



ASTRI

AUSTRALIAN SOLAR  
THERMAL RESEARCH  
INSTITUTE

ASTRI Australian Solar Thermal Research Institute

# Public Dissemination Report

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## Message from the Director

The Australian electricity market is transitioning to a low carbon future. This is being driven by significant uptake of renewable energy mostly in the form of PV and wind. These technologies generate energy when resources are available resulting in variable or intermittent energy supply. While low levels of variable renewable energy are manageable within Australia's electricity network, high levels can decrease system reliability and result in higher energy costs due to the need for additional generation capacity.

Addressing this problem requires access to electricity that can be dispatched on demand. At present, coal and gas fired generation meets this requirement. However, with existing conventional power assets reaching the end of their operational life and the shift to a low carbon economy, Australia's future electricity system will require renewable energy solutions that can dispatch electricity on demand. This will require renewable energy technologies that allow for the storage of energy and its subsequent use to generate and/or dispatch electricity.

Concentrated Solar Thermal (CST) is a technology that provides low cost, utility scale, dispatchable, renewable energy in the form of heat or electricity. Concentrated Solar Power (CSP) is the electricity generation subset of CST. Alongside technologies such as PV with battery storage and pumped hydro energy storage, CSP has the potential to contribute to a future low-cost Australian electricity system with a high proportion of renewable energy.

Worldwide the installation of CSP plants has seen a recent increase, especially in areas like South America, Northern Africa, the Middle East and China. While Australia has not seen many recent installations of CSP plants it is very well suited for low-cost CSP plants based on the high level of solar irradiation. Most recent studies have identified near-term opportunities for CSP plants on the fringe of grid and mid-term opportunities for larger CSP plants to replace aging coal-fired power plants to lead Australia to a more environmentally friendly power generation solution. These opportunities can only be realised with a significant reduction in cost of CSP plants over the existing solutions.

One of the key roles for the Australian Solar Thermal Research Institute (ASTRI) is to accelerate the reduction of the cost of CSP plants to match the need for commercial uptake in the time frame required by the Australian energy market. The Australian research institutions comprising ASTRI are also collaborating with U.S. research institutions undertaking CSP research (under the auspices of the U.S. Department of Energy's SunShot Program), to extend existing research collaborations including those established pursuant to the United States-Australia Solar Energy Collaboration.

The advances in CSP technology and reduction of cost will ensure CSP becomes part of the future mix of clean energy generation and enable Australia to transition to a higher level of renewable power generation. This will be a key part of a future affordable, environmentally friendly and reliable energy system.



Dietmar Tourbier  
Director, Australian Solar Thermal Research Institute, CSIRO

# ASTRI at a Glance

## Who we are

The Australian Solar Thermal Research Institute (ASTRI) is a consortium of leading Australian research institutions collaborating to help manage the transition to a low carbon energy system, as well as positioning Australia as a global leader on CST.

## Grant Recipient

CSIRO

## ARENA Funding

\$35 million

## Total Project Value

\$87.3 million

## Partners

- Australian National University
- The University of Queensland
- The University of Adelaide
- University of South Australia
- Queensland University of Technology
- Flinders University

## The Challenge

Australia boasts an abundance of solar resource. Our climate and landscapes have shaped a unique distribution of people, industry and resources resulting in a highly distributed national electricity grid and centralised load centres mainly along our Eastern and Southern coastlines. With growing concern over the impacts of climate change, energy markets are experiencing a rapid transition to renewable energy. This transition will require renewable energy solutions that can deliver power day and night.

CSP is a technology that can store solar energy and then send it out when required. Given the future importance of energy storage to a secure and reliable electricity supply, CSP has the potential to be an important part of our energy mix. Embedding CSP in Australia will have its challenges and will require new expertise and capability. Australia has the research expertise to develop leading-edge CSP technologies and to facilitate their commercial uptake to ensure that all Australians have access to affordable and reliable clean energy.

## Approach and Innovation

The ASTRI research team brings together experts both locally and internationally to meet the research challenges associated with next generation CSP systems and to leverage breakthroughs in CSP technologies globally. Our researchers are recognised authorities in their respective fields and our Institute Steering Committee informs our activities through their knowledge of technology and commercial developments around the world. With linkages to institutions in the US and Europe, ASTRI is well-positioned to deliver an optimised solution comprising cutting-edge technologies tailored to Australia's unique energy landscape. All of this is made possible with the support of the Australian Renewable Energy Agency and their commitment to developing affordable and reliable renewable energy.

Affordability requires low-cost supply. In order to achieve our targeted cost reductions, the next phase of the ASTRI program will focus on greater industry engagement to attract stronger market interest in the technologies and accelerate commercial uptake. By raising Technology Readiness Levels (TRL), ASTRI seeks to de-risk CSP component technologies to a level that is likely to attract commercial interest and market uptake. Once the R&D is successful, industry is best-placed to drive further cost reductions from competitive pressures, improved manufacturing processes, volume production and operational experience.

**International Partners**

National Renewable Energy Laboratory (NREL)

Sandia National Laboratories

Karlsruhe Institute of Technology (KIT)

The German Aerospace Center (DLR)

**Outcomes and Impact**

ASTRI aims to have commercially viable, next generation, high temperature CSP technologies developed and deployed in Australia within ten years.

Utility-scale, dispatchable, generation



Reliable supply of electricity

Low cost, multi-hour, energy storage



Fully flexible, low-cost supply of electricity

Firm capacity on demand



Improved system reliability and stability.

Complementary technology



Integrates with other energy technologies

Development of unique CST capabilities and skillsets within Australia



New sources of export revenue and local technical jobs

Broader generation mix with greater proportion of firming load



Affordable, reliable renewable energy. Savings on network augmentation and remote area subsidies

100% renewable energy solution



Reduced CO2 emissions

# The Australian Solar Thermal Research Institute

## Objectives

The Australian Renewable Energy Agency's (ARENA)'s purpose is to accelerate Australia's shift to an affordable and reliable renewable energy future. The Australian Solar Thermal Research Institute (ASTRI) is the primary vehicle for ensuring a coordinated, national approach to CST research, development and demonstration activities. Funded by ARENA, ASTRI was established to shape Australia's research capabilities to support global efforts to develop the next generation of CST systems. ASTRI commenced in late 2012 and, since that time, has been instrumental in establishing Australia as a world leader in CST technology development. This was confirmed in an independent review of ASTRI, undertaken in 2016, which concluded that ASTRI had met and in many cases exceeded its objectives.

During this next phase of the program, ASTRI will continue its efforts to demonstrate a role for CST in the Australian market and engage with industry in bringing proven technologies to market. ASTRI's objectives may be summarised as follows:

- Develop a clear value proposition for CST in the Australian energy market
- Develop and demonstrate the next generation of CST technology and be a leading collaborative research institute and advisor for CST worldwide.
- Develop in-country CST capability and position Australia as a leading authority on CST research and expertise.
- Promote industry takeup of the technology through engagement with both component manufacturers and system developers.

