AUSTRALIAN SOLAR THERMAL RESEARCH INSTITUTE

ASTRI Australian Solar Thermal Research Institute

Public Dissemination Report

May 2019

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ASTRI
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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 than 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 Concentrated Solar Thermal (CSP) power.

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 dispersed 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.

Concentrated Solar Power (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 sufficient to attract commercial interest and market uptake. 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 next generation, high temperature CSP technologies developed and deployed in Australia within ten-years as a commercially viable renewable energy option.

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 C02 emissions

Supporting ARENA's Strategic Investment Priorities.

ARENA's Investment Plan, released in 2017, detailed four strategic investment priorities. The ASTRI Program supports all of these investmnet priorities as detailed below.

Delivering Secure and Reliable Electricity: CSP is a technology specially designed to support the delivery of secure and reliable electricity. Through its use of stored thermal energy to generate and dispatch electricity as required, any time of day or night, CSP provides a utility scale option to maintain system strength and reliability in a high penetration renewable energy electricity market. ASTRI's activities will accelerate the commercial readiness of next generation CSP to ensure it is available in the Australian market when dispatchable renewable energy solutions are required in the next 10-years.

Accelerating Solar PV Innovation: CSP allows for high levels of variable or intermittent renewable energy generation. Specifically, when combined with CSP, higher levels of solar PV can be deployed without adverse impact on system reliability. ASTRI's support of next generation CSP Systems therefore aligns well with Australian research efforts to develop more efficient next generation PV systems.

Improving Energy Productivity: CSP systems have the capability to store thermal energy, which can be used for electricity generation, process heat or both. In Australia, over two thirds of energy used by industry is for process heat and CSP can improve energy productivity by providing industry with an alternative source of renewable process heat. While ASTRI's primary focus is on next generation, utility scale CSP systems for electricity generation, many of its activities are directly relevant to smaller scale CSP systems for industrial use. As ASTRI works closely with the commercial sector, it will continue to support industrial behind the meter CSP applications, particularly those involving combined heat and power solutions.

Exporting Renewable Energy: CSP provides renewable energy in the form of process heat or electricity, which can be used to support renewable energy exports (e.g. renewable hydrogen) or Australian commodity exports with high levels of embedded renewable energy (e.g. mineral/metals processing). Solar fuels is another area of research where CSP can be used as the input energy for the production of solar fuels, which can then be used by industry to deliver more cost effective and lower emission products. In developing next generation CSP systems, ASTRI will continue to support the use of next generation CSP to support new export markets and/or increases Australian competitiveness in existing export markets.

In addition to CSP for electricity generation, ASTRI has a small research program focussed on solar fuels. Over the past four-years, this solar fuels program has helped develop new solar thermal applications for the methane reforming and hybrid gas receivers. While ASTRI's immediate focus will be on next generation CSP for power generation, it is hoped that there will be an increasing awareness of the need for a renewable energy research funding program for industrial process applications, which would allow for the continuation of ASTRI's Solar fuels research activities.

The Australian Solar Thermal Research Institute

Objectives

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 CSP 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 CSP systems. ASTRI commenced in late 2012 and, since that time, has been instrumental in establishing Australia as a world leader in CSP 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 CSP 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 CSP in the Australian market
- Develop and demonstrate the next generation of Concentrated Solar Power (CSP) technology and be a leading collaborative research institute and advisor for CSP worldwide.
- Develop in-country CSP capability and position Australia as a leading authority on CSP 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:

- 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

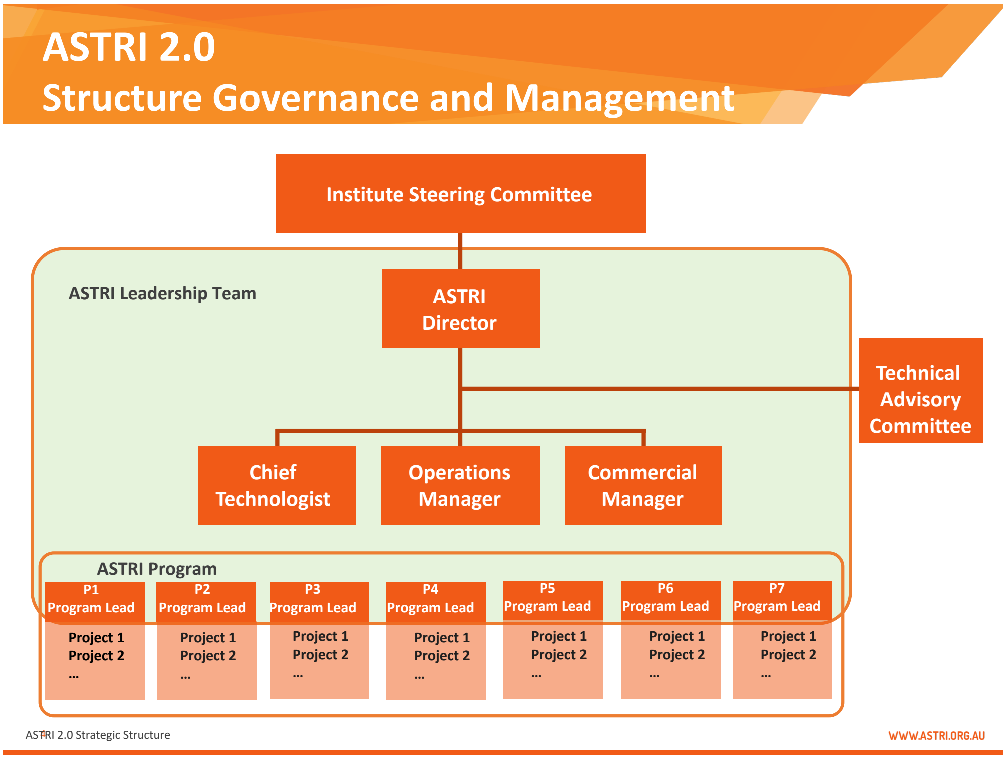


Figure 1 - Institute structure

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)

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 5 GW globally with most of the growth occurring in Spain (2.3 GW) and the US (1.7 GW). Despite this uptake, CST 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 generous 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 up to >16 hours. ASTRI are 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

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 CO2 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".

