskites has been redirected from application in storage to application in fuels, through P42.

Modelling activity:

These objectives were focussed towards obtaining a software platform that evaluates dynamic performance of different technologies and calculates LCOE.

- **Selection of model software platform:** Modelica (modelling language) & OpenModelica or Dymola (developing environment).
- **Review of forecasting options**: SAM was used as a reference software of CST techno-economic analysis. It was found that is not flexible enough for novel system configurations. Therefore, the modelling task was established to produce be able to simulate novel CST technologies.
- **Initial techno-economic assessment of technologies compared with molten salt:** A Modelica library of CST components was built and system model was implemented. Reference case was completed.
- **Fully operational beta model of techno-economic model:** Extension of the Modelica library with novel components. Na-PCM-sCO_2 system model completed.
- **Multiple scenarios assessed:** Preliminary techno-economic comparison between reference case and Na-PCM-sCO_2 system.

Industry Applications

TECHNOLOGIES	TRANSFERABLE KNOWLEDGE
Sensible Particle Storage	• The outcome of this study will provide the understanding of how high temperature particles can be charged and discharged from a storage with a minimum mechanical component. This knowledge can applied not only on CSP but also on minerals processing industry.
High temperature molten salt storage	• Novel ternary chloride salt mixtures were identified and tested, and showed a promising combination of low cost and high specific heat capacity, and an acceptably low melting point (e.g. the ternary NaCl + KCl + $MgCl_2$ salt mixture). The cost of the storage material in terms of USD/kWh is around 60% lower than current state-of-the-art solar salt material. In addition, thermal stability was found to be very good at temperature exceeding 700°C, if an inert gas environment is maintained in a closed system. Sensible salt storage using chloride salts could be configured as a two-tank system, the same as present commercial plants. Heating the fluid could be direct in a receiver, or indirect via a heat transfer fluid such as sodium. Both options are being investigated in ASTRI, and as part of a wider collaboration with partners in the US.
Carbonate looping thermochemical energy storage	• High temperature materials investigation: the need of evaluating long term thermal cycling experiments in materials is critical for CSP. Our expertise can help industry to understand the role of the thermal properties, chemical kinetics and materials degradation into CSP technologies. • Experimental demonstration at prototype level: 1-kWth is being developed in the project to evaluate the performance of the carbonate storage under solar-simulated conditions. This research is required to fill the research gaps into particle reactors and receivers. Improving receivers can help industry to understand the key factors to affecting efficiency under high fluxes of solar radiation.
Redox looping Perovskites Metal Oxides	• Development of a systematic methodology to evaluate thermal properties of materials using a desktop analysis. This can provide to industry a low cost tool to pre-select materials before addressing any costly experimental test

Liquid Chemical looping thermal energy storage	•	The unique thermo-chemical and thermo-physical properties of the liquid metal/metal oxides offer strong thermodynamic potential for use as a storage medium and heat transfer fluid (HTF). Nevertheless, harnessing this can be a challenge due to the corrosive nature of many metals at high temperature. We have therefore undertaken a range of assessments to identify applications and reactors that appear to have potential to harness the benefits and avoid the challenges.
	•	The application of molten metal oxides to a chemical looping process offers the potential to achieve phase change, sensible and/or thermo-chemical energy with an energy density approximately 6 times of the molten salt. This enables more compact devices with compatibility for integration to efficient gas turbine combined cycles. Molten metals also do not degrade with cycling, although they have other challenges as noted above.
	•	A bubble receiver/reactor is under construction at UoA, which can be employed for either the reduction of a molten metal oxide or the heating of a pressurised gaseous working fluid e.g. air or CO_2. The first target is for use with the super-critical CO_2 power cycle to minimise both the number of components and the system exergy loss.
System Modelling	•	Our expertise in CST object-oriented modelling coupled with economic analysis can help industry on decision making process and de-risk novel CST technologies and processes.

4.5.2 PHASE CHANGE MATERIALS (PCM)

The aim of this project is to develop and characterise reliable low cost phase change materials (PCMs) and to develop cost competitive thermal storage systems which can be used effectively in CST plants, specifically developing PCM systems compatible with ASTRI configurations.

Key PCM Challenges for CSP Applications

Thermal energy storage media store thermal energy either in the form of sensible heat, latent heat of fusion or vaporization, or in the form of reversible chemical reactions. Today, sensible heat materials in the form of synthetic oil and molten salt stored in two-tank systems are the most widely used storage materials in large-scale CSP plants, while systems that utilize latent heat, thermochemical, and other sensible heat materials are still being developed.

Although there has been significant development in sensible heat storage systems for CSP plants due to their ease of heat transfer and simplicity of the storage system, techniques that take advantage of latent heat to store thermal energy can offer further benefits. Latent heat storage approximates an isothermal process that can provide significantly enhanced storage quantities when compared to sensible storage systems of the same temperature range. Isothermal storage is an important characteristic because solar field inlet and exit temperatures are limited due to constraints in the heat transfer fluid (HTF), solar field equipment and power block. With the move to higher temperature CSP systems compatible with heliostat technologies leading to higher thermal efficiencies, current sensible storage materials are reaching their maximum temperature limits. Since the storage capacity of a latent heat system is governed mainly by the enthalpy of phase change, this can potentially enable a smaller, more efficient lower cost alternative to sensible heat thermal storage systems at the desired temperatures.

With this in mind, new low cost reliable PCMs need to be introduced and used for modelling, designing and building new reliable and responsive systems. Furthermore, the most economical system configuration matching the material, temperature and operational requirements of the CSP plant needs to be established.

ASTRI's PCM Research Methodology

New methods needed to be developed to characterise the thermophysical properties of high temperature PCMs which are accurate, simple and less expensive than existing methods.

A database of new potential PCMs with lower cost and better thermophysical properties was created with a shortlist of eutectic salts and metals to cover the required operational temperature range was created on the basis of cost, chemical compatibility and cycling testing .

Potential materials for construction of the storage tanks needed to be investigated and the best candidates were tested for their compatibility and reliability with candidate PCMs.

Computer models were developed of various storage system configuration containing different PCMs. These were used to carry out simulations to determine the thermal performance of the systems. Different construction materials, system configurations, thermal storage media and heat transfer fluids (including sCO2) were investigated.

Prototypes were built for the two most promising storage system types and these will be extensively tested using the UniSA high temperature test facility. One of the prototypes is of a coil-in-tank eutectic salt PCM configuration and the second is a cascade (hybrid) system containing both sensible (rocks) and latent storage (Aluminium PCM) materials.

Research Findings

Two storage system types were investigated – coil-in-tank whereby the PCM is contained in the tank and pipes are used to carry the HTF, and a packed bed.

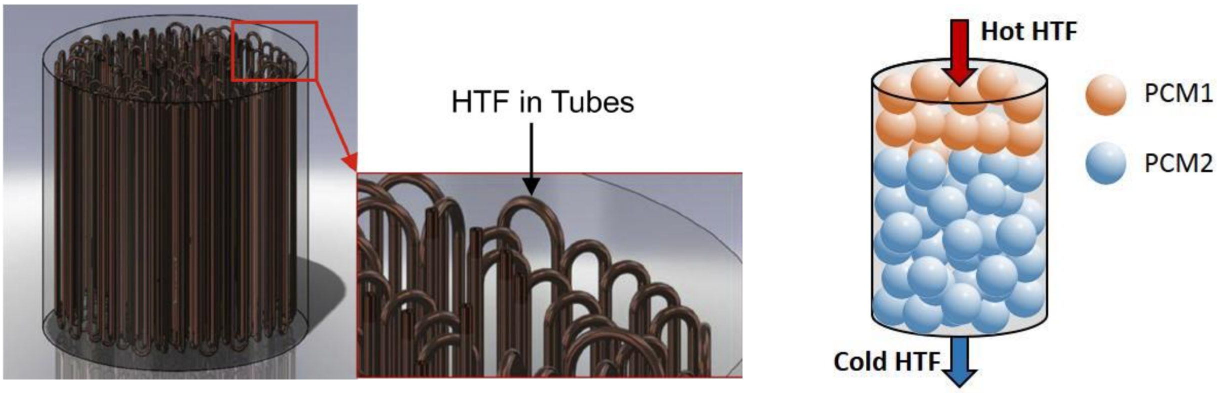


Figure 4.12. Schematic of coil-in-tank and packed bed system (with two different PCMs)

Two types of encapsulated PCMs systems were investigated. One was with PCM contained in shells, and the other a PCM composite.

Testing was conducted for PCM encapsulated in a geopolymer shell. A problem was found with the PCM leaching into the geopolymer. However, the capsules maintained strength and durability during the test. Suitable coating materials for the geopolymer were investigated but no solution has been found to date.

Figure 4.13 Geopolymer capsule showing leakage after 10 cycles

Considerable experimental work was conducted on encapsulated PCMs based on a composite material structure. A series of cost effective and high temperature salt ceramic composites with high thermal stability and good thermal conductivity were developed, such as α-alumina/mullite-based Na_2SO_4-NaCl composite with melting temperature of 626 °C. Various proportions of ceramic materials and salts were tested to determine the optimum condition of encapsulation. The salt Na_2CO_3-NaCl was tested in a CO_2

atmosphere and found to be very stable without weight loss at up to 700^oC. Furthermore, the energy storage density after 300 thermal cycles changed very slightly.

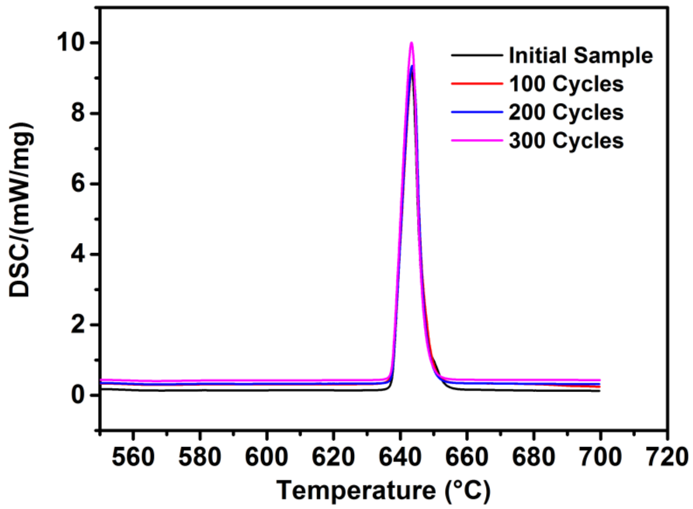


Figure 4.14 Comparison of initial sample with 100, 200 and 300 cycles of eutectic Na2CO3-NaCl in a CO2 atmosphere.

A new nitrogen atmosphere chamber for testing corrosion in metals in nitrogen has been designed, developed and tested. Preliminary testing has shown than the corrosion rate in stainless steel samples is reduced in a nitrogen atmosphere.

Figure 4.15 Nitrogen atmosphere chamber with samples (left) and chambers placed in furnace (right).

Testing the corrosion of various other materials has also been undertaken. Carbon steel 1008, duplex steel 2205, stainless steel 316 and Inconel 601 in two near eutectic mixtures of $NaCl+Na_2SO_4$ and $NaCl+Na_2CO_3$ have been tested. A combination of microstructural, electrochemical, and Kelvin probe force investigations were carried out to analyse the impact of cold-working versus annealing on the interaction of Inconel 601 and a eutectic molten carbonate salt at 450°C. Annealed Inconel 601 showed lower corrosion susceptibility compared to that of the cold-worked sample.

An apparatus for measuring the thermophysical properties of high temperature PCMs based on the T-history method has been designed, constructed and commissioned. Initial test results using this apparatus showed a significant difference between existing and literature data due to high heat loss between the samples and ambient air. Modifications are currently being made to reduce this.

Modelling of heat flow in both charging and discharging processes of PCM systems has continued using both Fluent and COMSOL. These models aided the design of the laboratory-scale prototypes which were constructed and will be tested. A new concept of charging and discharging thermal storage systems, also applicable to heat transfer in heat exchangers, was also modelled and found to improve heat exchange by up to 30%. A patent has been filed on this method.

A new methodology was developed for system optimisation for least cost. It was used to compare the coil-in-tank and fin based PCM energy storage systems. This facilitates system design. An analysis conducted using this technique showed that for tube geometries, the dominant property is the thermal conductivity of the PCM, with a 20% larger thermal conductivity resulting in a 100% cost difference. However, for coil-in-tank geometries with good thermal conductivity enhancement, the optimum geometry is based on the energy density, with the thermal conductivity of the PCM playing a smaller role. The cost of the tube material is found to play a large role, and because of the uncertain effects of corrosion products on PCM performance, expensive containment materials with large costs require further research as a viable alternative to cheaper containment materials with potentially less corrosion resistance.

Cost estimates were determined for several configurations of high temperature thermal storage systems utilising PCMs as the energy storage media. The systems studied included a two-tank molten salt system, an encapsulated PCM system and a thermocline system. Costing included the tank, storage material, piping and additional equipment such as heat exchangers, pumps and heat tracing elements. The costing was conducted for various differences in charging and discharging temperatures. The major conclusions of this study are listed below:

- Cascaded encapsulated PCM systems whereby PCMs with different storage temperatures are used, resulted in a lower cost for all temperature differences.
- The thermocline system utilising a geopolymer as the filler material resulted in a lower cost than a similar system utilising quartz/rocks as the filler material for all temperature differences.
- The encapsulated PCM system has a lower cost than the thermocline system with the geopolymer for a temperature difference less than 200 °C for both molten salt and air heat transfer fluids.
- For a temperature difference of 300 °C, the encapsulated PCM system, thermocline with quartz/rock and the thermocline with geopolymer filler result in a cost saving of 50 %, 35 % and 60 % when compared to the two-tank molten salt system.
- For a temperature difference of greater than 200 °C, the cost of the air-based encapsulated PCM and thermocline systems are approximately equal.
- For all heat transfer fluids (air and molten salt) the direct system results in a lower cost estimate than any indirect system.

The embodied energy and CAPEX of three high temperature thermal energy storage options were estimated. Of the systems studied, the encapsulated PCM system resulted in the lowest value with an embodied energy equivalent to 47.8 TJ/MWht. The coil-in-tank had a similar embodied energy to the encapsulated PCM system (65.2 TJ/MWht) whereas the sodium two-tank system had a significantly larger embodied energy (1,528 TJ/MWht). From these estimates the encapsulated PCM system resulted in the lowest CAPEX ($11.2/kWht) followed by the coil-in-tank ($19.2/kWht) and sodium two-tank ($43.4/kWht) systems. The encapsulated PCM, coil-in-tank PCM and liquid sodium two-tank system have been found to have energy payback periods of 1.2, 1.7 and 38.8 months, respectively.