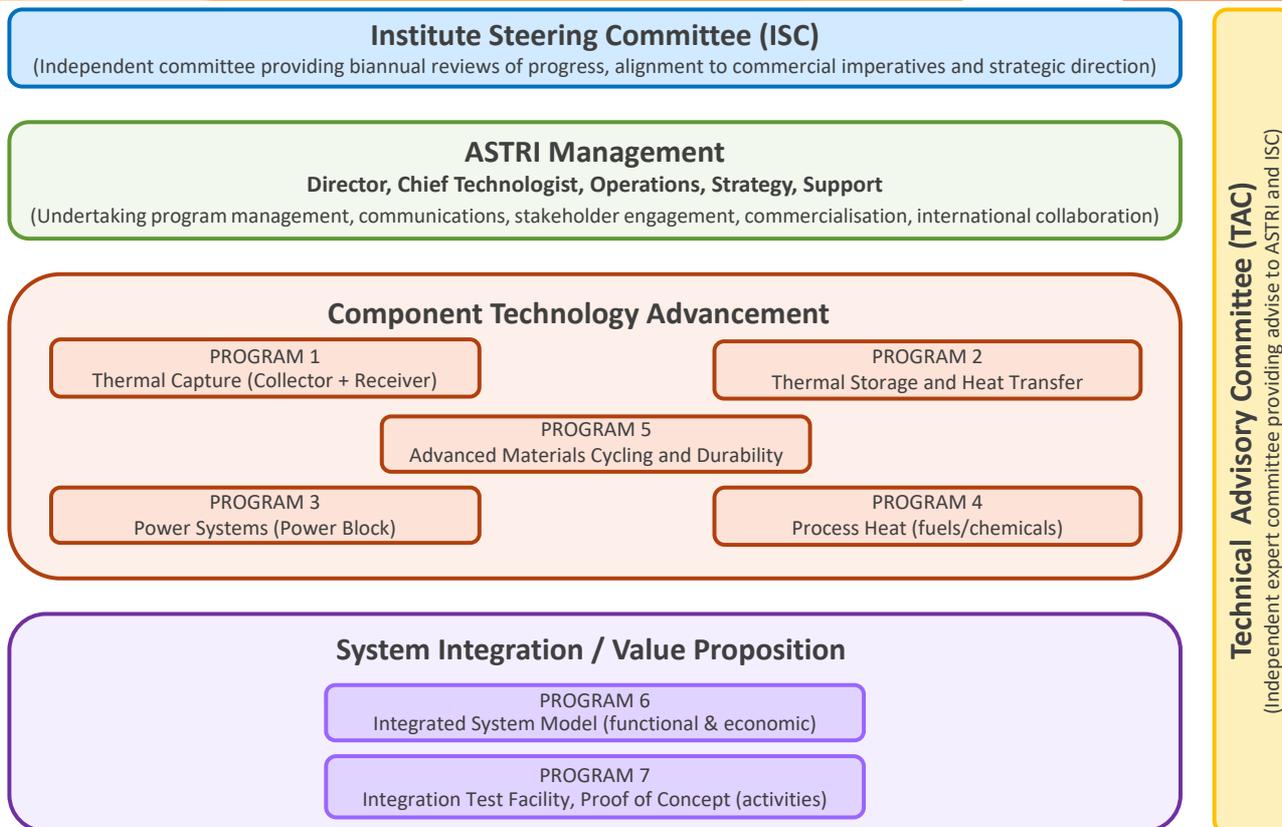
## Structure

ASTRI is an unincorporated joint venture between CSIRO, as the lead organisation, and six leading Australian universities including at this time:

- Queensland University of Technology,
- University of Queensland,
- The Australian National University,
- University of South Australia,
- Adelaide University and
- Flinders University.

ASTRI is given effect through a Funding Agreement between the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Australian Renewable Energy Agency (ARENA). ASTRI has a dedicated management team that is responsible for ensuring that ASTRI's key objectives and outcomes are achieved in a timely and competent manner. ASTRI is governed through the following structure:

- a. the Institute Steering Committee (ISC);
- b. the Technical Advisory Committee (TAC); and
- c. the ASTRI Director, Chief Technologist, Operations Manager, and Commercial Strategy Manager



**Figure 1. Current institute structure**

In addition to the above, the ASTRI structure also includes Program Leaders and Project Leaders. Program Leaders are responsible for managing program outcomes through the conduct of various supporting projects. These projects are managed by Project Leaders. Corporate and technical governance of ASTRI is overseen by the ISC and TAC respectively.

As lead organisation, CSIRO is responsible for the effective conduct of the institute and delivery of ASTRI program objectives. The ASTRI partnership is given effect by a Collaborative Research Agreement (CRA) between CSIRO and the partner universities as well as individual Project Agreements.

Project Agreements are typically shorter duration and specific to a particular project activity. They set out specific deliverables, partners to the project, milestone payments resourcing requirements and treatment of Intellectual Property.

## Governance

### Institute Steering Committee

The Institute Steering Committee (ISC) is an advisory body overseeing governance, management, and operations of ASTRI and delivery of its key objectives and outcomes. The ISC provides guidance and advice to ASTRI on the direction, conduct and application of its research, development and demonstration activities. In providing this advice, the ISC seeks to ensure that ASTRI is meeting its technical, economic and strategic objectives, within agreed timing and performance parameters. The aim being to ensure that ASTRI’s work



activities remain focussed on commercial uptake and system performance outcomes, as specified in ASTRI's Strategic Plan.

The ISC serves in an advisory capacity only. The ISC and ISC members do not have any executive powers, supervisory functions or decision-making authority in relation to the operations of CSIRO or ASTRI.

### **Technical Advisory Committee**

The Technical Advisory Committee (TAC) is responsible for providing technical and research advice and recommendations to ASTRI management and contributing to the development of Institute plans and reports. In addition, the TAC assists in developing collaborative partnerships with national and international research and industry bodies where consistent with ASTRI Strategic Plan. Composition of the TAC includes technical experts from industry, and non-affiliated research intuitions.

The purpose of the Technical Advisory Committee (TAC) is to provide strategic technical and scientific advice to the ASTRI management team and the ISC (if requested) on the activities and content of the Research Program to assist ASTRI achieve its strategic objectives.

## The Technology

### Concentrated Solar Power

CSP is a system of integrated components that together convert thermal energy into dispatchable electricity. The core technology elements include thermal capture (heliostat field with central tower receiver), thermal storage/heat transfer and heat engine/electricity generation. CSP technology is not new. The first parabolic trough system was developed in 1866 and powered a steam engine. Later parabolic trough systems were developed for irrigation purposes.

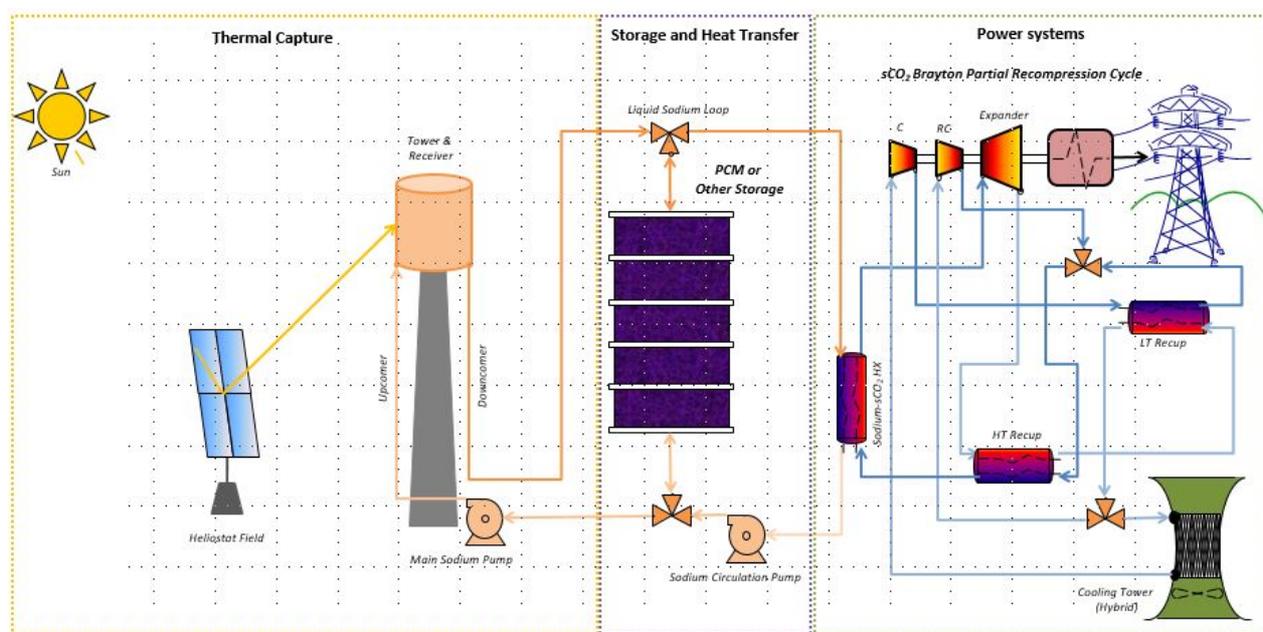
In 1968, the first system to use a heliostat field with a central receiver was commissioned in Italy and produced 1MW using a steam turbine. Since then, CSP installed capacity has reached over 5 GW globally with most of the growth occurring in Spain (2.3 GW) and the US (1.7 GW). Despite this uptake, CSP systems struggle to compete on price with photovoltaic (PV) solar panels which have seen exponential growth over the last two decades as a result of government subsidies, improvements in efficiency and significant cost reductions from mass manufacturing and industry competition. This market disparity is about to change as grid operators face the difficulty of balancing a complex system with a much greater penetration of intermittent sources of generation (such as wind and solar PV).

Next generation, high temperature CSP systems, promising heat to energy efficiencies of around 50%, offer firm, dispatchable generation with storage capacities of greater than 16 hours. ASTRI is at the forefront of this revolution.