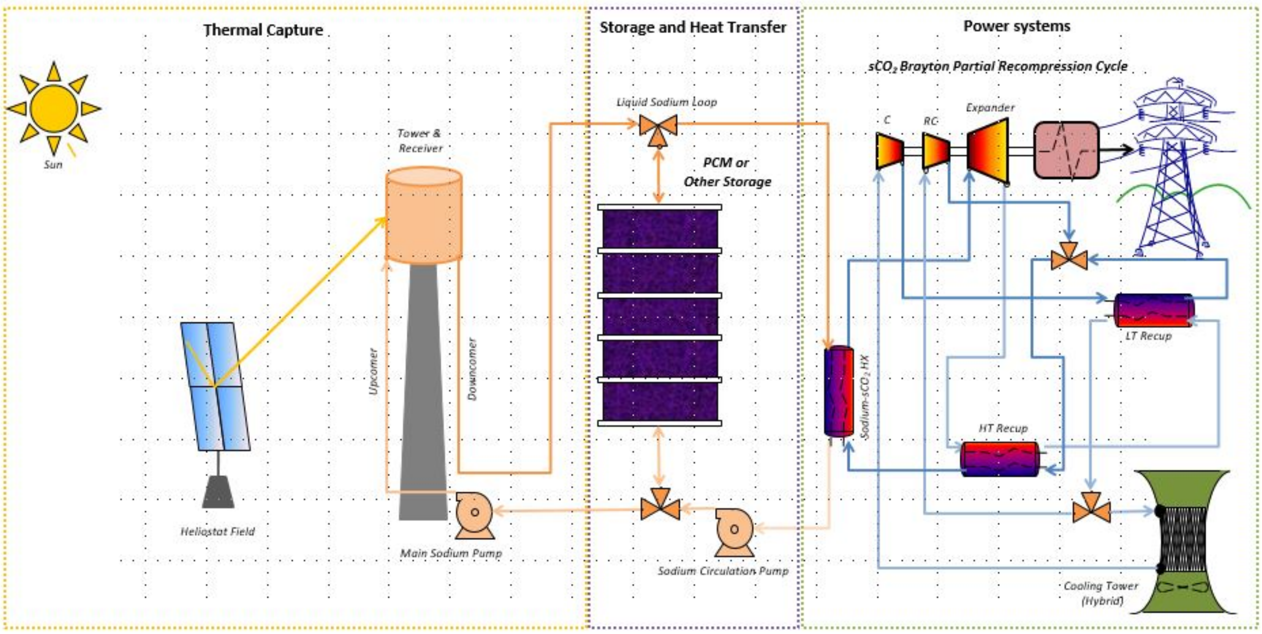


Figure 3 Schematic of Central receiver tower system with sodium receiver, phase change material for thermal storage and supercritical CO2 power block

Heliostats

Heliostats are highly reflective mirror surfaces usually arranged in an elliptical pattern around a central tower and positioned to reflect the sun's rays onto a central point (the receiver) at the top of that tower. To optimise reflectivity at different times of the day and across different seasons, heliostats employ dual-axis tracking devices that constantly monitor and vary the incidence angle and maximise solar flux at the receiver. In terms of optimising overall system efficiency, the heliostat field is the most critical component.

Next generation heliostats will to incorporate

a. condition-based monitoring in order to optimise maintenance expenditure
b. drop-in design for seamless replacement of mirrors
c. anti-soiling technologies
d. advanced coatings for durability

ASTRI have been at the forefront of heliostat design research in an effort to improve efficiency and reduce both capital costs and ongoing maintenance expenditure.

Figure 4 typical surround layout of heliostat field

Receivers

Receivers are designed to capture the concentrated thermal energy from the heliostats and transfer the heat using either a pumped fluid (molten sodium or salt, water/ steam, or air) or particles falling under gravity to a separate storage system. Receivers are critical to overall system efficiencies and next generation designs are working to overcome challenges around temperature ceilings, material durability, storage, heat transfer effectiveness and flow instabilities.

ASTRI research is considering one option using liquid sodium as a heat transfer fluid. Sodium was selected for a number of reasons; it has a broad liquid temperature range suited to high temperature concentrating solar power applications; it has outstanding heat transfer properties which allows 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 therefore there is much R&D and industry experience to draw upon. The main disadvantage of sodium is that it reacts explosively in water, and thus safety standards are of utmost importance. The Australian National University (ANU) are leading this stream of research under the Thermal Capture program.

Storage and Heat Transfer

Thermal storage is a key differentiator for CSP as a renewable generation source. Thermal storage can be achieved with many different materials which may be charged either directly by the sun's rays (such as graphite block or falling particles) or indirectly via pumped heat transfer fluids such as molten sodium or salts. Molten salt systems are unique in that they rely on salt as both the storage material and heat transfer fluid. Thermal Energy Storage (TES) in a CSP plant involves the capture of thermal energy in a material and the use of that heat on demand to power a turbine.

Conventional systems are constrained by either maximum operating temperatures (< 600degC for salts) or potential degradation at high temperatures (graphite oxidisation). ASTRI's Storage and Heat Transfer program team led by the University of South Australia (UniSA), are investigating the use of cascading Phase

Change Materials (PCMs) as a means of storing and releasing large amounts of thermal energy with minimal heat loss. PCMs rely on a change of phase of a material for gaining and releasing energy and will change their phase with a high degree of predictability. This makes PCMs ideal in principle as a thermal storage application.

The major challenges lie in successful integration of multiple PCMs in a system and materials compatibility and durability at very high temperatures (>700 degC) and repeated cycles, as well as poor heat transfer. UniSA are working with the Advanced Materials Cycling and Durability program team, led by Queensland University of Technology, to evaluate a number of PCM or PCM/ graphite combinations that are likely to meet cost, durability and efficiency targets. To evaluate the thermal performance and cost of various storage configurations, simulations were undertaken on a range of storage configurations to run a 50 MWe s-CO_2 power block for 10 hours, with a 6-hour charge time, assuming the thermal-to-electricity efficiency of 50 %. This analysis yielded a comparison table which suggests that a hybrid system utilising PCM and graphite would produce the lowest cost of storage of the tube-in-tank systems. Although two-tank systems in isolation are lower cost, they have either a lower maximum operating temperature (nitrate salts) or are highly corrosive (chlorides). Work is currently being undertaken on identifying the optimal hybrid PCM/ graphite solution.