4.6 Improve CSP System Efficiency

A major emphasis in ASTRI has been to improve efficiency through novel high-temperature cycles, advanced dry and hybrid condensers, receivers capable of high flux and/or high temperatures, and polygeneration. This requires a balance between the lower cost of power derived from higher efficiency and the higher cost of new materials early in their development phase.

ASTRI has developed world class capabilities in Supercritical CO2 Power Block Technology. ASTRI's capabilities in this area include:

- Cycle modelling of sCO2 systems. Tools and know how to accurately evaluate the performance of cycles and how this is affected by ambient conditions. (Figure 2)
- Cycle modelling tools validated against our own high pressure refrigerant and sCO2 test loop
- Expertise in designing and commissioning high pressure closed loop cycles including appropriate data acquisition systems.
- Experience in operating high pressure test loops.
- Expertise in the development of control systems and data acquisition systems for closed loop test cycles.
- Capabilities to analyse rotor-dynamics of high speed turbomachinery installations.
- Design tools and know-how for the radial inflow turbines operating with sCO2.
    - 0-D codes for preliminary design (Figure 1)
    - CFD capabilities
    - Inlet plenum and diffuser simulation codes (Figure 3)
- Ability to simulate and optimise the aerodynamics of sCO2 turbines.
- Modelling tools that allow the accurate prediction of foil bearing operation. These include the ability to predict steady state operation and to predict transient response to rotor dynamic excitations.

The research program has also examined alternative power block designs and techniques for optimising power block design and selection when off design conditions associated with CSP plant are considered. ASTRI's research uses a novel multidisciplinary approach integrating the suitability and cost of different power plant concepts. The research is delivering new concepts for Concentrated Solar Thermal power cycles though considering the effect of system design decisions.

The developed numerical codes can now be used to assess the design options for both topping and bottoming cycles (e.g. waste heat recovery). Using the developed charts, decisions can be easily made on the temperature, pressure ratio and working fluid to use. Additionally, the quasi-steady state turbine code is suitable to be used in developing the mean-line design of systems which are expected to be exposed to temperature and mass flow fluctuations.

4.6.1 SUPERCRITICAL CO2 POWER BLOCK

The aim of this project is to develop power block technology for a CST plant using a supercritical CO2 Brayton cycle. The power block technology selection is appropriate for power scalable in the range 0.3 – 5 MWe in dry areas. Specifically, a radial in-flow configuration has been pursued for the turbine and a natural draft hybrid cooling tower for the cooling system. There are three reasons why ASTRI is pursuing a supercritical CO2 power cycle for its pilot CST configuration:

i) It is more efficient than steam cycle
ii) It uses a simpler and more compact power block configuration, therefore will be cheaper
iii) In our pilot plant range (0.3 – 5 MWe), it can be scaled down and up with no efficiency penalties (if using a radial in-flow turbine configuration as chosen by the ASTRI team)

The missing technologies are the turbine and a suitable cooling system. The ASTRI team in its first four years achieved significant progress in both areas.

Turbine

At the present, there is no supercritical CO2 turbine in the market. There are projects around the world but they have not delivered a turbine yet and they are aiming for utility-scale plants, not the ASTRI plant size range (0.3 – 5 MWe).

A radial-in-flow turbine configuration was selected (as opposed to the axial configuration selected by the US project). This was because a radial-in-flow turbine can be built in the size range from 1-MWe up to 30-MWe without significant turbine efficiency penalties. The turbine efficiency is important. Simple cycle studies show that 1% in turbine efficiency is equivalent to 0.42% in cycle efficiency. A significant part of the turbine efficiency loss is due to leakage from the turbine. Leaking 1% of the fluid due to poor sealing in the turbomachinery components can reduce the overall efficiency by 5%. At small turbine sizes, the radial-in-flow turbine configuration offers better sealing capability and this confirms the ASTI turbine choice and the importance of delivering an efficient and well-sealed turbine system.

ASTRI Turbine Research Objectives

ASTRI's research has two research questions:

- What cycle configurations and what cycle operating conditions are most beneficial for CST? (Most beneficial means: Highest thermal conversion efficiency across the mix of operating conditions encountered by a CST installation throughout the daily and annual cycle)
- How to design a working and efficient sCO2 turbine for a 0.3-5 MW scale CST installation? Key challenges are developing a design that can cope with the high pressures, temperatures, and density of the sCO2 and how to manage the working fluid.

Methodology and Outcomes

Through a combination of numerical and experimental approaches, significant progress has been achieved towards both objectives.

For objective one we have been developing system and cycle models that allow the accurate simulation of a sCO2 cycle within CST applications. The models correctly capture the effects of changing boundary conditions, component dimensions, and component performance to allow calculations of cycle performance for different cycle configurations and how this is affected by changes in the ambient conditions. For example Figure 4.16 shows the system for two cycle configurations incorporating direct and in-direct cooling. These system models are accompanied by optimisation routines to generate cycle configurations that maximise benefit for CST. As models are only as good as the assumptions they are based on, we have also taken care to collect validation data. The high pressure test loop at Pinjarra Hills puts us in a unique position that we can validate component and system models using our own experimental loop.

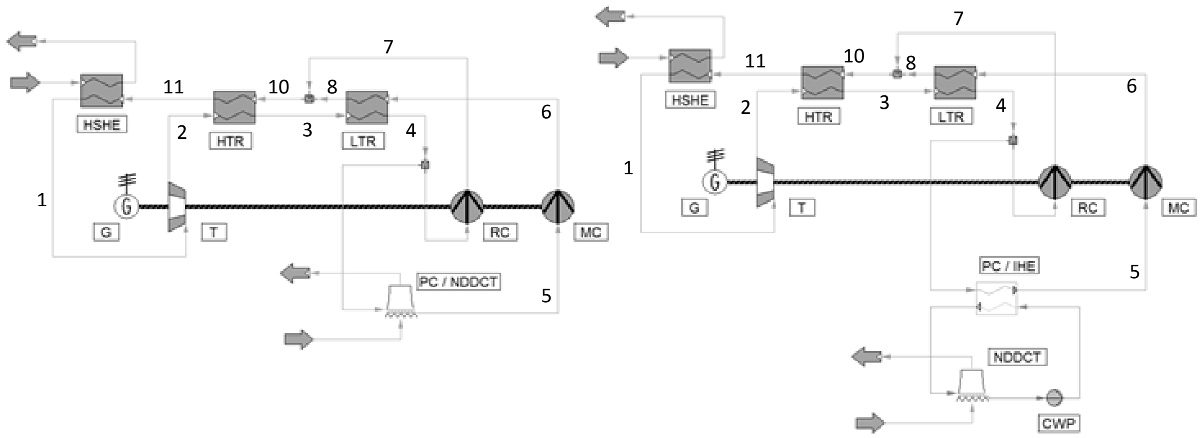


Figure 4.16: System models used for comparison of direct and in-direct cooled sCO2 cycle.

For objective two we are concentrating on the simulation of turbomachinery aerodynamics, development of design tools for individual components, and the development of prototype turbines that can be tested in our high pressure tests loop. The tools developed include 0-D preliminary design codes (Figure 4.17), detailed CFD simulation codes and optimisation routines for subsystems. A collection of these tools was used for the design of the 7kW R245fa turbine (Figure 4.18). We are continuing to test the 7kW R245fa turbine, to validate our design tools and design know how. At the same time the loop operation provides important data for the system simulation models.

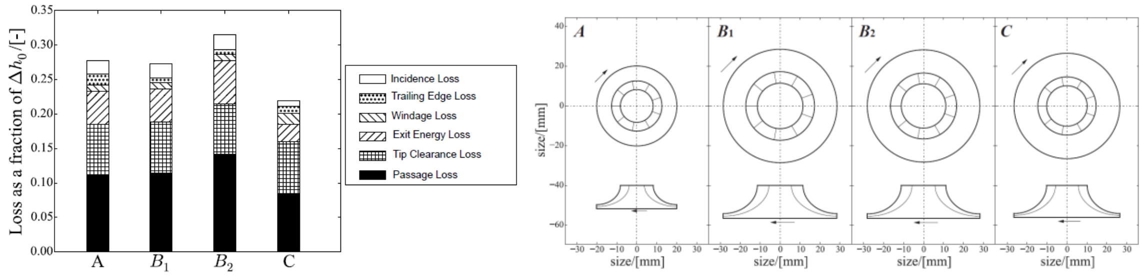


Figure 4.17: Results from a 0-D design space analysis for sCO2 turbine rotors in the 100-200KW range. Trends between turbine style and loss contributors were identified from (Publication [2]).

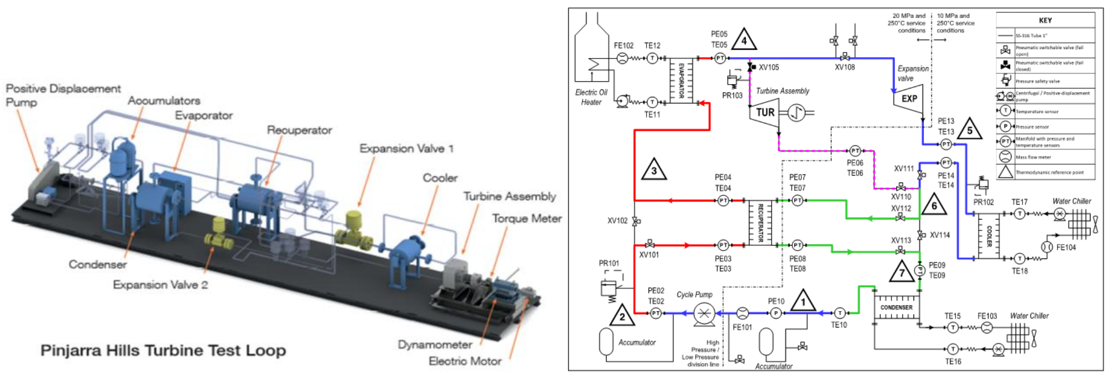


Figure 4.18: Pinjarra Hills High Pressure Test Loop. Now commissioned for sCO2 operation. With upgraded pump capable of flows up to 0.25 kg/s and maximum temperature of near 250°C.

The system studies we have completed provide new insight towards how sCO2 cycles are affected by changes in energy source and ambient conditions and how the cycle can be modified in order to maximise cycle output both at nominal performance points and at off-design conditions (e.g. during summer and winter months, or if latent energy heat source is used that has a changing supply temperature). For example Figure 4.19 shows the trends of cycle efficiency for different cooling arrangements and how the cycle performance is affected by changes in ambient conditions. These studies show a clear drop of in performance, however we are now looking at ways to recover this, e.g. through inlet air precooling on hot days to reduce the air temperature down to wet bulb temperature (the wet bulb temperature is typically 15°-20° below the ambient temperature in the target CST sites). These tools findings are important when defining sCO2 power block configurations and when sizing the components in the sCO2 system (Publication [1]).

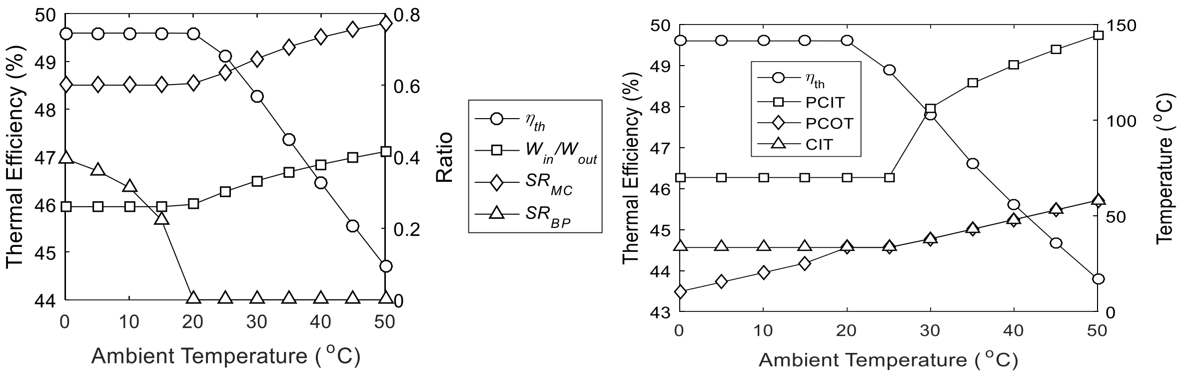


Figure 4.19: Effects of ambient conditions on cycle performance for (a) direct and (b) in-direct cooled sCO2 cycles, corresponding to cycle configurations from Figure 1.

In the area of turbine design we have developed extensive know-how in regards to the design of radial turbines. This covers the design and optimisation of the actual aerodynamic flow path, the mechanical design of the turbine hardware (rotating components, housing, seals, bearings, rotordynamics), and the design of the critical subsystems such as shaft cooling and sealing systems. This design and engineering know-how allows the design of mechanically robust and efficient turbine. The result has been new design approaches to develop for key turbine sub-systems (Figure 4.20) and the turbine rotor. All these turbine work-streams have come together to develop a first sCO2 turbine prototype (Figure 4.21).