**Figure 2. Crescent dunes in Nevada U.S. uses 10,347 heliostats to heat molten salt producing 1.1 GWh of energy storage, greater than grid-scale batteries worldwide (2018)**

Power-tower technologies, although less commercially advanced than trough systems, offer higher efficiency and better energy storage capability. A number of next generation, high temperature systems are presently being investigated including falling particle, sodium, advanced molten salts and gaseous heat transfer fluids. ASTRI and its international collaborating partners are researching the most viable pathway with a down select process scheduled for late 2020. ASTRI has taken up the challenge of developing high temperature, high pressure sodium as a heat transfer mechanism in a system designed to operate in temperature ranges up to 750°C. These higher temperatures can deliver significant improvements in system efficiency, size and cost. When linked to smaller, more efficient supercritical CO<sub>2</sub> power blocks, next generation CSP systems can increase system output efficiency by over 20%, offer capacity factors of over 60% (dependent upon system configuration and solar resource) and significantly lower the levelised cost of energy (LCOE). This is achievable with the development of novel technologies from the heliostat field to the turbine, or in solar vernacular, “photons to electrons”.



**Figure 3. Schematic of Central receiver tower system with sodium receiver, phase change material for thermal storage and supercritical CO<sub>2</sub> power block**

## Other Market Applications

CST processes capture a much broader range of applications than CSP. Solar thermal heat energy can be used in the supply of industrial heat, production of solar fuels and processing of chemicals. ASTRI researchers, in a Process Heat program led by the University of Adelaide (UA), are researching process heat opportunities across each of these applications.

### Process Heat

Using process heat direct from the source avoids the losses inherent in conversion to electricity or the uncertainty associated with the long term supply and pricing of gas for heating. The efficiency of direct use of process heat from thermal generation can be as high as 90% and in temperature ranges above 800degC, process heat from solar thermal can make a significant contribution to reducing greenhouse gas emissions. Both current technology and next generation solar thermal could displace gas in manufacturing industries in

regional areas. Some of the CST knowledge ASTRI is developing for electricity generation is also applicable to producing heat for industrial processes. These industrial processes include applications of solar-driven thermochemistry that can be used, for example, in cement production. Thermochemical processes can also be used in reversible reactions to provide long-term storage.

### Solar Fuels

It is important that renewable solutions be developed for all sectors, and this particularly includes transport. CST can be integrated into the transport market in three key ways – through grid-connected electricity for electric vehicles, hydrogen for future hydrogen-fuelled vehicles or using concentrated solar energy to produce “drop-in” fuels such as diesel or jet fuel. The thermochemical processes required for the latter two are endothermic, that is they require thermal energy to be added at temperatures typically higher than that for electricity generation. ASTRI’s particle receiver is capable of producing these higher temperatures. ASTRI is also investigating specific processes for the production of fuels.

## Why Does Australia need to consider CSP?

The Australian energy market is in rapid transition and will continue to be so into the foreseeable future. The convergence of numerous “game-changing” trends, including more engaged consumers, and rapid technology advancements will create some unique integration challenges for the Australian energy market. Central to these challenges is the need to ensure secure, reliable and affordable supply of electricity to consumers.

A successful transition will require markets to adapt to technological advancements on both the demand and supply side. On the demand side, the rapid uptake of behind-the-meter rooftop solar (BTM-PV) installations has resulted in significant changes to demand profiles across the National Electricity Market (NEM) creating load forecasting and system operations issues. As Australian summers get hotter, increasing air conditioning loads will continue to ensure an evening peak demand. Looking forward, electric vehicle uptake will impact on load profiles. This impact will be due to their charging requirements, as well as the possibility of such vehicles discharging electricity back into a household or the grid.



**Figure 4. Behind-the-meter, rooftop solar has recently tipped 5 GW in installed capacity in Australia**

A range of supply-side factors are also driving significant changes in Australia’s energy landscape. Solar rooftop installations have continued their upward trajectory despite the cessation of state-based feed-in tariffs. This reflects a maturing of the market, strong competition and significant reductions in manufacturing costs. Investment in larger scale PV plants is also strong with the number of new plants growing by 50% in the year to September 2018. The uptake of battery storage, in both residential and utility scale markets, will also impact on supply dynamics.

All of these demand and supply changes are occurring against a backdrop of aging conventional power generation infrastructure. Over the next two decades, AEMO anticipates the retirement of almost a third of Australia’s conventional generation capacity. While the lost capacity is expected to be replaced by renewable energy, it is the loss of the firm capacity provided by conventional generators that creates the greatest transitional challenge.

CSP is a technology that provides low cost utility-scale dispatchable, renewable energy and, while still in the early stage of global deployment, has been recognised by ARENA as a technology option that should be supported moving forward. This reflects current market views that there is no one single technology solution for Australia, with a mix of energy storage and generation technologies required to meet our future needs. It also reflects the view that markets should be provided with a range of viable technology options, to ensure that the optimal mix of technologies, from a cost and reliability perspective, is deployed.

In 2018, ARENA funded the development of a CSP Roadmap to examine commercial deployment pathways for CSP in Australia. The Roadmap indicated that CSP, in combination with other technology solutions, would play a role in Australia's future energy mix. Three key areas were identified.

1. CSP with 8+ hours of storage would provide a least cost solution within the transmission network, in areas of high solar irradiance.
2. CSP as part of a hybrid PV and battery system would provide a least cost solution in the distribution network in fringe of grid locations, and remote locations, where a high renewable energy fraction (>80%) is required.
3. the use of solar thermal energy for high temperature industrial process heat application as a means to improve the competitiveness of Australian industry in a future carbon constrained trading environment.

The CSP Roadmap concluded that CSP can play an important role in Australia's future energy mix by reducing energy costs and maintaining high levels of system reliability in both the transmission and distribution network.

## ASTRI Highlights and Achievements

The reporting period of 2018 and part of 2019 has been transformative for the ASTRI partnership from technical, operational and strategic perspectives. During this period a new governance structure was established as described in the “Governance” section above. The formation of both the Institute Steering Committee and the Technical advisory committees has drawn in local and international experts from government, industry, academia and market operations to ensure a broad representation of stakeholder groups and a diversity of opinion and ideas. During the reporting period, the ASTRI management team developed and presented to the ARENA board a comprehensive Strategic Plan highlighting the proposed technical direction and commercial agenda for the remaining term of the program. On the technical front, the ASTRI partners continued to progress the research effort and reported a number of key achievements within each program.

### Thermal Capture

#### Heliostat Field

During the reporting period, researchers from CSIRO and the University of Adelaide completed comprehensive wind-tunnel measurements on heliostats across a full range of azimuth and elevation angles, at various levels of turbulence intensity. This information will be used to compile a set of wind load design guidelines for prospective developers which can be used to optimise optical and structural components of the heliostat system.



**Figure 5. Heliostat field and central receiver at CSIRO Newcastle**

The microelectronics market is continuously miniaturising and decreasing the cost of sensors such as CCD and CMOS sensors, GPS, wired/wireless communications, MEMS-based devices, as well as the microelectronics

required to manage power and data processing. As the size and cost of these devices reduce, opportunities arise for low-cost control or monitoring systems to be deployed into heliostat systems. ASTRI researchers continue their work on design, development and testing of new microelectronic power, alignment and data processing technologies, within operational heliostats, to demonstrate improvements, and better inform commercial uptake and deployment of these technologies.

## Receivers

The ANU team is approaching final assembly of its purpose-built, sodium loop which will allow lab-scale testing of sodium systems at up to 750°C. Commissioning of the loop and associated control systems is expected by the end of 2019. The sodium laboratory at ANU will be used for testing thermal storage concepts in ASTRI, including a phase-change material (PCM) storage tank, a packed-bed storage concept, a commercially-available graphite-based storage technology and a miscible gap alloy concept. The loop will be used for testing sodium receiver sub-modules, making use of the high-flux solar simulator, and for carrying out corrosion tests at elevated temperature, to determine which materials are best suited to next-generation sodium-based CSP technologies.

ANU and CSIRO researchers completed a preliminary design of a high-performance, sodium cavity receiver. Analyses indicate that sodium cavity receivers will offer significant performance advantages due to their ability to operate at higher temperatures than conventional molten salt receivers and their ability to successfully address high flux operations and the impact of thermal stresses. Some challenges, like sodium drainage, scalability and manufacturing complexity will still need to be addressed prior to commercial readiness of the technology. For optimal performance, the cavity geometry must be tailored to match the optics of the heliostat field.



**Figure 6. First ANU cavity receiver design showing coiled pipe (containing Heat Transfer Fluid) and cavity aperture. Latest designs, which are subject IP protection, improve on the cavity concept.**

The ASTRI team selected liquid sodium as the preferred heat transfer fluid (HTF) because:

- it has a broad liquid temperature range suited to higher temperature CSP applications;
- it has outstanding heat transfer properties which allow for innovative new receiver configurations to minimise heat loss;
- it is compatible with affordable containment materials, so long as impurity levels are well-controlled; and
- it has been extensively used in the nuclear industry as a heat transfer fluid and accordingly there is a significant amount of technical and operation data.