Power blocks

The power block consists of a turbine connected to a generation unit. It converts pressurised, high temperature thermal energy into mechanical energy used to drive a generator. The most common form of power block is a steam turbine which relies on pressured steam to drive a turbine connected by shaft to a generator. The power block technology that is used in existing CSP plants is typically a sub-critical steam Rankine cycle with limited superheat and reheat stages that has a net efficiency of 35-38%.

There are several reasons for the selection of this power block that include the robust nature of the equipment, availability in a broad range of specifications and plant sizes and limitations to the operating temperature. Steam turbines are notable for economies of scale in both cost and performance terms, so it is difficult to develop a cost effective small CSP power plant using a steam turbine power block. Therefore, development of alternative power blocks that offer higher efficiency and, preferably, are appropriate for use on a smaller scale is an obvious area for improvement in the next generation of CST power plants.

ASTRI's Power Systems program led by the University of Queensland (UQ) has been at the forefront of development of a next-generation turbine using supercritical carbon dioxide (sCO_2) as a working fluid. CO_2 offers significant benefits over steam in that it requires relatively low temperatures and pressures at the cooling end in order to reach its supercritical state and once achieved, it takes a fluid form with very high density and incompressibility making it ideal for use in turbomachinery.

UQ are developing a world-first, radial design turbine suitable for power system operations up to 30MWe. This system will operate at efficiencies of 50 – 60% and will be significantly physically smaller than a steam turbine of similar output given the enhanced properties of sCO_2. This work comes with significant technical challenges given the need for precise clearances, high rotational speeds, heat exchangers or critical sub-components such as bearings and seals.

Other Market Applications

Concentrated Solar Thermal (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. Leading the Process Heat program, University of Adelaide (UA), in collaboration with other ASTRI partners, are researching process heat opportunities across each of these applications.

Industrial Heat

Using process heat direct from the source avoids the losses inherent in conversion from electricity or the uncertainty associated with the long-term supply and pricing of gas. The efficiency of direct use of process heat from thermal generation can be as high as 90% and in temperature ranges above 700degC, 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 manufacturing industries in regional areas. Some of the CSP 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. CSP 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 5. 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.

Solar PV and wind are intermittent generators. Changing cloud cover or wind velocity result in varying levels of generated energy, and managing this variability creates system security and reliability challenges. Conventional power plants are constantly generating and dispatching electricity, independent of weather, and this firm capacity ensures that system reliability is maintained (i.e. there is sufficient supply to meet demand). With the closure of conventional power plants, and the increased uptake of variable Solar PV and wind generation, there is loss of firm capacity and system reliability decreases (i.e. there may not be sufficient supply to meet demand).

The solution to address the loss of firm capacity involves uptake of dispatchable, renewable energy resources. Dispatchable, renewable energy solutions have a stored energy capability that can then be dispatched as required, day or night, to meet system demand. The storage can be decoupled from the generation source. The 2018 Integrated Systems Plan (ISP), prepared by the Australian Energy Market Operator (AEMO), identified the need for a large amount of dispatchable, renewable energy in Australia future energy mix.

The ISP identified solar PV with battery storage, Pumped Hydro Energy Storage (PHES) and Concentrated Solar Power (CSP) as dispatchable, renewable energy technologies currently available to the Australian market. The ISP noted that each technology has different characteristics that may make them suitable for deployment in different circumstances and locations within the Australian energy market. The ISP indicated that the small-scale utility of behind the meter PV and battery systems would likely see it meeting a large proportion of Australia's dispatchable generation needs. The ISP noted that the remaining need would most likely be met by utility-scale, dispatchable, renewable energy solutions, including PHES and CSP, with the amount of required utility-scale, dispatchable, resources steadily increasing from 2025 onwards.