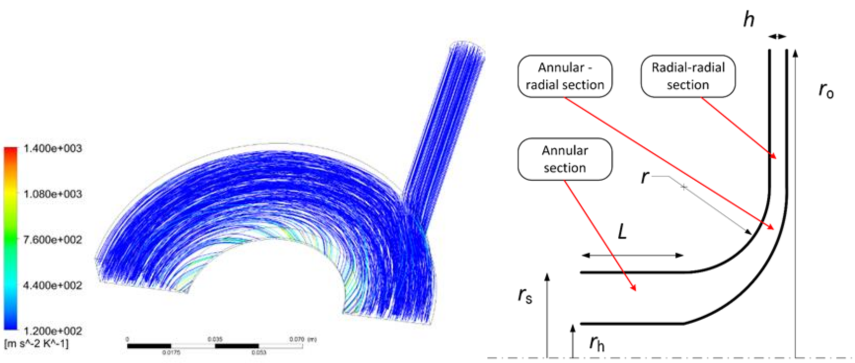


Figure 4.20: Simulation results from an optimised inlet plenum and set-up of a design optimisation of a space constraint diffuser. (Publication [4,6])

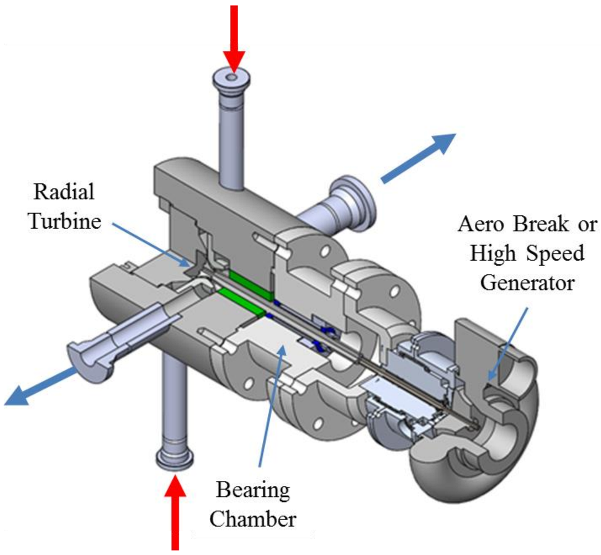


Figure 4.21: First iteration of a concept for small scale sCO2 turbine, developed in 2016

In addition we have conducted and in-depth numerical study on foil bearings and how these operate in the sCO2 environment. The outcome from this has been a suite of simulation tools that can perform steady state and transient fluid-structure-thermal coupled simulations of foil bearings (Figure 4.22). This has resulted in an improved understanding energy flows and cooling requirements that are critical to foil bearing operation. We are also using this to numerically investigate the effect of foil bearings on rotor dynamics.

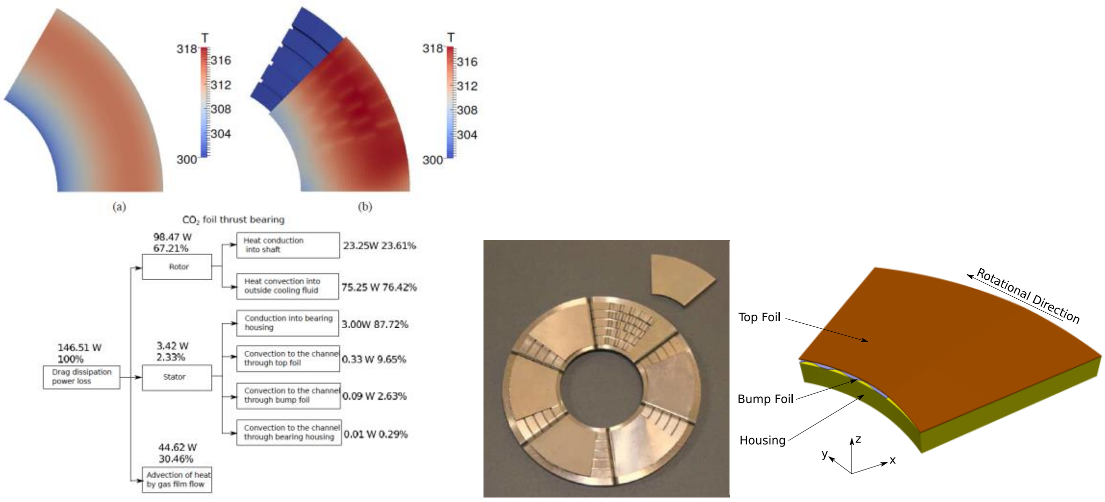


Figure 4.22: Results from a coupled fluid-structural-thermal simulation of a foil bearing operating with sCO2. Comparison to air bearings has highlighted a different distribution of heat loads, requiring a new approach to cooling. (Publication [3,5])

Publications

One patent application for a rotor arrangement that allows efficient balancing of the axial thrust loads was generated. This patent was maintained in 2016.

The following publications have arisen from the P31A turbine research stream:

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2. J Qi, T Reddell, K Qin, K Hooman, IHJ Jahn (2017), Supercritical CO2 Radial Turbine Design Performance as a Function of Turbine Size Parameters, Journal of Turbomachinery 139 (8)
3. K Qin, IH Jahn, PA Jacobs (2017), Effect of Operating Conditions on the Elastohydrodynamic Performance of Foil Thrust Bearings for Supercritical CO2 Cycles, Journal of Engineering for Gas Turbines and Power 139 (4)
4. JA Keep, AJ Head, IH Jahn (2017), Design of an efficient space constrained diffuser for supercritical CO2 turbines, Journal of Physics: Conference Series 821 (1)
5. K Qin, IH Jahn, PA Jacobs (2016), Prediction of Dynamic Characteristics of Foil Thrust Bearings Using Computational Fluid Dynamics
6. JA Keep, IJ Jahn (2016), Design method and performance comparison of plenum and volute delivery systems for radial inflow turbines, 20th Australasian Fluid Mechanics Conference
7. ZM Fairuz, I Jahn (2016), The influence of real gas effects on the performance of supercritical CO 2 dry gas seals, Tribology International 102, 333-347
8. K Qin, I Jahn, R Gollan, P Jacobs (2016), Development of a computational tool to simulate foil bearings for supercritical CO2 cycles, Journal of Engineering for Gas Turbines and Power 138 (9), 092503
9. MF Zakariya, IHJ Jahn, Performance of Supercritical CO2 Dry Gas Seals Near the Critical Point, ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition
10. Braden Twomey, Andras Nagy, Hugh Russell, Andrew Rowlands, Jason Czapla, Rajinesh Singh, Carlos A de M Ventura, Ingo Jahn (2016), The University of Queensland Refrigerant and Supercritical CO2 Test Loop, ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition
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12. J Keep, I Jahn (2016), Development of a space marching throughflow code for radial inflow turbines, ASME Turbo Expo 2016: Turbine Technical Conference and Exposition
13. K Qin, I Jahn, P Jacobs (2016), Development of a fluid-structure model for gas-lubricated bump-type foil thrust bearings, Applied Mechanics and Materials 846, 169-175
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4.6.2 EFFICIENT COOLING SYSTEMS

The conventional global CST practice does not apply in a dry continent such as Australia. The CST plants using wet cooling towers consume 2.7-3.6 m^3 of fresh water for every MWh they generate. Australian CST plants cannot afford these water consumption figures and have to use dry cooling.

The dry cooling using fan is the off-the-shelf option. However, in hot climates, conventional dry cooling using fans have severe efficiency penalties. The published data suggest that cooling fans will waste 5% of its power generation from thermal power plant. This loss will be higher on hot days. The existing natural draft cooling tower technology, i.e. cooling towers with no parasitic losses, is not applicable at the ASTRI target plant size of 0.3 – 5 MWe. ASTRI need to develop the design tools and the proof-of-concept demonstration for the future ASTRI plants to generate extra 5+% power by utilising natural draft instead of fans.

Objectives for ASTRI's Cooling Tower Research Stream

ASTRI's cooling tower research activities set out with the overall aim of developing a cost-effective cooling system for ASTRI CSP technology. This aim was divided into five goals:

i) Increase the power plant output by 5% through elimination of parasitic losses associated with running fans in conventional air coolers. Although the natural draft dry cooling technology is mature for large power plants (200+ MWe), it is not suitable for short towers required for the ASTRI target plant size range.

ii) Significantly reduce the O&M costs for CST in general and ASTRI power plant in particular. The fan O&M costs are about 50% of the power block O&M costs. By having a natural draft tower, we avoid these costs.

iii) Develop inlet air precooling technology to maintain the plant performance on even very hot days (hybrid cooling)

iv) Achieve these aims without a significant addition to the capital investment.

v) Develop tools to select and size heat exchangers for an optimum supercritical CO2 system.

In ASTRI1 we demonstrated that it is possible to use natural draft dry cooling towers at the target plant size range. We identified cross-wind as the main operational challenge for small plants and developed mitigation strategies. We created a novel cooling tower design using steel tubes and tension membranes. This design is scaleable and can be built fast at a relatively cost. Using funding from the Queensland State Government, we built a test tower on our Gatton campus to demonstrate this technology. These developments mean that we achieved the above first four objectives through design and computer simulations. We are hoping to experimentally demonstrate them on our Gatton tower in the next two years. Significant progress was also achieved in regard to the fifth objective but progress has been slower than the other four areas because of the delays in ASTRI defining a target pilot plant configuration.

Fully instrumented UQ Gatton (See Figure 4.23) tower has been extensively tested and data has been collected in various ambient conditions. The tower is the first demonstration of its type and the biggest research facility in the world dedicated to testing short cooling towers. The very first observation made was that cooling towers do not scale; not in cost nor in performance. This means that with the current tall tower knowledge of the industry, one cannot design a functional short tower. Moreover, the cost curves for tall towers cannot be extrapolated to predict the costs of short towers. We are now starting to validate in-house models and CFD tools developed during ASTRI 1.

Figure 4.23 – UQ Gatton tower (sized to cool a 1-MWe sCO_2 power block)

Modelling results (Figures 4.24 and 4.25) show that crosswind has negative effect on the cooling tower performance and a wind break wall can turn this negative effect into a positive one. Demonstration of the effectiveness of the proposed wind break wall is proposed as part of ASTRI2 research.

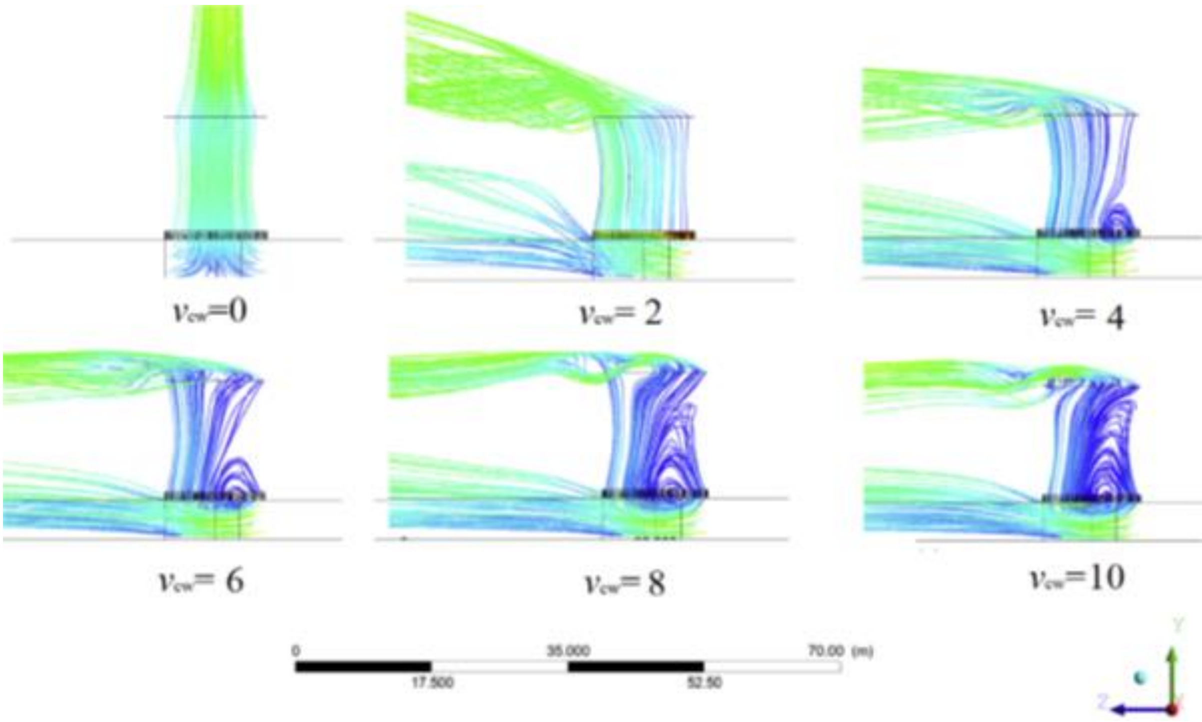

Figure 4.24 Modelling results of crosswind effect (with Gatton tower)

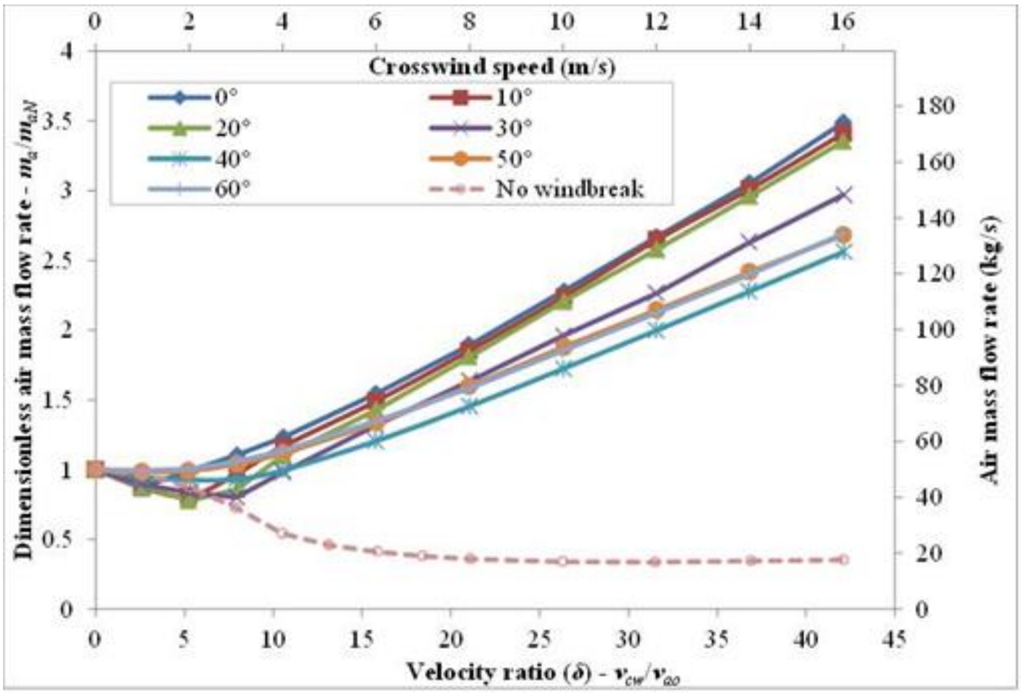

Figure 4.25 - Modelling shows windbreak wall significantly improving cooling tower performance

With regard to hybrid cooling, numerical modelling (Figure 4.26) show that an optimised spray system can achieve a 95% water evaporation to prevent the droplets reaching the heat exchanger, and a significant reduction of inlet air temperature of about 8-10 degrees. This optimised spray system will be verified in the Gatton tower tests in ASTRI2.