In addition, an on-sun test of a CSIRO receiver (approx. 700kWth) with high temperature sodium is planned for 2020.

ASTRI's Particle Receiver research team, led by CSIRO and supported by the Australian National University and University of Adelaide, have made significant progress over the reporting period with the completion of detailed engineering designs for a 550~800kWt capacity receiver ready to be sent to manufacturers. Particle receivers consist of particles falling through a cavity, where they are irradiated directly by concentrated sunlight. The particles are released through an opening at the base of a hopper above the receiver, producing a thin sheet (or curtain) of particles falling through the receiver aperture. A slide gate or similar mechanisms can be used to control the mass flow of particles into the receiver to accommodate varying levels of irradiance. The particles can be heated to temperatures above 1000°C (if necessary), stored, and used to provide heat for industrial processes or electricity production. In optimising the design, researchers successfully cold-tested a multi-stage, falling particles receiver designed to obstruct and slow the passage of particles across the aperture. This increases residence times and helps maintain a consistent curtain of particles as they descend.



**Figure 7. The staged falling particle receiver on the right, provides a more stable particle flow and increases residence time**

A significant advantage of particle receivers is that the particles can be irradiated directly, eliminating heat-transfer resistance and flux limitations associated with indirect heating through tube walls (as occurs in liquid receivers). The key advantages of particle receivers include:

- can operate at a wide temperature range;

- does not freeze/solidify in piping;
- can achieve temperatures over 1000°C;
- there is no trace heating;
- involves direct heating of particles – simpler and cheaper design with no complex material issue
- involves direct storage of inexpensive particles; and
- particle handling/heat exchange/storage is well established.

During the reporting period, progress was made on other critical system components. This includes:

- Commencement of fabrication of a heat transfer test rig
- Development of a high efficiency, low cost and scalable heat exchanger
- Development of wind and water tunnel test rigs
- Design of a dual-tank, thermal storage silo and
- Development of a comprehensive system performance model

These are critical milestones in the team's progress toward Gen2 testing in Sep/ Oct 2020.

### Thermal Storage

Thermal Energy Storage is a critical enabler of dispatchable renewable generation. The next generation systems under development by ASTRI researchers led by the University of South Australia team will operate at temperatures exceeding the operating range of existing molten salt systems.

During this reporting period, a technoeconomic analysis of various types of thermal energy storage systems for the next generation solar thermal power plants has been completed. The analysis showed that the storage options pursued by ASTRI can achieve the SunShot target of \$0.06USD/kWhr, while phase change material (PCM)-based thermal energy storage systems could deliver the lowest LCOE.

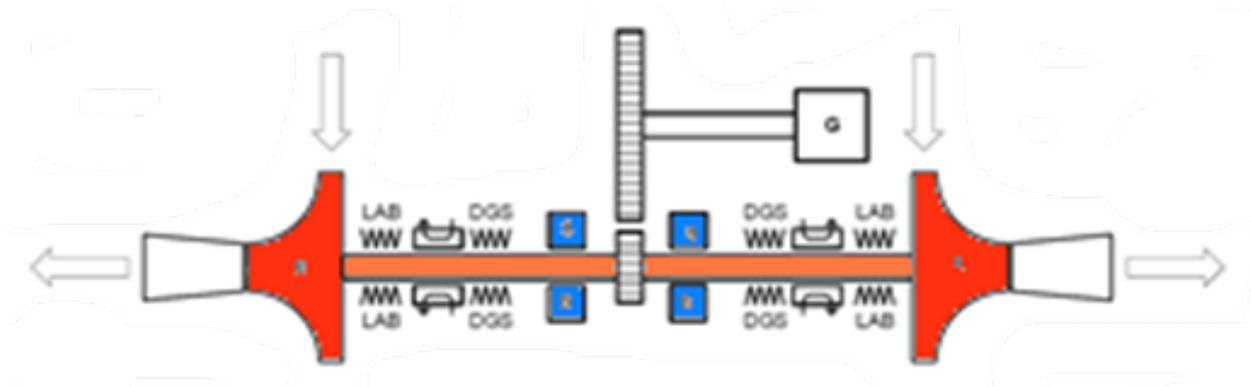
Considerable effort has been devoted to better understanding high temperature PCM's. ASTRI research has shown that they are still stable after 200 cycles, corrosion reactions with stainless steel 316 are minimal (tested up to 400hrs) and that the reaction with supercritical CO<sub>2</sub> is benign. A manufactured cost has been provided by industry for a PCM prototype design and quotes for a larger PCM tank and Na/CO<sub>2</sub> heat exchanger suitable for the Integrated Test Facility.

### Power Systems

The use of supercritical carbon dioxide (sCO<sub>2</sub>) promises a step change in efficiency and at a lower capital cost than conventional steam-powered (Rankine cycle) turbines. Carbon dioxide takes a gaseous form at standard temperature and pressure (STP) and a solid form when frozen. If pressure, and to a lesser extent temperature, of CO<sub>2</sub> are increased from STP conditions to be at or above its critical point, it can adopt properties midway between a gas and a liquid. Specifically, it behaves as a supercritical fluid above its critical temperature, expanding like a gas but retaining the density of a liquid. In this form, sCO<sub>2</sub> is extremely effective at driving a turbine.

Led by the University of Queensland (UQ), ASTRI researchers have completed preliminary designs on a sCO<sub>2</sub> radial turbine able to generate electricity up to 30MW. Their "back-to-back" rotor design employs a sophisticated cooling zone between the Labyrinth and Dry Gas seals. A dual-seal (dry gas) arrangement separately seals against temperature and pressure and helps reduce radial stiffness across the unsupported length. The design of the cooling zone represents a significant design breakthrough given that heat transfer data at the proposed speeds, temperatures and pressures did not exist. This design breakthrough was

possible by one ASTRI PhD student developing the appropriate set of CFD-based and experimentally-verified heat transfer correlations.



**Figure 8. Schematic of dual-rotor turbine design proposed by UQ showing placement of Dry Gas Seals (DGS) and Labyrinth seals (LAB)**

Discussions with potential manufacturers have generated an interest in collaborating on manufacture of a prototype and the use of facilities for testing. Similarly, a number of industry partners have been approached to supply a gearbox.

ASTRI has developed world class capabilities in sCO<sub>2</sub> Power Block Technology. During this reporting period ASTRI has developed detailed sCO<sub>2</sub> cycle models to understand their performance under a range of ambient conditions, and validated these models against a high pressure refrigerant and sCO<sub>2</sub> test loop. Supercritical CO<sub>2</sub> radial inflow turbines have been investigated in relation to rotor dynamics and aerodynamics. A crucial component of these turbines is the bearings, and foil bearings have been investigated for their performance under steady state operation as well as transient response to rotor dynamic excitations.

The UQ team has also evaluated five options for the development of a Low-temperature Aerodynamic Test Facility. These include:

- A refurbished UQ Pinjarra site with high-temperature capabilities
- UQ Pinjarra Hills site using CSIRO equipment
- CSIRO Newcastle site
- SouthWest Research Institute, San Antonio, Texas
- Chinese Academy of Sciences, Innovative Power Systems Laboratory, Hengshui

### Process Heat and Solar Fuels

The application of concentrated solar energy goes beyond electricity generation. As part of the ASTRI strategy ASTRI Management has selected five projects to be further developed:

#### Solar hybridised dual fluidised bed (SDFB) gasification

This technology employs concentrated solar thermal heat to drive the gasification process of agricultural residues. The project, led by the University of Adelaide, is integrating the ASTRI solar particle receiver technology with the commercially-available dual fluidised bed technology, which was chosen because its operating temperature of about 850°C is quite compatible with the solar technology.

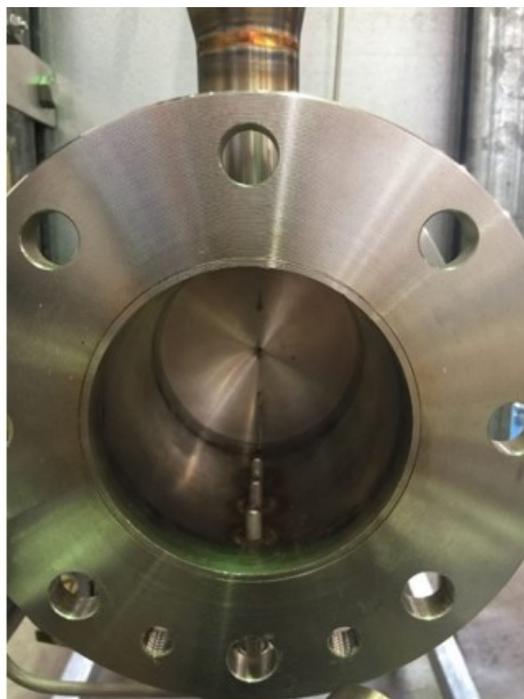
The ASTRI project is targeting a range of feedstock with both a good biomass and solar resource, including rehabilitated mine sites, cotton stalk and some sugar mills, seeking to convert the solar biomass into liquid

fuels, such as synthetic diesel, to achieve a circular economy for these regions through sustainable fuels production. Recent work has been focussing on the development of a char separator, to separate the char from the bed material, together with techno-economic assessments.