Concentrated Solar Power (CSP) is a technology that provides low cost utility-scale dispatchable, renewable energy in the form of heat or electricity. CSP is well suited to Australia's solar resource 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 Strategy Moving Forward

ASTRI aims to be the leading collaborative research institute and advisor 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.

ASTRI Phase 1	ASTRI Phase 2	Demo project
2013-2018	2019-2022	2022-2024
TRL 2-4	TRL 5-7	TRL 8-9

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.

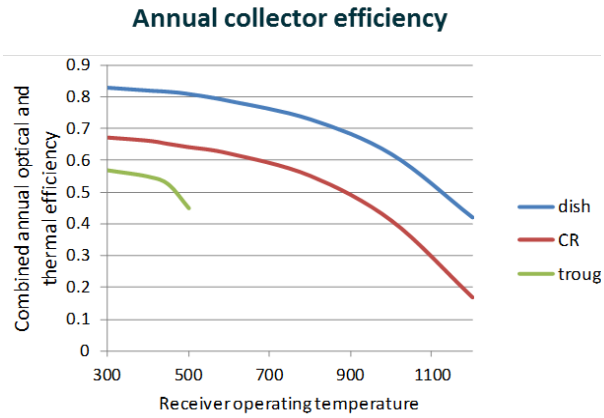
Approach moving forward

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 CO2 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.

CSP System Efficiency = collector efficiency x turbine efficiency



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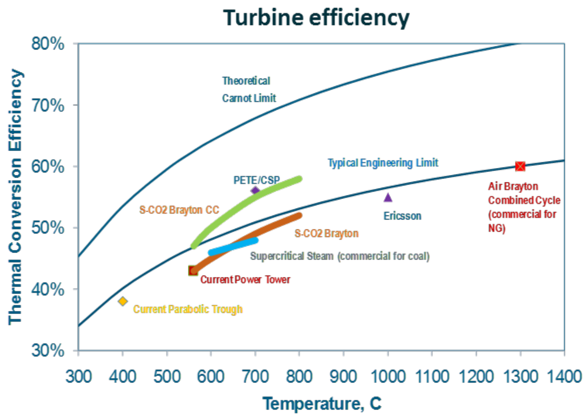

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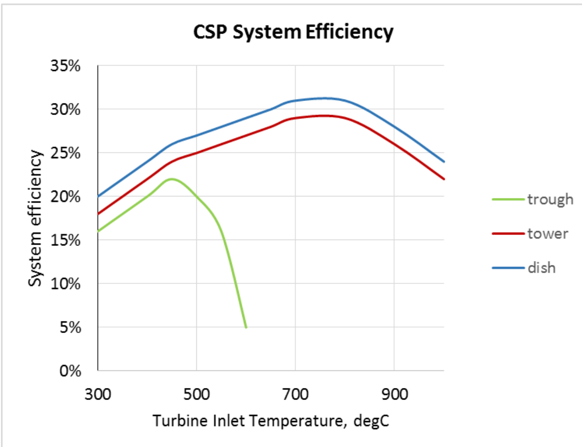


Having selected tower technology, with a target turbine inlet temperature of around 700°C there are a range of component technology choices. Consideration of these choices form the basis of the Phase 2 ASTRI research, development and demonstration program. The new program reflects the evolution of ASTRI 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 CO2 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 CO2 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 significant lower technology and investment risk for industry.