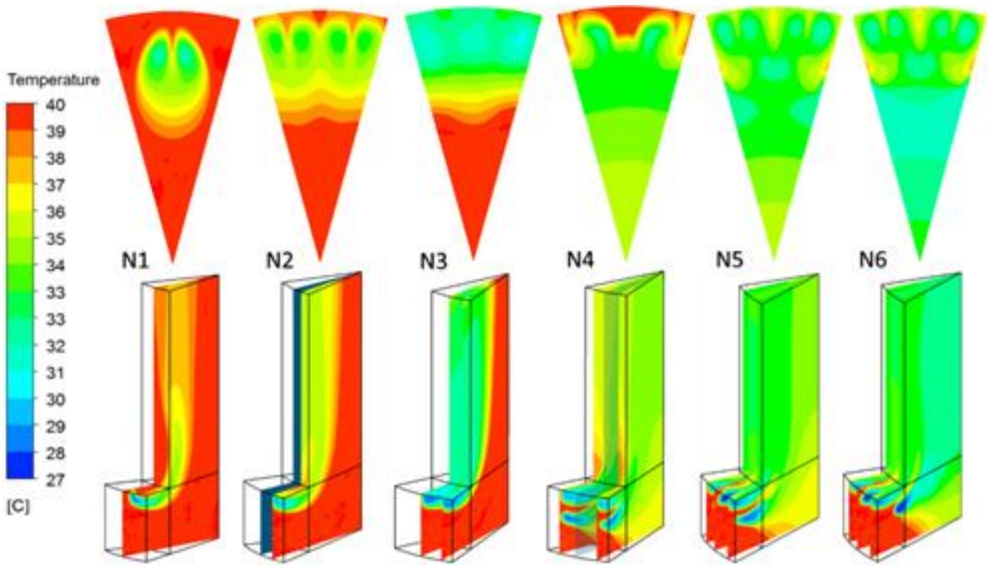

Figure 4.26 - Temperature profile in cooling tower with spray cooling

In terms of selecting and sizing supercritical CO2 heat exchangers suitable for the future ASTRI pilot plant, preliminary modelling shows that supercritical CO2 behaviour is very different from the behaviour of the cooling water in conventional towers. For example, as seen in Figure 4.27, the top and bottom surface temperatures of a 25-mm steel tube cooling supercritical CO2 may differ by 10 degrees. This is totally outside the water cooling experience, where there is no such difference. This means that air-cooled heat exchangers for supercritical CO2 cannot be designed using the conventional ACC experience. More work is needed in this area as proposed for ASTRI2.

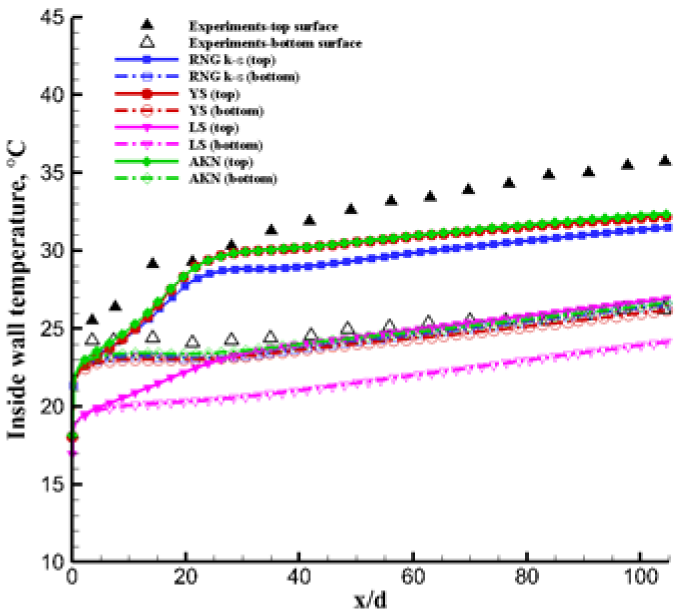

Figure 4.27 - Modelling results for sCO_2 heat exchanger with different models

Publications

1. Alkhedhair, A., Z. Q. Guan, I. Jahn, H. Gurgenci and S. Y. He (2015). "Water spray for pre-cooling of inlet air for Natural Draft Dry Cooling Towers - Experimental study." International Journal of Thermal Sciences 90: 70-78.

2. Alkhedhair, A., H. Gurgenci, I. Jahn, Z. Q. Guan and S. Y. He (2013). "Numerical simulation of water spray for pre-cooling of inlet air in natural draft dry cooling towers." Applied Thermal Engineering 61(2): 416-424.
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16. Lu, Y. S., Z. Q. Guan, H. Gurgenci, A. Alkhedhair and S. Y. He (2016). "Experimental investigation into the positive effects of a tri-blade-like windbreak wall on small size natural draft dry cooling towers." Applied Thermal Engineering 105: 1000-1012.
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4.6.3 ALTERNATIVE POWER BLOCK

The Alternative Power Block project aims to evaluate power block equipment and configurations that may offer significant cost and performance benefits compared to the current steam Rankine cycle systems. A broad range of cycles will be considered, including Rankine, Brayton and Combined cycles with a range of different working fluids (eg. helium, air, organics, supercritical steam, etc) and different types of engine (eg. steam and gas). In addition to standalone power blocks, the project scope also includes the addition of bottoming or topping cycles where efficiency improvements may be achieved for conventional cycles in a cost-effective manner. Integration with different storage types that are currently available or proposed will be considered as part of the analysis, relying heavily upon the findings of other ASTRI projects or external studies. An assessment of the process options including different cycle configurations, types of turbine or engine, temperature of operation and type of working fluid used will be conducted to establish which ones are the most suitable.

Challenges Associated with Alternative Power Cycles

Literature shows that there are many methods that may be used to identify a good cycle design. There is a great number of papers available that discuss the fluid selection, cycle design and component optimisation problems. Many are applied to specific conditions, or have developed guidelines given certain assumptions. Comparing two different approaches would result in two different designs. It needs to be established which methodology would be most suitable, or if there is a strong relationship between turbine, cycle and fluid choice. Consequently, this research has the potential to improve efficiency though the development of improved design methodologies and identification of where choice criteria apply. The work in this period [November 2016 – April 2017] addresses the following questions:

- Does cycle design affect turbine off-design performance?
- Are there any limitations of the pressure ratio and temperature that would benefit from a different fluid choice?
- Are there improvements to the Recompression Brayton cycle (adding, removing or improving components)?

Methodology

The present research sought an approach to establish the performance of various systems, focusing on the identification as to when a fluid performs the best in comparison to all other fluids. Doing so necessitated new approaches.

A multidisciplinary approach simultaneously optimising and selecting different power cycle components to deliver new concepts has been developed and applied.

To establish the effect of cycle design performance on turbine operation a quasi-steady-state simulation code was developed. The code was based on established empirical loss models and is developed in such a way that optimisation of off-design performance is possible. Several cycle designs were considered, ranging from both low to moderate temperatures and powers (620, 973 and 1073 K / 1 and 2 MW).

A semi-analytical approach was established to identify correct cycle configuration for the recompression Brayton cycle. This method is used to generate cycle efficiency data to establish which fluids would be selected to provide optimal performance. With the optimal performance established, a study of the effect of NTU and maximum pressure on efficiency is conducted. The study of these parameters is performed to provide insight into factors that are not considered in criteria on fluid selection.

ASTRI Research Findings

Changes in power, pressure and fluid typically saw only minor changes in on-design efficiency. Each case group operates at a different specific power, pressure and temperature combination for which turbine geometry is optimised to generate power at highest possible efficiency. There is little variation in efficiency for cases producing the same total power for the different cycle configurations. Yet, efficiency changes in response to the total power being generated. Figure 4.28 shows that there is a clear relationship between off design performance and cycle configuration. The results showed that through implementing active control the negative effect of variations in some cases can be reduced to ensure no reduction from nominal efficiency.

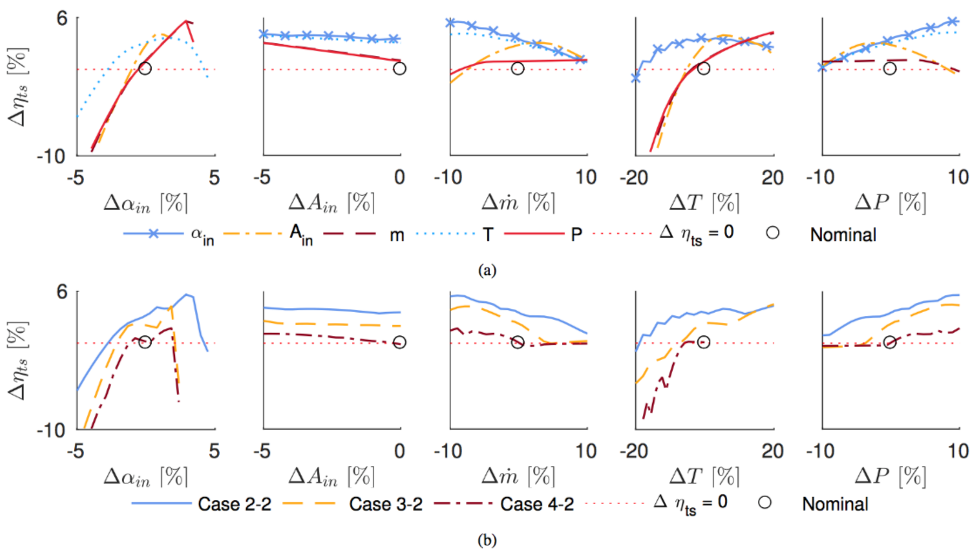


Figure 4.28 Two-Way off-design optimisation showing a) correcting variable and corresponding maximum efficiency for Case 2-2 and b) composite efficiency for cases with different specific powers (Cases 2-2 and 3-2, CO2) and different curves fluids (Case 4-2, SF6)

Each fluid then has an optimum pressure ratio where departure from the optimal pressure ratio causes a reduction in efficiency which is often substantial. This is caused by factors such as the maximum temperature before fluid property changes and increasing losses in compression with pressure ratio. Figure 4.29 shows that CO2 dominates fluid selection due to the preferable compressibility at the minimum temperature. The recompressor ensures the internal heat exchange reaches maximum effectiveness, and that the energy transfer to the gas chiller is reduced. However, not all the investigated fluids benefited from the use of a recompression. Under the investigated conditions, Air and Argon cycles, made minimal use of the recompressor.

Finally, the effect of maximum pressure and NTU on the resulting system configurations was evaluated. Changing the pressure and heat exchanger sizing was found to have substantial effect on the fluid selection, and overall efficiency. Reducing NTU results in minimal changes of the optimal pressure ratio for CO2; whereas the Air decreased its temperature range of applicability by 100◦C with a consequent performance reduction across the range (e.g. η_{II} reduces from 57% to 47% for T=600 PR=2 with a 60% reduction in NTU). Changes in pressure had a greater effect on efficiency compared to heat exchanger sizing variation. Efficiency did not change as much between pressure levels due to the differences in heat exchanger effectiveness not being linearly related to size. Changes in pressure leads to air no longer being a viable working gas choice. The internal heat exchange process is fundamental to the system, and in the development stages, off-design performance should consider the heat exchangers and optimise their size.

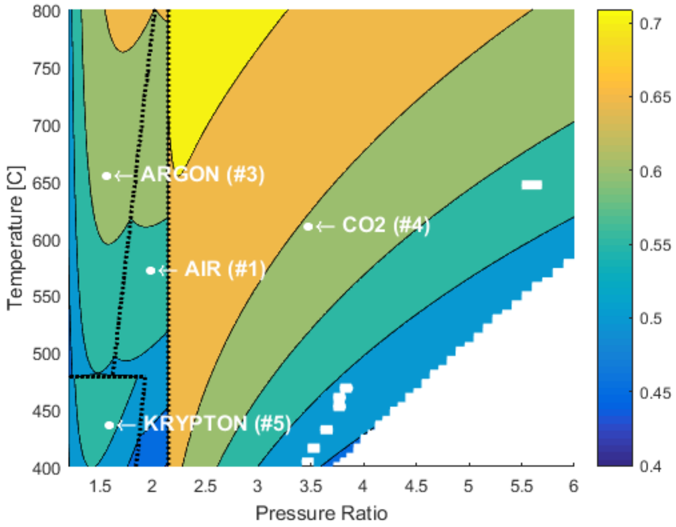


Figure 4.29 - Parametric analysis of the effect that Pressure Ratio and Turbine Inlet Temperature has on fluid selection for the Recompression Brayton cycle. The chart shows that, for the given assumptions, for any pressure ratio above 2.1 CO2 results in optimal system efficiency.

Publications:

Persky, R., Sauret, E., Post, A., Beath, A. "Robust design and optimisation of a radial turbine within a supercritical CO2 solar Brayton Cycle", Proceedings of the 11th World Congress on Structural and Multidisciplinary Optimisation (WCSMO-11), Sydney, 2015. (joint publication QUT/CSIRO)

Persky, R., Sauret, E., Post, A., Beath, A. "Systematic Design of Novel Thermodynamic Cycles for Solar Thermal Power Generation Systems", APSRC (Asia-Pacific Solar Research Conference), Brisbane, 8-10 Dec. 2015. (joint publication QUT/CSIRO)

Post, A., Kisi, E., Sugo, H., Beath, A. "Thermionics – a new approach to highly efficient solar energy", APSRC (Asia-Pacific Solar Research Conference), Brisbane, 8-10 Dec. 2015.

Persky, R., Sauret, E., "Preliminary and robust design analysis of a solar thermal power block", ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition, GT 2016; Seoul; South Korea; 13 - 17 June 2016.

Post, A., Beath, A., Sauret, E., Persky, R., "Valuing Power Block Parameters for 100MWe Scale CSP", SolarPAces 2016, Abu Dhabi. (joint publication QUT/CSIRO)

Post, A. D., King, B. V. and Kisi, E. H. "Computational model and optimisation of a vacuum diode thermionic generator for application in concentrating solar thermal power", Applied Thermal Engineering, Volume 117, 5 May 2017, Pages 245–253.