### **Solar bubble receiver/ reactor**

The solar bubble receiver has been developed to allow the use of molten metals for their catalytic effects and/or excellent heat and mass transport for solar thermo-chemical processes. Bubbling media were chosen because, although their high rates of heat and mass transport are well known in other fields, they had not previously been applied to solar thermal receivers. Recent work at the University of Adelaide has developed a patented configuration and confirmed high rates of heat transport through a paper recently published in the international Journal of Solar Energy. Six other papers published in the Journal of Applied Energy, Solar Energy and the Journal of Energy Storage compared the performance of Red-Ox reactions of metal oxides in solid and liquid phases, identifying the potential to achieve a high energy density over a range of temperatures spanning 800-1200°C. Current work is now targeting its application in hydrogen production, using bubbling media because of its strong potential to lower the reaction temperature over their solid reaction media counterparts. This is desirable because it reduces both the radiation losses and the constraints on the heliostat field, offering a pathway to further lower the potential production cost.

The Hydrogen-Sulfur (HyS) cycle has been identified by the US DoE as a cycle of highest priority for H<sub>2</sub> production and demonstrated by the German Aerospace Centre (DLR) at TRL-5 under the European projects HYTHEC and HycycleS. This previous work developed a directly irradiated solar receiver/reactor, in which a catalytic coating (Fe<sub>2</sub>O<sub>3</sub> or CuFe<sub>2</sub>O<sub>3</sub>) was applied to a SiSiC honeycomb structure to decompose sulphuric acid (H<sub>2</sub>SO<sub>4</sub>). However, the use of solid-state catalysts under conditions of relevance to HyS cycle is technically challenging due to the heat transfer constraints in the gas-solid systems, corrosiveness of the gaseous reactant/products, deactivation of the catalysts under the harsh conditions, inevitable thermal shocks associated with the abrupt fluctuations in the intensity of the concentrated solar thermal energy (CST) and the intermittent nature of solar thermal energy. The patent-pending SBRR offers tremendous potential to address these limitations through the use of a molten phase catalyst, which has been recently developed and demonstrated. The ASTRI project will develop the second generation of the HyS cycle (HyS Gen2), through demonstration of the cracking of sulphuric acid, as the key step in HyS cycle, using a molten catalyst in an SBRR. The project will also identify potential alternative applications of HyS cycle to co-produce hydrogen, oxygen and sulphuric acid for the copper industry in Australia.



**Figure 9. The solar thermal bubbling receiver, under development at The University of Adelaide for hydrogen production**

### **Advanced Sabatier**

Photocatalysis is an emerging technology that has the potential to generate fuels directly from solar energy. The best known example is water-splitting but it has also been demonstrated for CO<sub>2</sub> reduction (to produce hydrocarbons such as CH<sub>4</sub> and MeOH) and there are a few examples for N<sub>2</sub> reduction (into ammonia). The photocatalytic reduction of CO<sub>2</sub> to clean, versatile hydrocarbon fuels using solar radiation not only provides an energy efficient and renewable energy source but when coupled with other fuel production processes is able to effectively reduce the CO<sub>2</sub> footprint of the whole system and turn a waste product into profit. The simplicity of photocatalysis means that little capital expenditure is required and operational costs are also small. For this reason, techno-economic assessments of photocatalytic water-splitting technology have shown that hydrogen produced by this approach could be competitive even against fossil fuel-sourced products.

Within ASTRI, the University of Adelaide and Flinders University teams have developed suitable catalysts to form hydrogen (H<sub>2</sub>) from water under photocatalytic conditions and used the hydrogen to reduce CO<sub>2</sub> directly to liquid hydrocarbon fuels such as methanol and longer hydrocarbons. We have successfully identified metal cluster-based catalysts for both reactions, characterised their properties to develop a deeper understanding of what makes them active and improved their stability and longevity. Based on these results, we have further identified metal cluster-based photocatalysts that combine the two reactions in a single photo-reactor and undertaken investigations into their effectiveness.

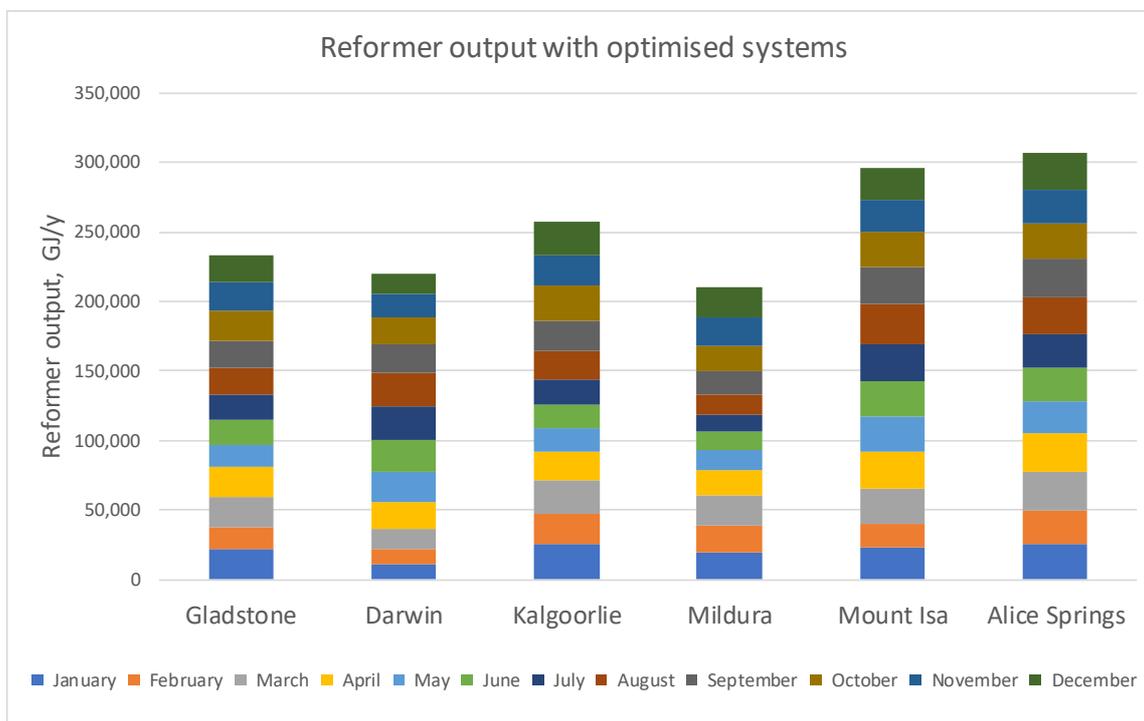
### **Supercritical water gasification (SCWG)**

ANU conducted techno-economic evaluations of biomass-to-fuels processes. The processes used microalgae as the feedstock, assumed to be grown in seawater raceway ponds on non-agricultural land. The microalgae is gasified under conditions of high pressure and temperature in order to produce the carbon monoxide and hydrogen mixture referred to as syngas, as well as a small fraction of methane. This methane is further processed using several alternative steam reforming options to produce additional syngas. The syngas

composition is adjusted by either dumping carbon dioxide as a waste product, or by adding hydrogen from a separate photovoltaic-powered water electrolysis process. The syngas is then fed to a standard Fischer-Tropsch process which converts the gas in to liquid hydrocarbons suitable as a drop-in replacement for standard transport fuels. The modelling completed during this period included an evaluation of the sensitivity of this overall process to the cost of the make-up hydrogen supply. It was found that the cost of hydrogen is a key determinant in which kind of reforming process should be selected. This work (Shirazi et al., 2019) was published in the journal Energy Conversion and Management <https://doi.org/10.1016/j.enconman.2019.04.008>.

### Solar reforming of renewable carbonaceous feedstocks

Solar reforming of natural gas has been identified as one of most cost-effective paths towards production of liquid fuels that are equivalent to current conventional fuels, but uptake is hindered by a past lack of suitable thermal storage technologies that can improve the reliability of the process and the relatively limited (~25%) renewable input into the fuels. An assessment of the application of particle receivers and storage has indicated that high capacity factors at temperatures appropriate for reforming (800-850°C) can be achieved at competitive cost for a broad range of Australian sites. The assessment is now being expanded to consider linkage to biogas production sites where waste heat from the solar process can be applied to increasing biogas production in combination with enhancing the biogas value through solar conversion to high value liquids with 100% renewable content. During the reporting period an abstract submitted and accepted for a presentation at the 2019 Asia-Pacific Solar Research Conference.