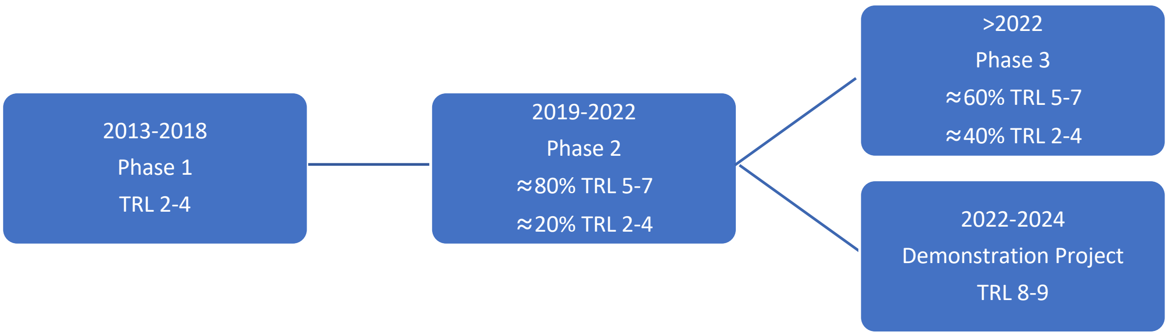
ASTRI is currently exploring the options of using existing facilities such as the CSIRO Newcastle heliostat field and sCO2 loop facility and the Vast Solar liquid sodium CSP demonstration plant in Jemalong, NSW, in order to make use of existing infrastructure where possible. Early discussions with Vast 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.

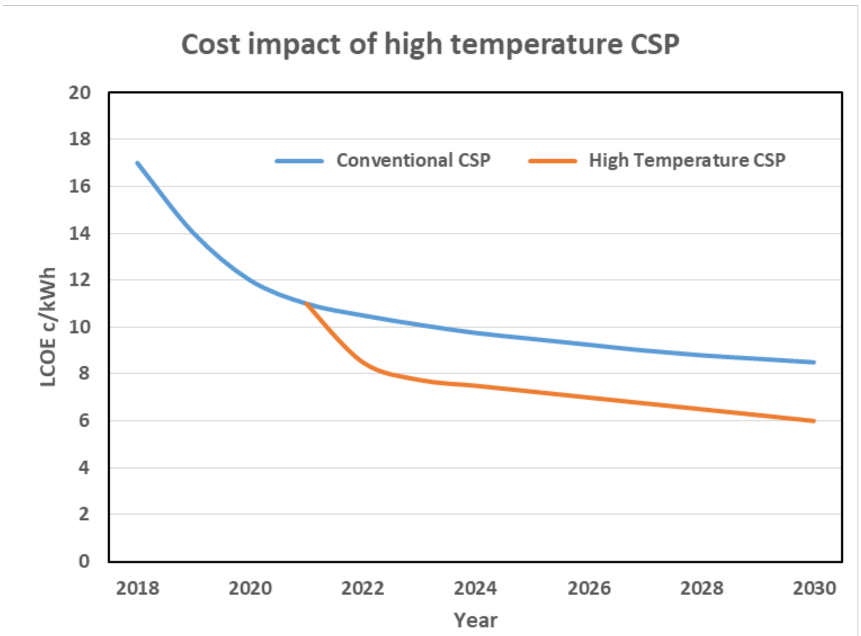
The ASTRI Phase 2 Research Program is primarily focused on high temperature CSP systems for power generation. However, The Phase 2 Program does include a small element of proposed work on solar fuels. This work would build on the solar fuels work undertaken in the Phase 1 ASTRI Program and is included 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 distruptive change in the cost curve, which will see CSP entering the market sooner.



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ASTRI Highlights and Achievements

Driving down the Cost of Concentrated Solar Thermal Power in Australia

In the first four years of this project, ASTRI has been developing the key components of a concentrating solar thermal (CST) power plant configuration that would result in a conservative levelised cost of energy (LCOE) of 12.9c/kWh including storage, with an overall annual efficiency of 16.5%. The proposed central receiver tower power plant design is based on capacities ranging from 25 - 100-MWe closed-loop supercritical carbon dioxide (sCO2) Brayton cycle power block, with single-tank phase change material (PCM) thermal storage and sodium (Na) receiver. This novel configuration reflects research outcomes to date and will be further improved.

Heliostats

Three heliostat design concepts were investigated, with down-selection to two concepts in 2015 (A&C). An overview of key features of ASTRI heliostat concepts is provided below.

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

- 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 of 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.

Receivers

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, tubular, liquid metal, volumetric, falling film), 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 taking into account 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.