4.7 Adding Product Value

The Add Product Value node combines research in developing new value products, namely solar fuels, and reducing Operations and Maintenance (O&M) costs.

Australia has unique local opportunities for applications in CST for intensive industrial processes and resources. The US has already demonstrated the use of CST steam for enhanced oil recovery and US researchers are also initiating solar fuel research. While the US SunShot objectives are exclusively targeting electricity generation, other US programs are developing solar fuel technologies. ASTRI is defining solar chemistry as solar thermochemical processes where at least one the solar chemistry products will be ultimately consumed in some secondary process.

On this basis, ASTRI proposes to place a primary emphasis on electricity generation and a secondary emphasis on solar chemistry to directly produce products such as fuels or providing a solar boost to Australian mineral and energy industry processes.

Operations and Maintenance (O&M) costs are an inevitable aspect to any process, with an emphasis on driving these costs down through design improvements based on experience and know-how. The key areas of research identified for ASTRI are self-cleaning reflectors, corrosion control and automation of performance monitoring for O&M scheduling. Research on O&M can help to reduce the risk and uncertainty of the effect of O&M on future revenue.

4.7.1 O&M AND MIRROR CLEANING CAPABILITIES

Overview

The O&M mirror cleaning research has focused on a particularly uncertain O&M cost driver, mirror cleaning, including modelling of mirror soiling, automatic assessment of heliostat reflectivity, mirror cleaning schedules optimization and the modelling and surface cleaning of mirrors by high-pressure spray-jets. So far, a physical soiling model for predicting heliostat reflectivity losses has been developed and integrated in a preliminary cleaning optimisation methodology. To enable real time measurement of reflectivity losses, a methodology for calibration camera-based reflectivity monitoring has been developed and tested in CSIRO Energy Centre, Newcastle. A Condition-Based Cleaning (CBC) methodology for the optimisation of the cleaning schedules, considering time-varying critical factors such as weather and electricity prices has been developed. Computational Fluid Dynamic modelling of the spray cleaning process has been developed along with an approach to experimentally validate the modelling. Future studies will focus on the further tests of the developed soiling model and camera reflectivity tools and their inclusions in the evaluation of CBC methodology as well as validation of the CFD models.

Cleaning Methods for CSP Mirrors

The development of the best cleaning methods for the CSP mirrors to ensure the high surface reflectivity is maintained. The optimal policy for mirror cleaning is obtained from a trade-off between revenue received from generating electricity and the costs of conducting cleaning operations (e.g. water, labour, etc.), which depends strongly on the local mirror soiling rates, electricity market and weather conditions (DNI, rain, etc.). However, currently available cleaning policies have not considered variation in electricity prices nor the potential for “natural” cleaning events (e.g. rain). In addition, there is currently a lack of an economically feasible technique for detailed online heliostat reflectivity monitoring to adjust and update the cleaning policies. For site-specific soiling rates, a physical soling model for eliminating the need for *ad hoc* experimental soiling measurement is also missing from the current research.

ASTRI's Bottom Up Approach

To this end, the O&M group started up with a bottom-up methodology. The cleaning of mirrors with water through different nozzles was modelled and is being validated through experimental work. Additionally, without requiring experimental data, a dust soiling model based on physical laws were developed and validated with literature data.

The need for automatic assessment of soiling condition has triggered the development of camera-based reflectivity monitoring methodology, which was experimentally tested with the available research facility in CSIRO Energy Centre, Newcastle.

Finally, the further tested soiling model and camera-based reflectivity monitoring will be integrated into the CBC methodology for a holistic mirror cleaning schedules optimization.

Dust soiling model for heliostat reflectivity degradation and development of laboratory facilities

The physical model for time-varying dust soiling degradation (Figure 4.30) was continuously refined with the inclusion of hourly DNI of a selected site for receiver flux estimation. A sensitivity analysis was conducted and reviewed to generate more refined and reliable results. Ongoing effort has focused on the inclusion of a more detail rain model for an improved understanding of soiling dynamics and better soiling predictions. The design and manufacturing of an experimental solar mirror test-rig at QUT (Figure 4.31) has been completed as well as another lab area to conduct soiling and cleaning experimental work to validate past theoretical work completed. Once the test-rig associated with a dust monitoring station is installed, experimental activities will be undertaken to regularly measure mirror reflectivity and environmental inputs, including wind, temperature, rainfall, humidity and airborne dust concentration for calibration and validation of the developed soiling model. Experimental work to validate the spray cleaning work will also be completed. In the future, the validated model will be integrated into an optimal mirror cleaning schedules with site-specific soiling patterns. Based on the developed soiling model, an extended abstract with the title "A Model of Heliostat Soiling and Its Application to O&M Cleaning Studies" has been submitted for the SolarPACES 2017 conference.

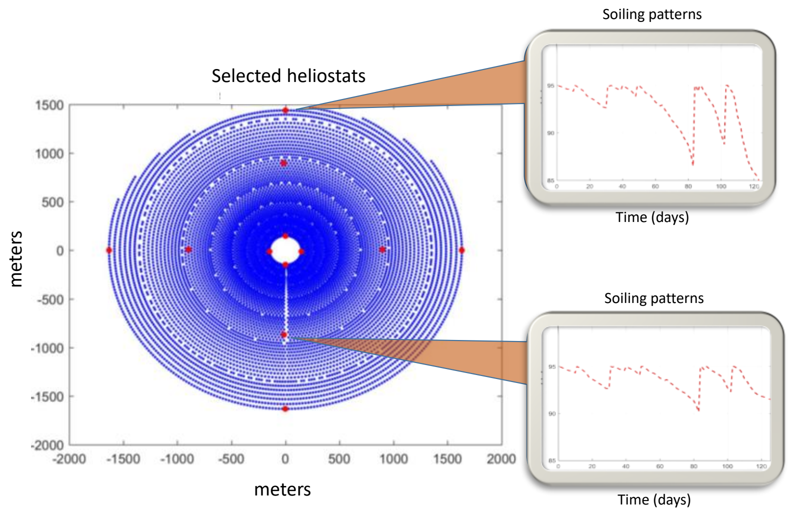


Figure 4.30 - Time-varying soiling degradation across the solar field

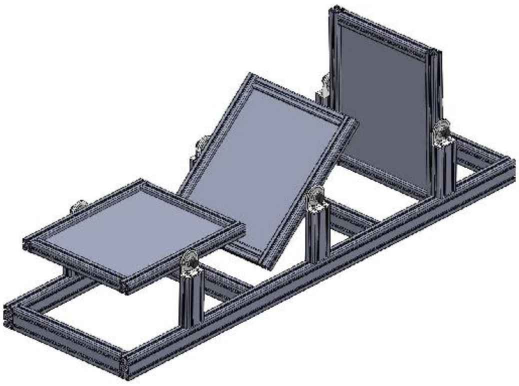


Figure 4.31. Solar mirror test-rig

Camera-based heliostat reflectivity monitoring

To inform the optimal cleaning strategy with real time measurements of reflectivity losses, the O&M group has continuously tested and refined the proposed camera-based heliostat reflectivity monitoring with more field experiments conducted at the CSIRO Energy Centre, Newcastle (shown in Figure 4.32). An elliptical Gaussian distribution based image processing technique was utilised to extract the reflected irradiance of each mirror under different soiling conditions, normalized by time-varying DNI and cosine losses. A linear correlation between the normalized image power and mirror reflectivity loss was identified and validated. The proposed method was further verified through the comparison of camera-based reflectivity estimation and actual reflectometer measurements with only a maximum absolute error of 1% reflectivity, which is comparable to the variability of the reflectometer measurements themselves. A journal paper titled “In-situ Reflectivity Monitoring of Heliostats using Calibration Cameras” is being reviewed by the journal “Solar Energy”.

Figure 4.32. The CST tower facilities at the CSIRO Energy Centre, Newcastle, Australia

Optimal mirror cleaning schedules

In the last six months the Condition-Based Cleaning (CBC) methodology, conceptually depicted in Figure 4.33, was refined and applied to real environmental and economic data (DNI, prices, rain, etc.). This allows the evaluation of the typical economic benefits expected not only from the optimal CBC policy, but also from the fundamental information provided to the optimisation algorithm by the mirror soiling model and the reflectivity monitoring (discussed in the previous paragraphs). Optimal cleaning schedules are obtained by striking an optimal balance between productivity losses due to soling and direct cleaning costs, which is strongly dependent on time-varying electricity prices, solar DNI and the opportunity of potential “natural” cleaning.

For the effectiveness of this CBC policy, different simulation scenarios highlighted the increased benefit of CBC in case of high washing costs. Simulations also allowed to identify and quantify the effect of cleaning lead time, which would practically occur between the decision and the actual cleaning operation. Based on current research outcomes, a journal paper titled “Optimal Condition-based Cleaning of Solar Power Collectors” has been finalized and submitted to “Solar Energy” for review. Future studies will focus on the variability of soiling across the field and its impact on optimal cleaning sequences. Once the soiling model and camera reflectivity tools will be further tested, the impact of imperfect measurements and predictions will be also included in the evaluation of CBC.

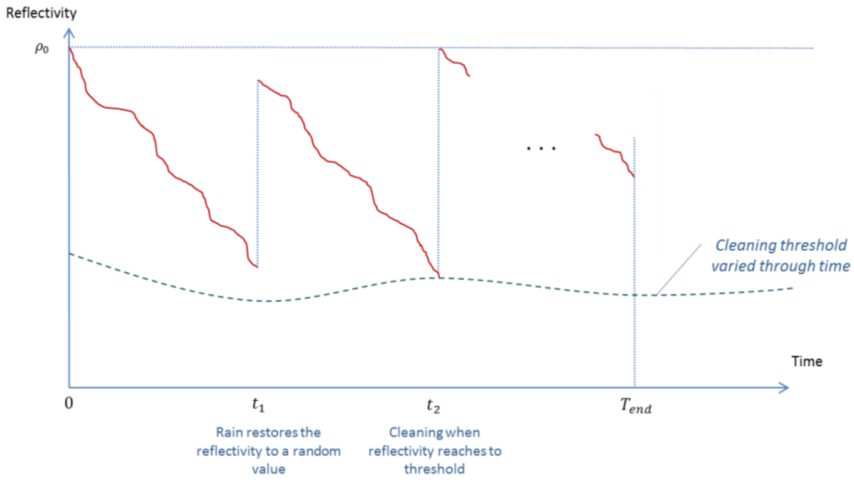


Figure 4.33 Model concept of CBC methodology with reflectivity degradation and cleaning threshold

Collaboration and Recruitment

The O&M group has been continuously collaborating with internal and external partners (e.g. CSIRO and NREL). The ongoing collaboration established with Politecnico di Milano (Giampaolo Manzolini) has resulted in the commencement of a joint PhD supervision (Giovanni Picotti) to continue the degradation modelling of the solar field and the development of similar models for critical equipment in the power block, receiver and storage systems. The O&M group has been contacted by DLR for the developed dust soiling model and a potential collaboration is currently under development. Another PhD student from UQ has started and the work is being coordinated to ensure no duplication of effort is present.

Industry Applications

Mirror cleaning to maintain high reflectivity is critical to an efficient CSP facility and doing this properly with a validated approach can be applied to any industry requiring this. The ongoing O&M research has allowed the team to understand the order of magnitude of cost savings which are possible with the CBC methodology (5-25% of total cleaning costs compared with a fixed-time traditional cleaning strategy, depending on the cost of cleaning operations).

In the Australian economic environment, we expect savings in the upper part of the range considering high labour and resource (water, etc.) costs. The experimental activity with the camera-based reflectivity monitoring at the CSIRO Energy Centre has shown that cheap and automated remote sensing of mirror reflectivity is possible (max. absolute reflectivity error of 1%).

Finally, the soiling model allowed the team to clearly identify the relative importance of different physical phenomena, design parameters and environmental conditions on heliostat soiling rates. This key knowledge will support industry allowing a more cost effective decision making and planning of cleaning operations in the solar field.

Capabilities to Support Industry

The ongoing developments would provide CST industry with the following potential capacities:

- Condition-Based Cleaning (CBC) methodology for the optimisation of mirror cleaning schedules based on real environmental and economic data (DNI, prices, rain, etc.). The optimal policy is responsive to a continuously changing economic and weather environment. It has been demonstrated with the capability to achieve a cost savings in the range of 2-6 cents/kWh (LCOE equivalent) for industry, depending on the estimate of current cleaning cost and location-specific soiling patterns.

- A low-cost heliostat reflectivity monitoring using already-installed calibration cameras (e.g. CCD cameras). This would facilitate industry with automatic reflectivity measurements and continuous adjustment and updates of an optimal cleaning policy.
- A physical soiling model. This would provide industry with site-specific estimation of soiling rates for optimal cleaning schedules optimization and the benchmarking and budgeting of new plant designs.