**Figure 10. Annual production of reformed product from a 50MWt particle receiver system at a range of Australian sites**

### Advanced Materials

One of the key challenges for high-temperature CSP application will be the identification of suitable materials that can last at the high operating temperatures and are compatible with the heat transfer fluids, the power cycle working fluid and the thermal energy storage medium. The aim of this project is to de-risk future

investment in CSP through the identification and appropriate testing of candidate materials at the ASTRI temperature and environmental conditions.

During the reporting period the Advanced Materials team led by the Queensland University of Technology and Flinders University has made significant progress in the evaluation of suitable materials for high-temperature CSP. Three priority areas were identified – sodium containment, compatibility with sCO<sub>2</sub>, and PCM compatibility. A shortlist of containment materials for application in the ITF has been identified. In addition, a shortlist of potentially suitable materials has been identified for long term environmental testing under the ASTRI CSP conditions and a detailed test matrix and processes for metals and PCM's completed.

In addition, a number of workshops have been undertaken to consider PCM (salt)/containment metal and sCO<sub>2</sub>/containment metal to agree on materials for testing. An important analysis was conducted looking at material cost vs strength – the cost impact of using superalloys can be substantially mitigated by being able to use less material to achieve the same strength outcome.

Internationally, the US DoE Gen3 program was supported through investigating salt characterisation for the storage concept using a solid salt wall boundary between the liquid salt and the tank wall.

Other work completed included:

- Developed understanding and agreement across ASTRI on failure mechanisms, creep and transient creep and progressed work to determine degradation rates of selected metals in PCM and sCO<sub>2</sub>
- Completed initial exposure/material interaction work for upcoming ASTRI HAZOPS (Na/PCM and Na/sCO<sub>2</sub> interactions)
- Material knowledge gaps at ASTRI design conditions “Materials compatibility for the next generation of Concentrated Solar Power Plants” published in Energy Storage Materials
- Placed order for a state-of-the-art tensiometer to test and understand material strength properties at elevated temperature

## Operating and Maintenance

A key contributor to the cost of today's CSP plants is the cost of operation and maintenance (O&M). In order to significantly reduce the O&M cost a better understanding of degradation of system components as well as more automation for operation and maintenance will be required.

During this reporting period the ASTRI O&M team led by the Queensland University of Technology and Flinders University has considered ways to reduce the cost of mirror cleaning through better understanding the cost of cleaning differently-sized heliostats and undertaking two time and condition-based preliminary studies on the benefits of sectoral cleaning.

A number of papers were presented including at SolarPACES 2018: “In-situ Reflectivity Monitoring of Heliostats Using Calibration Cameras” and “Modelling the Soiling of Heliostats: Assessment of the Optical Efficiency and Impact of Cleaning Operations”, and Solar Energy Journal - “Development and Experimental Validation of a Physical Model for the Soiling of Mirrors for CSP Industry Applications”. There was also attendance and discussion about O&M issues for industrial plants (with potential partners) at CSP Madrid in November 2018.

In addition to the above work on heliostats, degradation modelling was commenced on high temperature coatings for the receiver, as well as for the sCO<sub>2</sub> power block

## Integrated System Model

In the system modelling project, the objective is to determine how a combination of novel CSP system components, such as a sodium receiver, phase-change material (PCM) storage and high-temperature, high-pressure carbon-dioxide-based (sCO<sub>2</sub>) turbine power block can be combined together in a way that minimises the cost of the electricity produced by the system. It is important to consider the dynamic operation of the plant, including the weather, daily and seasonal changes in the energy available from the sun's radiation. Optical models of the reflector system must also be incorporated, as must the various operational strategies that determine when pumps and turbines are operated, and when electricity should be dispatched to the grid.

In developing the required models of the ASTRI systems of interest, a series of open-source CSP system models are being produced and shared with the global research community, which have led to new collaborations with partners in the United States, Italy, Cyprus and France on major programs such as the 'G3P3' program relating to high-temperature particle-based CSP systems. System models of these particle-based CSP systems, as well as high-temperature salt systems, and the ASTRI sodium-PCM-sCO<sub>2</sub> system have been developed within this period and are being refined as the project proceeds. A journal paper describing the main ASTRI system concept has been submitted and is in review, and there are upcoming presentations from this work at the SolarPACES 2019 (Korea) and APSRC 2019 (Canberra) conferences.

## Strategic Outlook

ASTRI aims to continue to be one of the leading collaborative research institutes and advisors for CSP worldwide. Over the next 4 years ASTRI will support research to develop and demonstrate the subsystems and integrated processes to de-risk solar thermal power generation to enable CSP to be brought to market as an economically competitive or more optimal energy production and storage solution system over other renewable or conventional energy options, to the benefit of the Australian and international community.

The proposed ASTRI R&D program is designed to develop and prove the component and process technologies that would result in a cost of <7c/kWh with at least 4 hours of storage (down from the original ASTRI goal of 12c/kWh). This will require a disruptive approach to all of the components in the system - none of the components in commercial use today would render such a cost reduction. There is also little room for trading off the cost or performance of one component against another – the targets set for each component are each disruptive in their own right, and need to be achieved simultaneously.

### Overarching strategy

There are a number of technologies that, on paper, could contribute to these cost targets. It is essential that the best concepts progress from early stage TRL 2-4 through to TRL 5-7, with a subsequent demonstration of approximately 5MW at TRL 8-9, at which point it would become largely the role of industry to progress further to commercialisation.



This “valley of death” has not been adequately addressed in Australia to date and the role of ASTRI should be to assist the best technology across that gap. Note that TRL 7/8 represents the proposed demonstration project beginning towards the end of the second ASTRI phase, proposed by ASTRI, designed by ASTRI/industry and built by industry.

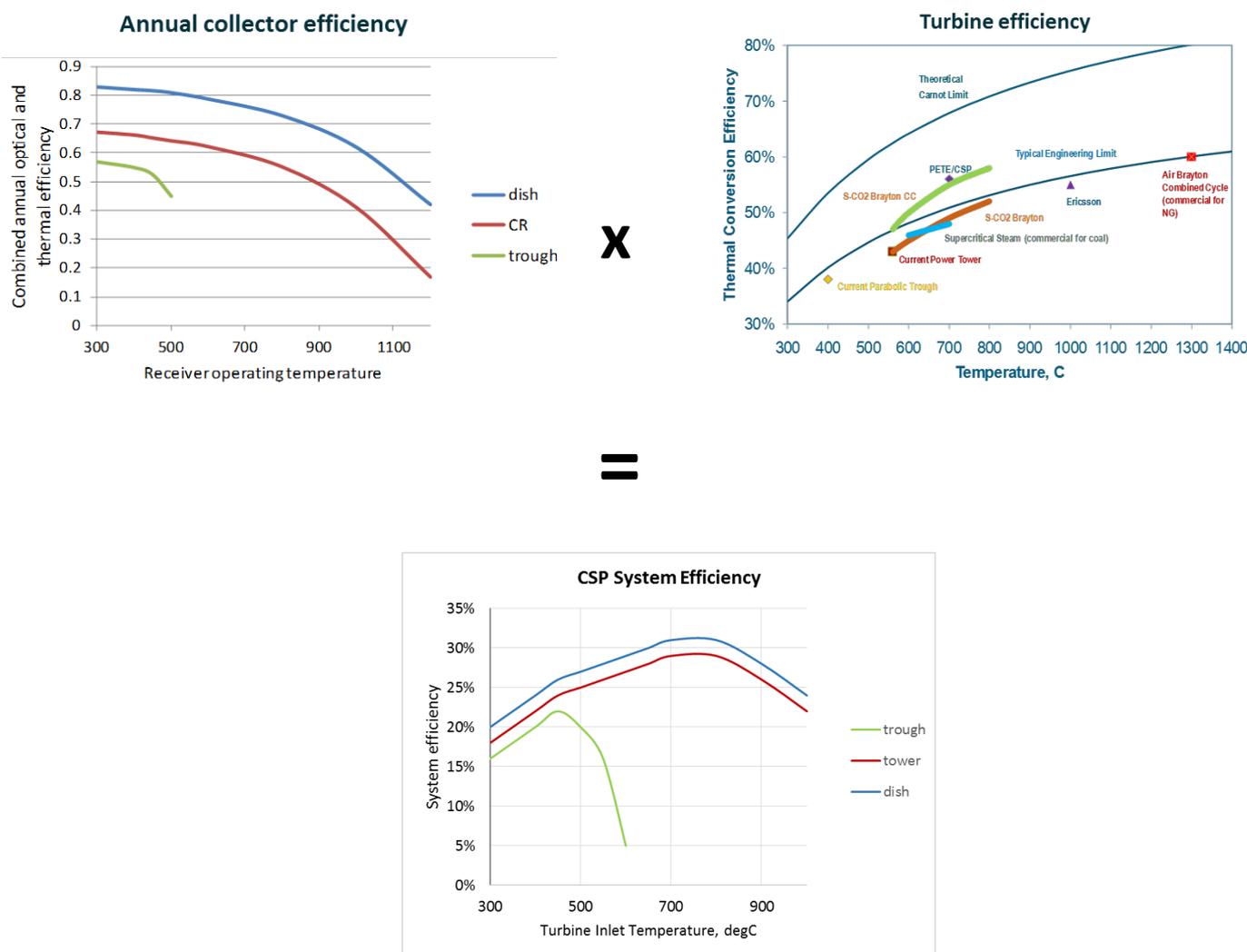
### Approach moving forward

CSP is a system of integrated technologies that together convert thermal energy into dispatchable electricity. The core technology elements include solar collection (e.g. heliostats), thermal capture (e.g. receivers), thermal storage/heat transfer and heat engine/electricity generation. ASTRI proposed future work program focuses on the next generation, high temperature application of these technology elements.