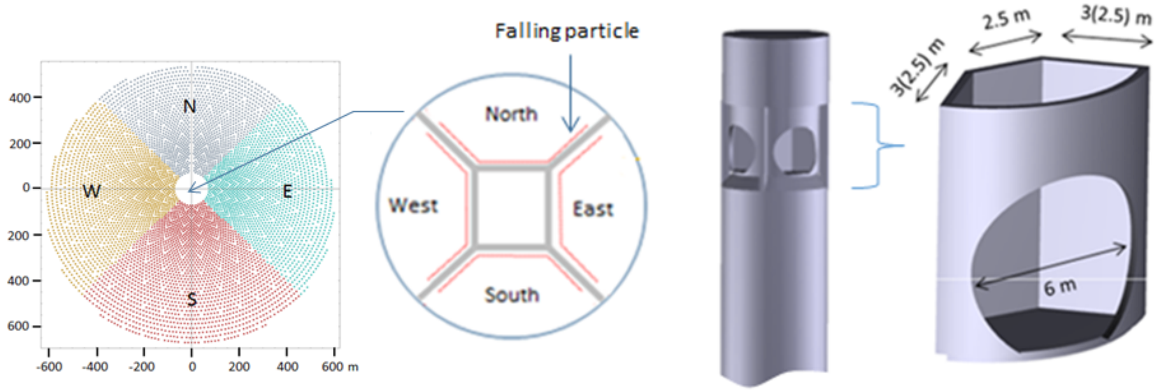
The project was then structured around the three receiver concepts selected for development - the sodium receiver, falling particle receiver, and solar expanding vortex receiver.

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.



Concept geometry of a particle receiver employing 4 cavities compatible with the ASTRI reference field optimised for a system in Alice Springs, Australia

- Concepts for a scaled-up receiver employing four cavities were analysed, with preliminary performance predictions for different sun positions (see figure above).
- Major development of falling particle receiver technology was 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 is a partner in this project.

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.

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 an attribute that can differentiate CSP from other weather dependent generators. Both thermo-physical and thermochemical storage are major capabilities of research within ASTRI.

Technologies	**Transferable Knowledge**
Phase change materials	• Promising candidate material samples were formulated for testing. Material and thermophysical properties of high temperature PCM's suitable for integration with a supercritical CO2 turbine cycle were measured. Modelling of charge/ discharge cycles, including in a hybrid combination with sensible heat storage materials such as graphite.
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 be applied not only on CSP but also on minerals processing industry.
High temperature	• 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

molten salt storage	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. Corrosion control is the major impediment.
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 under-stand the key factors 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 there-fore 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 that 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 CO2. The first target is for use with the super-critical CO2 power cycle to minimise both the number of components and the system exergy loss.
System Modelling	• Our expertise in CSP object-oriented modelling coupled with economic analysis can help industry on decision making process and de-risk novel CSP technologies and processes.

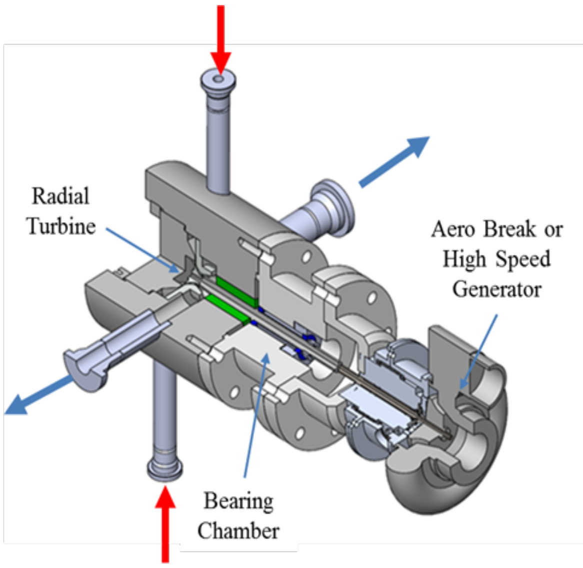
Improve CSP System Efficiency

Supercritical CO2 turbine

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 (s-CO2) Power Block Technology. ASTRI's developments in this area include:

- Cycle modelling of s-CO2 systems. Tools and know how to accurately evaluate the performance of cycles and how this is affected by ambient conditions.
- Cycle modelling tools validated against our own high-pressure refrigerant and s-CO2 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 s-CO2.
  - 0-D codes for preliminary design
  - CFD capabilities
  - Inlet plenum and diffuser simulation codes
- Ability to simulate and optimise the aerodynamics of s-CO2 turbines.
- Modelling tools that allow the accurate prediction of foil bearing operation. These include the ability to predict steady state operation and the transient response to rotor dynamic excitations.