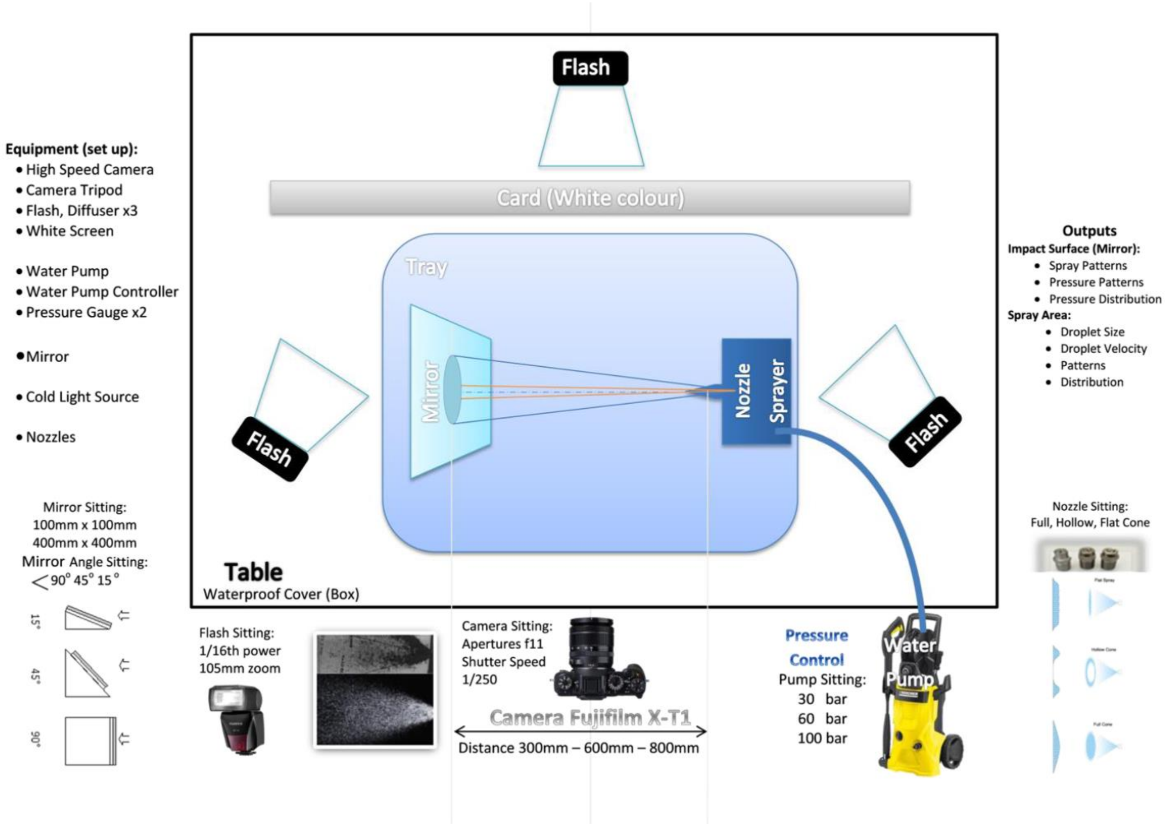


Figure 4.33A Set-up for mirror spray cleaning using high-speed camera to visualise spray.

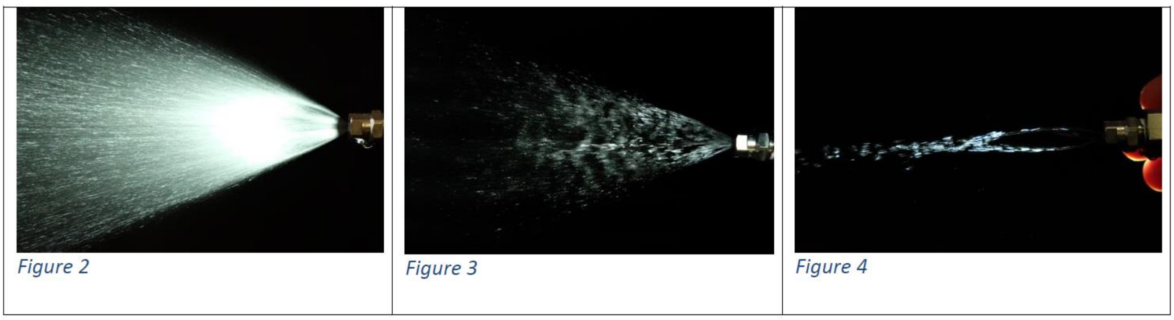


Figure 4.33B High-speed photography (Figure 2-4) of spray cleaning of mirror

4.7.2 SOLAR FUELS

The Solar Fuels project aims to develop a series of technologies for the production of liquid fuels with CST through to on-sun demonstration, pending additional funds, based on down-selection of a series of proof-of-concept demonstrations at lab-scale. ASTRI is seeking to develop a series of technologies with the following levelised cost of fuel (LCOF) targets for liquid transportation fuels:

- Horizon-I: A target of $1.0/L for solar reforming of natural gas;
- Horizon-II: A target of $1.20/L for "Gen-II" biomass-derived feedstock (e.g. wood and residues) with a life-cycle emission of CO2 that is at least 50% lower than conventional diesel (noting the present biomass is typically not carbon-neutral); and
- Horizon-III: A target of $2.50/L for "Gen-III" sustainable feedstock (e.g. CO_2 and algae) with a life-cycle emission of CO2 that is at least 50% lower than conventional diesel.

Research Needs

TECHNOLOGIES	RESEARCH QUESTIONS
Solar Reforming of natural gas (H-I)	• Technical and economic feasibility of solar reforming systems with storage to identify preferred configurations, systems and applications. • End-to-end, on-sun demonstration of the entire process from natural gas through to liquid fuels production at significant scale, incorporating storage.
Solar hybridized dual fluidized bed, SDFB (H-II)	• Technical and economic feasibility of the proposed solar hybridized dual fluidized bed gasification concept to identify preferred configurations, systems and applications. • Interaction of bed material and ash generated from combustion and gasification of the proposed biomass feedstock, agricultural residue, which has a higher ash content than coal or wood. The ash can cause particle agglomeration in the particle receiver, particle storage and the dual fluidized bed gasifier. • On-sun demonstration of whole process, through to liquid fuels production to reduce risk and increase confidence in techno-economic viability.
Supercritical water gasification, SCWG (H-III)	• Given the advantages of a process that eliminates feedstock drying and is inherently suited for a tubular reactor-receiver, can we identify and address the thermal, chemical and containment material challenges that currently delay adoption? • Can we determine how competitive the SCWG process could be, by building up a complete integrated model of the whole feedstock-to-fuel process, including both performance and cost?
Redox CO_2 and H_2O splitting **(H-II – H-III Solar/ Hybrid thermochemical processing)**	• Develop novel materials that can provide greater oxygen storage capacity, faster kinetics, sintering resistance and long term thermal shock resistance than state-of-the-art metal oxides. Our target from these efforts is to achieve solar to fuel efficiencies greater than 40% (baseline efficiency for thermochemical cycles performing methane partial oxidation coupled with H_2O and CO_2 splitting).Demonstration of the redox reactions at the prototype level by designing a novel concept of receiver/reactor. • Dynamic performance of the whole solar syngas plant based on redox thermochemical cycles up to liquid hydrocarbons.
Advanced Sabatier (H-III)	• Development of stable photoactive materials for direct thermo/photocatalytic reduction of CO_2 to methanol and other liquid hydrocarbons
Fischer-Tropsch (H-I)	• The impact of the solar-only process (which involve start-up, shut-down and turn-down) on the FT liquid yield and quality of the FT liquid

ASTRI's Approach to Solar Fuels Research

- ASTRI has established a comprehensive framework with which to assess on a common basis the production of liquid transport fuels with all of the alternative types of CST technology described above, accounting for the entire system with an integrated with Fischer-Tropsch liquids (FTL) production, incorporating solar resource variability, economic feasibility, sustainability and stage of development;

- ASTRI is continuing to identify preferred combinations of feedstock and CST-FTL technologies using the above analysis tools, considering both solar-only and hybrid concepts together with short and/or longer term applicability, with strong potential for development.
- ASTRI is advancing preferred systems through to proof of concept using analysis tools and experimental demonstration. Our aim is to progressively demonstrate on-sun (pending further funding), at least one system for each of the three technology horizons listed above. The key components in our research are;
    - Whole of system modelling to identify systems with strong potential to improve performance relative to state-of-the-art and relative to alternative technologies, using commercially available components where available;
    - Develop novel components in preferred systems where commercial components are not available, notably for solar thermal reactors and storage systems, using a combination of modelling and experimental testing;
    - Meet the gap for new data that limits capacity for reliable design, such as reaction kinetics, heat transfer and operational behaviour under novel conditions relevant to the new reactors; and
    - Review and refine concepts relative to each other and to other programs under development internationally to ensure resources are only directed where it is justified.
    -
- ASTRI is also supporting the advancement of solar thermal production of high value fuels by targeted and collaborative development of the downstream liquid fuels synthesis processes in ways that augment the value of the solar fuels.

Benefits for Industry

TECHNOLOGIES	TRANSFERABLE KNOWLEDGE
Solar hybridized dual fluidized bed gasification, SDFB	• Pseudo-dynamic process modelling and economic evaluation has identified SDFB as being one of the lowest cost paths proposed to date for production of low-to-negative net carbon liquid fuels with "Gen-II" feedstock. • Feedstock cost is a major contributor to the LCOF. For this reason, agricultural residues, either raw or upgraded via torrefaction, are now being targeted. • ASTRI is now addressing the lack of understanding of the mechanisms of agglomeration between the biomass ash and bed material. • Systems analysis and laboratory testing associated with materials handling is also being performed to identify configurations with lowest parasitic losses and greatest reliability.
Supercritical water gasification, SCWG	• We have built up skills to analyse solar fuels processes, including equilibrium-based reactor models with radiative and convective heat transfer, as well as system level performance optimisation at the design point. • We have found through our performance optimisation that it is costly to work towards total conversion of all bio-carbon, and that some in-process CO_2 emission may be cost-optimal for fuel production. • Operational conditions for SCWG are quite challenging from materials and structural points of view, and require more detailed modelling than has so far be undertaken by researchers in this field. • Our initial process was based on algae, but the high current cost of algae necessitates a broader study of alternative feedstocks adapted for this process.
Redox CO_2 and H_2O splitting	• Using natural gas as a feedstock provides a low cost alternative as compare to non-hybrid redox cycles. This can produce low carbon emissions and cost within the H-II approach. • The major contributions to the cost are related to the syngas storage system required to provide a constant flow to the FT unit. Dynamic model of solar fuel plant and economic evaluation of the production of liquid hydrocarbons have found that continues production of syngas is possible by controlling the operating strategy without high cost syngas storage. This pathway can reduce considerably the cost of the process bellow the price obtained in an initial economic assessment.

		• The work is now moving towards demonstration 1000 thermal cycles (equivalent of a 1000 days of operation in a solar-syngas production plant). Industry can apply this learning to materials performance and degradation of materials over thermal cycles. • Demonstration at the prototype level is critical to reduce further demonstrate the viability of this technology under solar-simulated conditions. The team aims to demonstrate a receiver concept in the next state of the project.
Advanced Sabatier		• Development of novel catalysts to yield higher value products from the Sabatier process (CO_2 + H_2). • Demonstration that atomically-precise Ruthenium cluster-based catalyst can give extremely high hydrocarbon production efficiency and selectivity towards specific products such as methanol. • The identification of suitable catalysts means that scale-up can now be considered.
Fischer-Tropsch		• The challenges to variable operation of FT synthesis have been better identified through an experimental campaign measuring sensitivity to changes in the syngas flow rate and to changes to the purging gas composition during a shut-down period.

Skills to Support Industry

- Modelling tools for solar-driven chemical processes, accounting for solar resource variability through time-series of historic data sets, feedstock, storage and liquid fuels synthesis. These include:
  - Aspen or Modelica process models of the chemical plant;
  - In-house codes to account for solar-resource variability;
  - Techno-economic models
- Performance data on performance, cost and CO_2 emissions for a series of reference technologies, feedstock and solar resource conditions against which other alternatives can be compared;
- Experimental facilities for testing of solar-driven chemical processes spanning a range of feedstock from wet to dry and a range of operating temperatures; and
- Trained engineers and research staff with expertise in solar thermo-chemical processing in both experimental and numerical techniques.

4.8 ASTRI Facilities

4.8.1 OVERVIEW

ASTRI has world class research infrastructure to support Australia’s best concentrated solar power researchers to develop, test and commercialise technologies side by side with industry partners and research institutions around the world.

4.8.2 NATIONAL SOLAR ENERGY CENTRE, NEWCASTLE AUSTRALIA

The CSIRO has developed and operates Australia’s largest solar thermal research hub at the CSIRO National Solar Energy Centre. The hub comprises two operational solar fields and supporting research laboratories including:

- 550kW$_{th}$ Central receiver solar tower and heliostat field
- 1.2MW$_{th}$ Central receiver solar tower and heliostat field
- 750kW$_{th}$hr high temperature thermal storage system
- Laboratories for thermal storage, heat transfer, reforming catalyst development and component evaluation.

The facility is designed to be a focal point for Australian and international researchers, allowing Australia's best concentrated solar power researchers to develop, test and commercialise technologies side by side with industry partners and research institutions around the world.

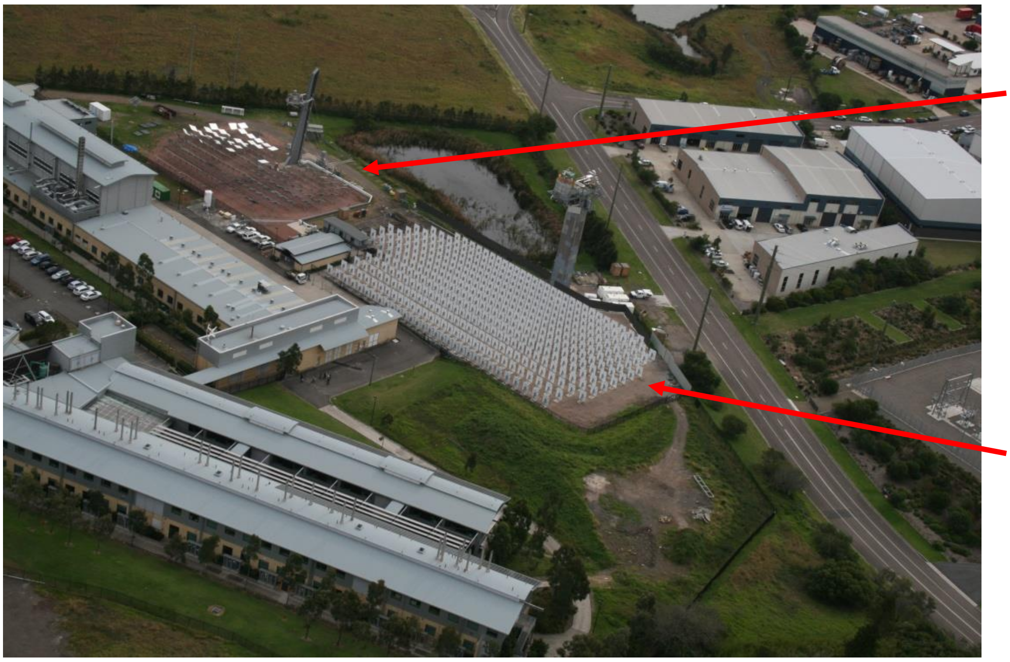


Figure 4.34: CSIRO's National Solar Energy Centre, Newcastle, Australia

Field One

Commissioned in 2005

550kW thermal peak

180 heliostats

Field Two

Commissioned in 2011

1.2MW thermal peak

451 heliostats

4.8.3 HELIOSTAT TEST BED

To complement existing facilities within the ASTRI team (e.g. the heliostat field at CSIRO Newcastle), ASTRI has developed a customised heliostat test bed at CSIRO Lindfield (Figure 4.35). The heliostat has been modified from a commercial design to enable:

- Testing different mirror geometries up to 6.25m^2 using a customised sub frame.
- Evaluate a commercial concrete free foundation system.
- Test the optical closed loop tracking system.
- Evaluate cheap orientation sensors for use in tracking.
- Test wireless communication and data logging.