Existing CSP systems operate at 565°C. The ASTRI Program, in close collaboration with international research partners, targets temperature ranges > 700°C. These higher temperatures can deliver significant improvements in system efficiency, size and cost. When linked to smaller, more efficient supercritical CO<sub>2</sub> power blocks, next generation CSP systems can increase system output efficiency by over 20% and significantly lower the levelised cost of energy.

In order to achieve a step change in CSP system cost reduction and system efficiency, ASTRI will pursue solar tower technology, as it is the only technology that can reach the targeted higher temperatures at low cost. The figures below show that the highest system efficiency for tower technology is approximately 700-750°C. Dishes do offer a higher efficiency, but at a much higher \$/m2 cost which more than outweighs the efficiency/performance advantage.

$$\text{CSP System Efficiency} = \text{collector efficiency} \times \text{turbine efficiency}$$



Having selected tower technology, with a target turbine inlet temperature of around 700°C there are a range of component technology choices. Consideration of these choices form the basis of the Phase 2 ASTRI research, development and demonstration program. The new program reflects the evolution of ASTRI Phase 1 activities and key lessons learnt. The proposed Phase 2 builds on successful Phase 1 research outcomes for thermal capture, heat transfer and advanced materials, as well as a more informed understanding of associated CSP component and system integration costs.

Importantly, the Phase 2 Program directly supports ARENA CSP strategy, as recently endorsed by the ARENA Board. It specifically targets research, development and demonstration activities that support the commercial availability of next generation, high temperature, utility scale CST systems in the timeframes required to meet Australia’s emerging dispatchable, renewable energy needs. In addition to supporting domestic

deployment of cost effective CSP Systems, the Phase 2 Program seeks to embed Australian technologies into next generation systems deployed globally.

Over the next two years, ASTRI will develop the following component level technologies

- Thermal Capture – including the design and testing of high temperature sodium receivers where Australia is recognised as a world leader and which builds on the expertise established by ARENA through its investment in Vast Solar.
- Thermal Storage and Heat Transfer – including work on large-scale, Phase-Change-Material (PCM) thermal storage systems and associated heat exchange technologies. Australia leads the world on high temperature PCM research, with such systems having the potential to reduce thermal storage costs by 50%.
- Heat Engine (power generation block) – including work on a super critical CO<sub>2</sub> radial turbine. These radial turbines can deliver a 20% increase in CSP system output efficiency and could support smaller CSP power block applications (up to 20MW) – making them ideal for future fringe-of-grid and industrial behind-the-meter applications. ASTRI's radial turbine work complements international efforts to develop large axial supercritical CO<sub>2</sub> turbines for utility-scale electricity generation.

In support of work on these component technologies, the ASTRI program also seeks to undertake a range of essential support activities including:

- Advanced Materials Cycling and Durability – allowing for an evaluation of the long term impact of higher temperatures on CSP materials, which is critical to understanding whole of life costs and key component maintenance cycles, as well as assisting with material selection for lowest cost appropriate to the duty cycle;
- Integrated system model to understand the cost and capability trade-off between different system components, and what combination provides the optimum balance between cost and system reliability. This model would complement a NREL CSP cost model, with a focus on higher temperature system elements, interactions and associated costing.
- Integrated Test Facility for real world testing of new high temperature components both individually and as part of an integrated test facility. This test facility is viewed as critical to ASTRI's phase 2 program aimed at accelerating commercial readiness on next generation CSP systems. The ability to view new components in an operational CSP test system, will significantly lower technology and investment risk for industry.

ASTRI is currently exploring the options of using existing facilities such as the CSIRO Newcastle heliostat field and sCO<sub>2</sub> loop facility and the Vast Solar liquid sodium CSP demonstration plant in Jemalong, NSW, in order to make use of existing infrastructure where possible. Early discussions with Vast Solar and CSIRO have indicated that both facilities can be available in that time frame, but would need modifications prior to the testing.

After the successful testing of the component technologies ASTRI is planning to go through a down select process and a review to decide on the further improvement in efficiency and cost as well as an integrated demonstration test of a down selected system design in the final two years.

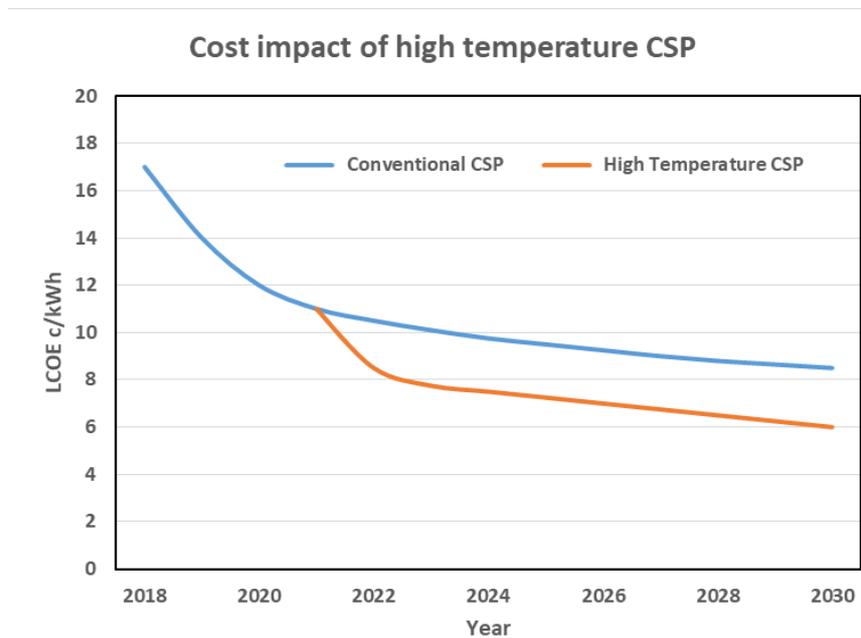
The ASTRI Phase 2 Research Program is primarily focused on high temperature CSP systems for power generation. However, The Phase 2 Program does include a small element of proposed work on solar fuels. This work would build on the solar fuels work undertaken in the Phase 1 ASTRI Program and is included to provide future options for renewable deployment in, and decarbonisation of, Australia's high temperature industrial process heat applications

While the introduction of solar process heat and solar fuels is further into the future than the application of electric power generation from CSP, it has the potential to be a much larger market in Australia for concentrated solar thermal applications. Many of the technologies proposed for the high-temperature CSP systems are also applicable for future solar process heat and solar fuels. Part of the proposed strategy is to identify possible applications for high-temperature solar process heat based on the technologies developed for CSP. The focus on industrial process heat is also aligned with ARENA’s Energy Productivity and Exporting Renewables Strategic Investment Priorities.

ASTRI’s Phase 2 Program has been driven by the imperative to accelerate the commercial readiness of next generation, high temperature CSP systems. To this end, the Phase 2 Program fully reflects the mid-term review recommendations to collaborate internationally and focus on technology pathways of greatest commercial interest to industry. In support of commercial uptake, the Phase 2 Program aims to successfully demonstrate high temperature system components at the test facility level within two years and then work collaboratively with industry to deliver a commercially ready technology into the market within ten-years.



The impact of ASTRI is detailed in the following diagram. Without next generation CSP, the cost of existing CSP systems will follow a tradition learn curve. However, with the success of next generation CSP, there will be a disruptive change in the cost curve, which will see CSP entering the market sooner.