Figure 4.35. Heliostat test bed at CSIRO Lindfield

At the University of Adelaide, instrumented heliostat models have been built for wind tunnel testing (Figure 4.36).

Figure 4.36 Heliostat scale model in Thebarton wind tunnel at the University of Adelaide

4.8.4 SOLAR MIRROR TEST RIG FOR SOILING EVALUATION

A solar mirror test-rig associated with a dust monitor has been designed and manufactured for validation and refinement of the developed physical soiling model at QUT.

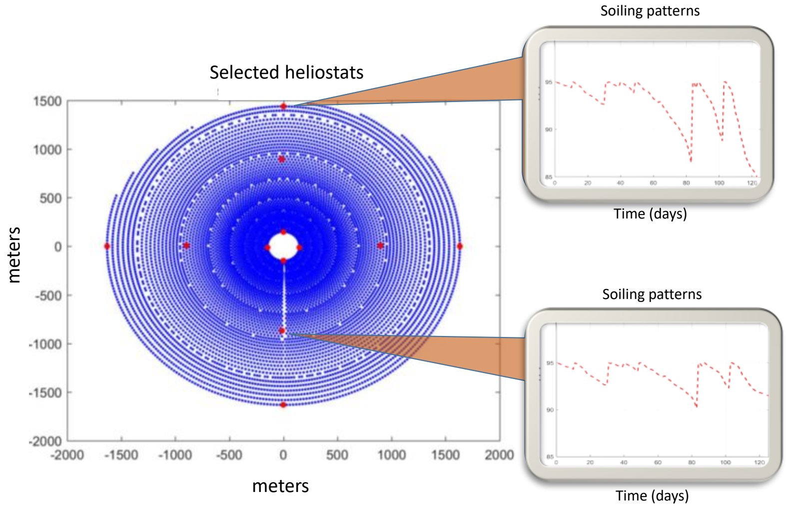


Figure 4.37. Time-varying soiling degradation across the solar field

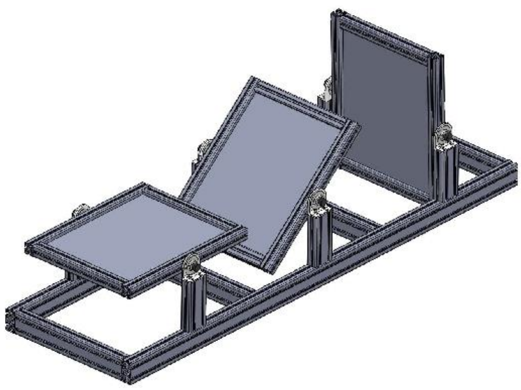


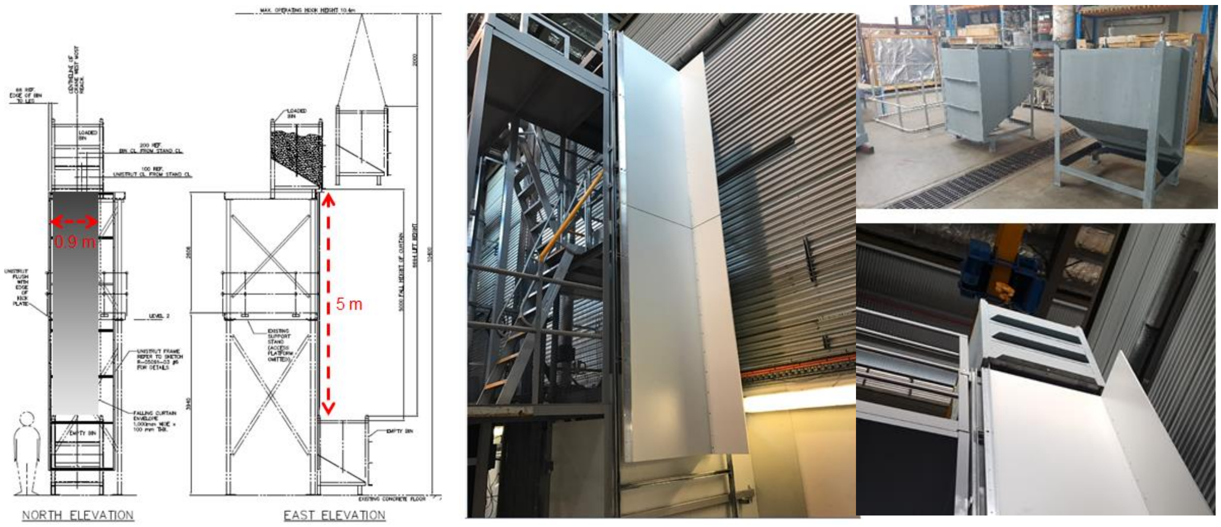
Figure 4.38. Solar mirror test-rig

4.8.5 SODIUM TEST LABORATORY

ANU has completed design of a sodium test laboratory, adjacent to a high-flux solar simulator. The laboratory will be used for testing laboratory scale prototypes, and for materials compatibility testing. Laboratory equipment is currently under procurement, and the laboratory will be fully operational by early 2018.

4.8.6 FALLING PARTICLE TEST RIG

CSIRO is in advanced stages of development of a 6-m high falling particle test rig, designed for cold flow testing of its new falling particle receiver concept (Figure 4.39). First tests are planned for mid-2017.



(a) (b)

Figure 4.39. Cold-flow falling particle test rig at CSIRO showing (a) the tower and (b) the two particle hoppers used at top and bottom of the tower.

4.8.7 COMPARTMENTALISED PARTICLE STORAGE SYSTEM

Compartmentalized particle storage system has been installed according to Figure 4.40. The work will complement and enable commercial potential of particle receiver concept. There is good opportunity to collaborate with Sandia who is working on particle receiver. The availability of viable, low cost bulk particle thermal storage system will also support other thermo-chemical storage approaches using particles.

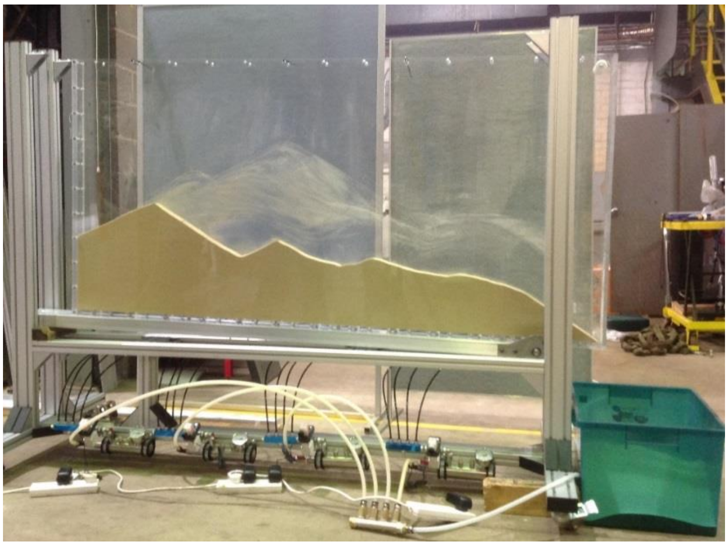


Figure 4.40 Experimental rig compartmentalised particle storage design of ASTRI

4.8.8 MOLTEN SALT TEST RIG - CORROSION AND HIGH TEMPERATURE DENSITY

An experimental rig for molten salt corrosion and high temperature density measurement was designed and commissioned at ANU recently (Figure 4.41). The furnace is atmosphere controlled with dry air, Ar and N_2 as the inlet gases. Density measurement is done using Archimedes method with a pure Ni sphere immersed in molten salts kept in graphite crucibles. The density of the molten salt is one of the important thermo-physical properties and a decisive factor in sizing the storage tank. The density of the developed molten salt mixtures will be measured in coming months. Further, the thermal conductivity of the salt mixtures will be measured using laser flash analyser (LFA) in few months. In efforts to improve the thermal properties of these developed molten salts, an addition of oxide based nanoparticles is considered. A detailed experimental campaign for the measurement of heat capacity and thermal conductivity will be conducted during the final year of Gowtham's PhD.

Figure 4.41 Atmosphere controlled corrosion and high temperature density measurement rig at ANU

Heat exchange between the high temperature heat transfer fluid and the storage medium (Figure 4.42) is a huge challenge and the conventional heat exchangers are an expensive proposition given the high corrosivity of chloride salts. Phase solubility of pure sodium in NaCl and vice-versa is quite small (<3%), which makes the direct contact heat exchange (DCHE) between salt and sodium quite interesting. Theoretically, DCHE also provide much higher area of heat transfer between the hot and cold fluids. Consequently, a concept HX with Na and ternary molten salt ($NaCl-KCl-MgCl_2$) was explored to assess the feasibility.

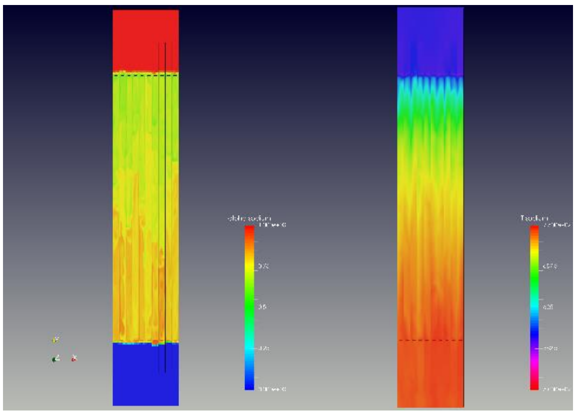


Figure 4.42 Multichannel direct contact heat exchanger between sodium and molten salt. Figure shows the spatial distribution of sodium and the temperature distribution in the heat exchanger (α_{sodium} is the phase fraction of sodium)

4.8.9 SOLAR THERMOCHEMICAL REACTOR

A solar thermochemical reactor for demonstration of carbonate looping thermochemical energy storage has been designed and built. The solar reactor built in ANU is presented in Figure 4.43. The reactor auxiliary equipment is being purchased now and the experimental demonstration is going to be delivered in the next stage of ASTRI. This reactor can be potentially applied to other processes that use particulate media in ASTRI.

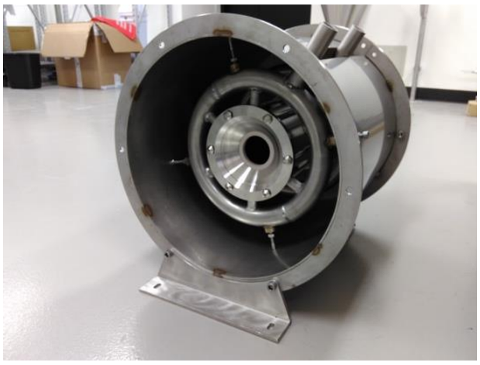


Figure 4.43 Picture of the thermochemical reactor constructed at ANU for carbonate looping thermochemical energy storage

4.8.10 SOLAR BUBBLE RECEIVER/REACTOR

Our work on reacting molten metals and gases has recently led is to development a new patent-pending solar bubble receiver/reactor at the University of Adelaide. (For this reason it has been funded under P21 to date, but could be moved to P12 if desired). This indirectly heated receiver/reactor employs an efficient bubbling medium to enhance the heat transfer rate, and hence mitigate the exergy destruction, in heating a pressurised gas or deriving an endothermic reaction. Hence this concept also appears to have potential for application to the direct and efficient heating of CO_2 for ASTRI s-CO_2 power cycle, although this potential is yet to be evaluated. A 1-kW bench scale of this receiver has been designed and built at the University of Adelaide, as shown in Figure 4.44, for testing and demonstration of the concept. The demonstration of the receiver is planned to be performed using gallium and N_2 as heat transfer medium and working fluid, respectively, in the next few months. We are also looking into alternative materials to support heating pressurised CO_2 for sCO_2 cycle. Preliminary discussion about the potential of this receiver has begun with Professor Ted Steinberg (QUT) and CSIRO personnel. The proposed receiver also has potential to leverage from the work at ANU on the ASTRI Na receiver, either through the use of bubbling into tubular receivers or through shared use of expertise and facilities.

Figure 4.44 1-kW solar bubble receiver/reactor (UoA)

4.8.11 SUPERCRITICAL CO2 HIGH PRESSURE TEST LOOP

UQ test loop was operated with r245fa to test the UQ designed 7kW refrigerant turbine. This facility and the modular 7kW turbine allows the quick testing a iteration refrigerant pressures under at moderate pressures and temperatures (up to 1.6MPa and 150°C).

In early 2017 the loop was commissioned for operation with supercritical CO2. This provides a capable test bed for sCO2 technology developments. The operating range of the loop is up 20MPa, up to 250°C and flow rates up to 0.25 kg/s.

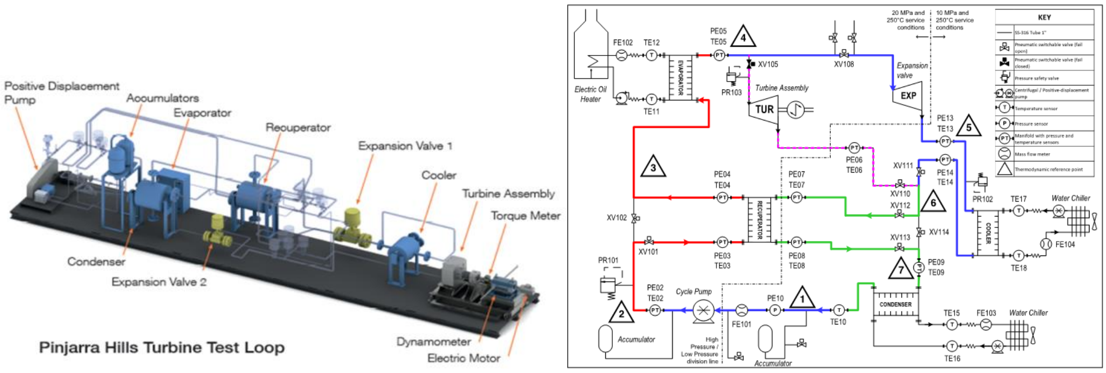


Figure 4.45: Pinjarra Hills High Pressure Test Loop. Now commissioned for sCO2 operation. With upgraded pump capable of flows up to 0.25 kg/s and maximum temperature of near 250°C.

4.8.12 1MW NATURAL DRAFT COOLING TOWER

Gatton natural draft cooling tower (NDDCT): The Gatton experimental NDDCT, a patented design and world-unique installation, is of hyperbolic shape and is 20 m high with same diameter of 12.5 m both at the top and at the heat exchanger level. The tower is constructed using a steel truss and a PVC membrane. The heat exchanger bundles are horizontally installed at a height of 5 m. A diesel-fired oil heater provides up to 1-MW of heating at controllable temperatures in simulation of the waste heat from a thermal power plant. The tower is exposed to the ambient wind. The ambient wind cannot be controlled but it is recorded by the tower instrumentation system.

Figure 4.46 – UQ Gatton tower (sized to cool a 1-MWe sCO_2 power block)

4.8.13 WIND TUNNEL FACILITIES

The tunnel consists of a centrifugal fan (75-kW) at inlet, a diffuser section (with 3 screens) after the fan, a settling chamber (with a honeycomb and 4 screens), contractions (three sizes for various air speeds), a transparent working section (can be adjusted up to 1.7x1.7 m^2), an exhaust air scrubber and an exhaust fan. In addition to sensors for flow, temperature, pressure, humidity, etc, a Malvern 2600 laser diffraction analyser is used for droplet and particle characterisation. PIV and PDPA systems provide flow visualization and particle size characterisation.

The tunnel is used in two projects in ASTRI:

i) nozzle sprays optimum for inlet air precooling in cooling towers
ii) nozzle sprays optimum for mirror cleaning at different ambient wind conditions

4.8.14 COOLING ZONE TEST RIG

We have completed the design of a test facility to investigate the operation of the shaft cooling zone and heat transfer in high pressure sCO2 regions. This facility will be operational for ASTRI 2.0

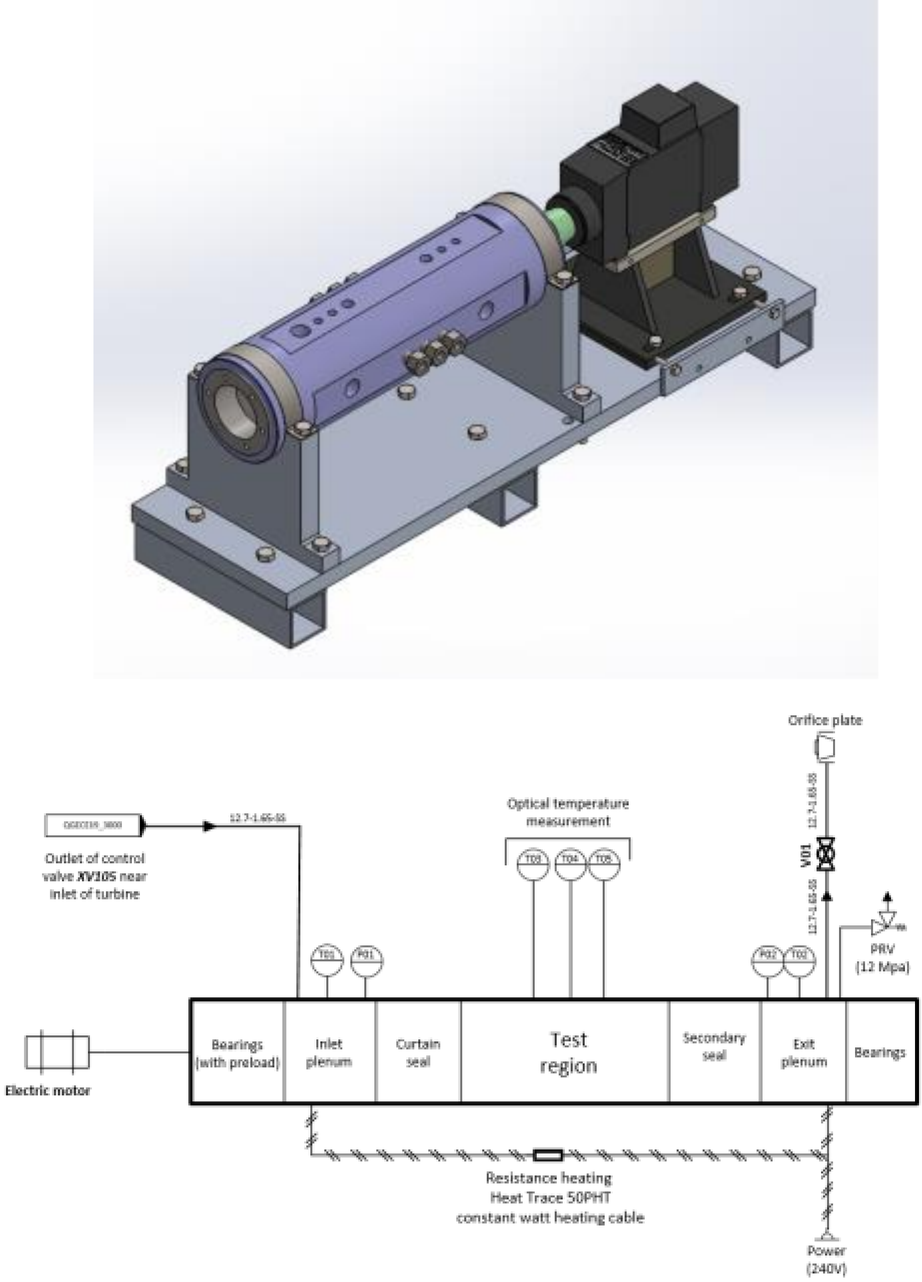
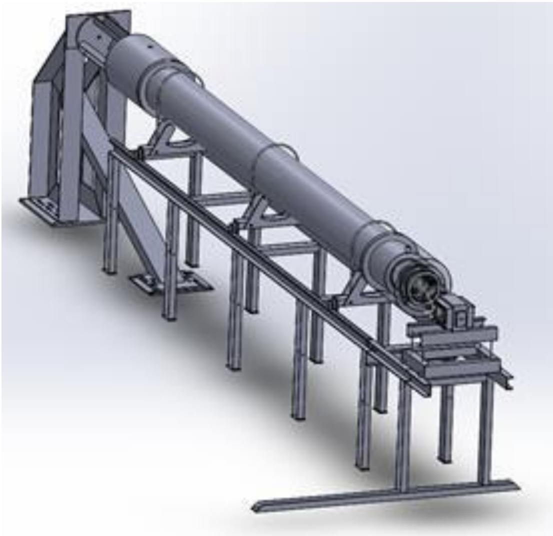
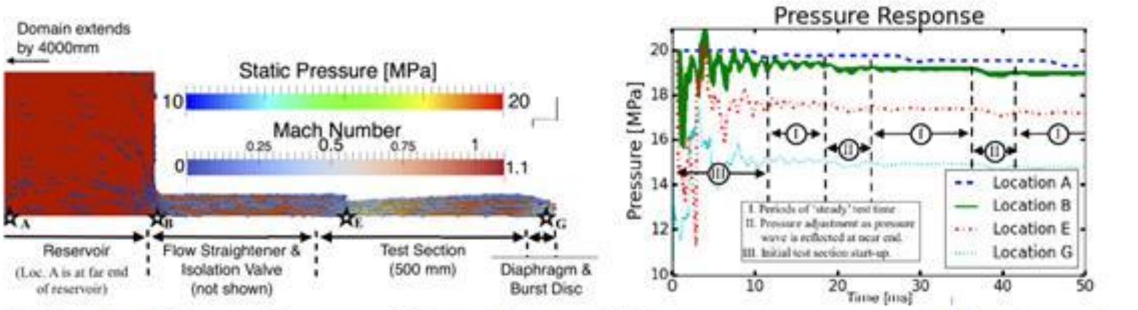


Figure 4.47: Test arrangement for measuring the shaft heat transfer in supercritical CO2 conditions. Using optical measurement techniques the temperature of the high speed shaft is monitored and the potential of different cooling arrangements can be evaluated.

4.8.15 TRANSIENT HIGH CAPACITY SUPERCRITICAL CO2 TUNNEL

The design of a transient tunnel to perform component tests at flow rates up to 20kg/s was commenced during ASTRI part 1. The design and manufacture of a large portion of the main components has been completed. Assembly is imminent.





(a) Snapshot of Pressure Contours and Velocity Vectors at $t = 30$ ms.

(b) Static pressure traces at various locations confirming periods of steady test time.

Figure 4.48: Test facility to create short duration high flow rate sCO2 conditions to investigate fundamental aerodynamics in supercritical CO2 flows.

4.8.16 SOLAR HYBRIDIZED DUAL FLUIDIZED BED – LAB SCALE REACTOR

This lab-scale reactor aiming to simulate the various SDFB environments in order to study the mechanisms of agglomeration between the selected feedstock and bed material as shown in Figure 4.43. This facility consists of a high temperature furnace (up to 1100°C), gas mass flow controllers (Alicat), a steam generator (Bronkhorst - Controlled Evaporation and Mixing, liquid mass flow controller and gas mass flow controller).

Cold flow model facility for particle storage (also addressed through P21).

Figure 4.49 Experimental setup to simulate various SDFB environments to understand the mechanisms of agglomeration between the selected feedstock and bed material.

4.8.17 SUPERCRITICAL WATER GASIFICATION RIG

The lab-scale custom-designed supercritical water gasification rig is able to operate at conditions of up to 250 bar, 550°C with high-concentration biomass mixtures into a heated flowing pressurized water stream. The exhaust gases are analysed using a downstream mass spectrometer (PfeifferVacuum Omnistar GSD 320). The safety, monitoring and controls for the rig are implemented using a custom built LabVIEW VI. See Figure 4.50.

Figure 4.50. Experimental rig for supercritical water gasification of biomass. Left: the complete system, mounted on wheels and ready for installation in a walk-in fume cupboard. Algae and water flow-rates are controlled by the two HPLC pumps at bottom left. Right: detail of the furnace section, where a U-shaped tube is fitted with electrical heating elements and with thermocouples to measure process temperature.

4.8.18 REDOX CO2 AND H2O SPLITTING – LAB SCALE REACTOR

The lab-scale reactor consists of an 8 kW high-temperature infra-red gold image furnace, which has a fully automated temperature and gas flow control system, and a downstream gas analysis via mass spectrometer (Figure 4.51). This facility enables simple high-temperature testing and more sophisticated cyclic reactions (i.e. reduction/oxidation) for any number of repeated cycle steps. The maximum operating temperature of 1700°C and the rapid temperature changes in the furnace (more than 100°C per minute) allows for a wide range of materials testing capabilities under high fluxes of radiation. It is also equipped with a steam generator.

Figure 4.51 Thermochemical materials testing facility. From left to right: Data acquisition PC, mass flow controllers with pneumatic safety valves, IR gold image furnace, and mass spectrometer (top right) and gold–IR furnace temperature controller (bottom right).

System modelling tool for solar fuel production plant. Figure 4.52 shows an example of solar hydrogen production plant using redox cycles. The system includes libraries of fluid and solid media, reactor models, heliostat field, weather data, sun model, valves, heat exchangers, storage tanks for solids and seasonal control strategy.

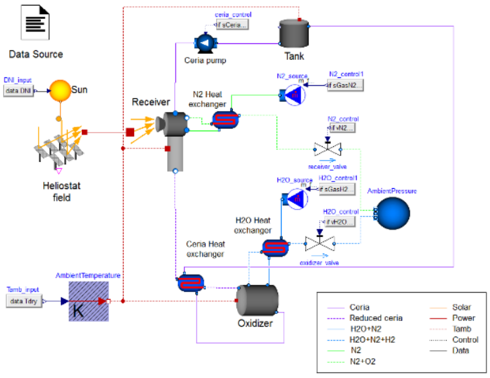


Figure 4.52 Hydrogen production plant based on CeO_2 thermochemical redox cycle

4.8.19 ADVANCED SABATIER

Batch and continuous flow reactor for the advanced Sabatier process has been developed (Figure 4.53) for testing small quantities of metal-cluster based catalysts.

The reactors are fitted with high precision temperature and pressure control. Hydrocarbon product distribution can be determined from rapid analysis using both mass spectrometry and gas chromatography.

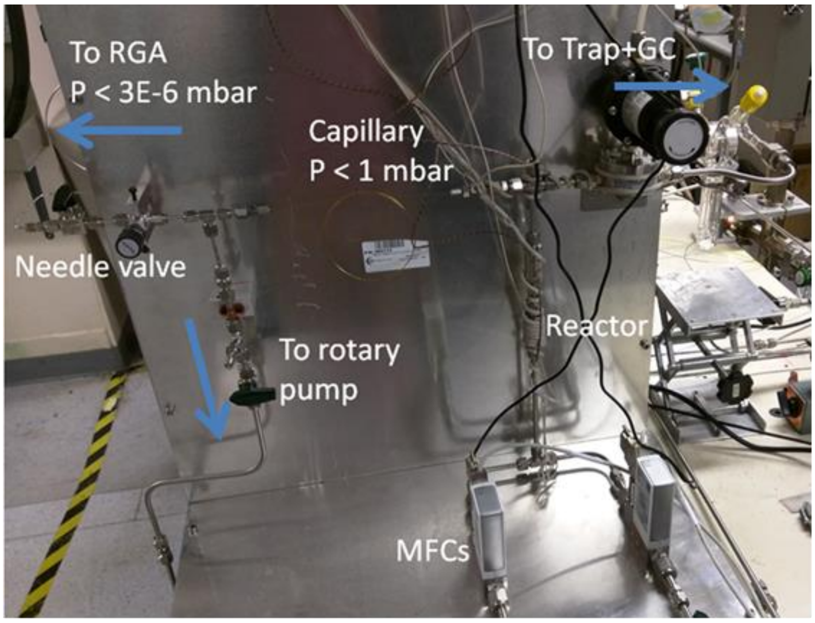


Figure 4.53 Experimental setup for the flow-through continuous reactor for the advanced Sabatier process. A small quantity of metal-cluster based catalyst (10-50 mg) can be readily tested and the hydrocarbon product distribution determined rapidly via gas chromatography and mass spectrometry.

FOR FURTHER INFORMATION

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