## Collaboration, Engagement and Knowledge Sharing

The ASTRI leadership roles include Principal Investigators providing strategic advice to the Director and responsible for the overall contribution of their organisation, Program Leaders responsible for delivering on key CST technology challenges based on a systems approach, and Project Leaders to deliver quality science with strategic technology outcomes.

ASTRI researchers have been participating in collaboration, project management and supervision of younger researchers. This has resulted in a strong sense of a team and purpose, with high attendance at internal events. Young researchers, such as postdoctoral fellows, have been able to take on project management roles and gain valuable leadership skills and experience.

There has also been a number of partnerships forged with CSP industry, locally and internationally. These will improve both short and long term impact on the goals of ASTRI, as well as for the companies concerned.

### International Collaboration

The US DoE's Generation 3 Concentrated Solar Power Systems (Gen3 CSP) funding program builds on prior research for high-temperature CSP technologies. Projects focus on de-risking CSP technologies by advancing high-temperature components and developing integrated assembly designs with thermal energy storage that can reach high operating temperatures. Three teams compete to build an integrated system with thermal energy storage that can efficiently receive solar heat and deliver it to a working fluid at temperatures greater than 700 °. The Gen3 CSP program is exploring several pathways to achieving higher temperatures for CSP plants—using either liquid, solid particle, or gaseous materials—and this funding program aims to identify, and later demonstrate, a cost-effective and reliable integrated solution. This program will progress through three interconnected phases:

- Phase 1 advances the development of specific components that have been identified as key risks in an efficient, integrated system.
- Based on the results of Phase 1, Phase 2 will focus on designing an integrated system with thermal energy storage that can withstand high temperatures. Designs developed by the Phase 2 awardees will undergo a rigorous review and selection process.
- In Phase 3, one awardee will be chosen to build a test facility that allows diverse teams of researchers, laboratories, developers, and manufacturers to test components and systems through a wide range of operating conditions necessary to advance the next generation of CSP technology.

ASTRI partners are proud to have been selected to participate in the Liquids and Solids pathways.

### Solids Pathway

Sandia National Laboratories was selected as Project lead on the *Gen3 Particle Pilot Plant: Integrated High-Temperature Particle System for CSP* project. This project will design and test a multi-megawatt thermal falling particle receiver system in the first two Gen3 CSP phases. It will have the potential to operate for thousands of hours, provide 6 hours of energy storage, and heat a working fluid like supercritical carbon dioxide or air to a temperature of at least 700 °C. In Phase 3, if selected, the team will validate the ability to meet the Solar Energy Technologies Office CSP cost and performance goals via a commercial-scale test

facility. The ASTRI partners led by CSIRO and including ANU and UA has a significant role to play in delivering the research outcomes required of the program. Specifically, ASTRI responsibilities cover:

### Liquids Pathway

The National Renewable Energy Laboratory was selected as Project lead on the Gen3 *Liquid-Phase Pathway to SunShot* project. This team will test the next generation of liquid-phase CSP technology by advancing the current molten-salt power tower pathway to higher temperatures and efficiencies. The project will design, develop, and test a two megawatt thermal system consisting of the solar receiver, thermal energy storage tanks and associated pumps, heat exchangers, piping, valves, sensors, and heat tracing. If selected for the third phase, the system will be validated in a commercial-scale test facility.

The DoE GEN3 strategy and the ASTRI strategy have been developed independently, yet they are nearly identical in approach, cost and performance targets and fundamental technologies. Importantly, both are undertaking highly targeted R&D in order to rapidly move to higher TRL, not just undertaking R&D with the hope that it lands on a winner. It is due to this strategic parallel that ASTRI is a collaborating partner in NREL's Liquid Pathway and Sandia's Particle Pathway projects as shown in the table below. Indeed, Australia has the most technical and fiscal involvement of any country. Phase 3 of GEN3, discussed above, involves the selection of a technology to build at demonstration scale in the US. It is entirely plausible that ASTRI's sodium technology could be selected as the receiver of choice.

### Engagement and Linkages

Over the last 12 months, ASTRI has continued to foster close working relationships with leading CST research institutions globally. These relationships allow us to leverage the resources and expertise of major research organisations and also ensures that we are not duplicating research effort. Since inception, ASTRI has proven itself as a valuable international research partner with established links into the National Renewable Energy Laboratory, Sandia Laboratories, the Karlsruhe Institute of Technology and others.

In early 2018, ASTRI researchers were successful in their application for funding and participation in the U.S. Department of Energy Gen 3 program. The Gen3 program is a 4 year, \$USD80m program focussed on identifying the optimal CST technologies capable of achieving the target temperatures (700 degC at the turbine). The primary objective is to develop a fully integrated, next generation, high temperature CSP system ready for industry uptake within the next 4 years. There is strong alignment between the Gen3 and ASTRI program and the US has identified \$AUD15.7m in ATSR work that they would like included in the program.

ASTRI has sought to strengthen ties with the German Aerospace Institute (DLR) and the Karlsruhe Institute of Technology (KIT) who have significant experience in the use of sodium in energy systems. ASTRI is also seeking to explore opportunities in China, which is a large emerging market for CSP technologies.

### Knowledge Sharing

ASTRI's knowledge sharing has continued to gain momentum, with an increase in publications and conference presentations, presenting research outcomes in a range of science and industry forums.

### APSRC

The Asia Pacific Solar Research Conference is Australia's leading conference for renewable energy, with CSP represented in both plenaries and dedicated streams. ASTRI also uses the conference as a time to update members on status and key activities.

## SolarPACES

Australia is a member country of the IEA's SolarPACES (Solar Power and Chemical Energy Systems) Implementing Agreement. Australia has previously hosted the SolarPACES conference (2000) and Executive Committee meetings (2013). SolarPACES is the leading international body for CSP and provides a forum for sharing the latest research, market mechanisms and commercial activity. The annual conference is the largest CSP conference each year and brings together researchers, owners and developers, and investors. Australia is usually one of the leading countries in terms of papers presented at this conference.

Selected ASTRI students are provided financial support from a project within ARENA's International Engagement Program.

## Publications

Scientific publications are a key component of ASTRI's knowledge sharing activities. Over the past 12 months, ASTRI partners have collectively published numerous journal publications through a wide variety of scientific/ research titles. A comprehensive list of ASTRI publications appears on our website at <https://www.astri.org.au/publications/journal-publications/>

## Techno-economic analysis

### System target cost

Recent modelling by Energeia suggests that the unsubsidised price of CSP needs to be less than 7c/kWh in order to be competitive in the wholesale market, and 12c/kWh in small capacity systems in some fringe-of-grid locations, taking into account movements in other technologies such as PV's, wind and batteries. Though LCOE is not the best measure of value in a market with time-based peaks and troughs, this particular figure of 7c/kWh has considered future time-of-day revenue streams with the majority of revenue arising from operation during evening peaks. In broad terms the cost of the technology needs to be reduced by more than 50% from today's prices in order to be competitive by 2030, which is when energy system planners believe that large, utility-scale, dispatchable, renewable energy systems will be required.

It is unlikely that the CSP technology being deployed today (2-tank molten salt central receiver) will be able to reduce costs to this degree. Each of the components – heliostat field at 60% optical efficiency, receivers at 90% thermal efficiency, storage at 98% thermal efficiency and sub-critical steam turbine at 41% efficiency – are working close to their maximum operational performance levels. Cost reductions are still occurring, mostly due to “learning-by-doing” – establishment of supply chains and local component suppliers, lower unit costs through replication and tooling, technical risk reduction, lower cost of finance, etc. This is a fundamental and crucial part of achieving cost reductions but an industry-only approach, without step-change technology improvements, would not achieve the cost reductions in the time frame required.

A typical figure for learning rate for CSP is 90% [IEA]. Specifically, for every doubling of installed capacity there is a 10% reduction in cost. The figure below shows that at 90% learning rate the 7c/kWh target would not be achieved, and even with an 85% learning rate would require deployment of 2.5GWe before market parity was attained.

The following outlines the immense value and leverage of RD&D as part of a sustained strategy. This strategy is based on an accelerated RD&D program targeted at high temperature CSP system.

A coordinated RD&D program, such as ASTRI working in collaboration with international research agencies, and with a subsequent demonstration pilot plant, reaches 7c/kWh much more quickly. Importantly, the required support from outside of the market is reduced by \$0.5B to \$1.6B (including ASTRI plus a future 5MW demonstration project). The key message is that R&D not only significantly reduces the time to reach market parity, but also provides a backbone technology to support a lower cost, cleaner and more reliable Australian electricity supply than would otherwise be the case.

## Partners



Australian  
National  
University



Flinders  
UNIVERSITY



THE UNIVERSITY  
of ADELAIDE



University of  
South Australia



THE UNIVERSITY  
OF QUEENSLAND  
AUSTRALIA