Efficient turbine cooling systems

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:

1. 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.
2. Significantly reduce the O&M costs for CSP 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.
3. Develop inlet air precooling technology to maintain the plant performance on even very hot days (hybrid cooling)

4. Achieve these aims without a significant addition to the capital investment.
5. Develop tools to select and size heat exchangers for an optimum supercritical CO2 system.

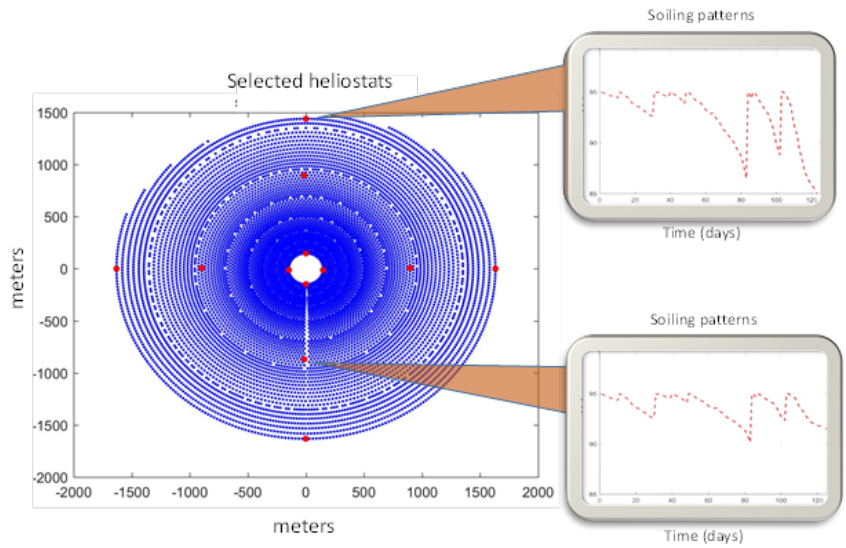
The first four of these were achieved using computer modelling, with early results developed for the fifth. Queensland Government funding was used to build a prototype 1MWe cooling tower which could be used for future ASTRI testing and model validation.

Adding Product Value

O&M Mirror Cleaning

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).

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.

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.

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Solar Fuels

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.

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 CO2 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 & 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 & 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 & to changes to the purging gas composition during a shut-down period.

Capability development

People. ASTRI has continued to attract a diverse array of quality researchers. Over the past year, there has been particular growth in the number of students and postdoctoral fellows. Over 140 researchers have worked on ASTRI projects. Currently it has 125 people with 41 post-graduate students, 18 postdoctoral fellows, 49 researchers and 17 people in leadership roles. The ASTRI leadership roles include Principal Investigators providing strategic advice to the Director and responsible for the overall contribution of their organisation, Node 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.

Large-scale Collaboration

The third year of ASTRI has been devoted to using a systems approach to develop configurations that can achieve the technical goals. In addition to refining the portfolio of research project proposals to ensure system interconnectivity to meet our objectives, a gap analysis was undertaken to highlight the research topics still to be addressed. Key areas from the gap analysis were related to de-risking the configurations under consideration, which included materials science.

ASTRI continues its commitment to collaboration across the six universities and CSIRO, spanning three states and the Australian Capital Territory. This collaboration has represented a step-change in the commitment of Australian researchers to the success of CST, as well as equipping highly trained graduates ready to deliver success in CST industries both in Australia and on the International stage.

ASTRI continues to develop its international connections with collaboration, contributions and cooperation with the US under SunShot remaining the core. A key interaction will be technical and economic review of the ASTRI configurations.

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 ATSRI 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.

International Collaboration

The US DoE’s Generation 3 Concentrating Solar Power Systems (Gen3 CSP) funding program builds on prior research for high-temperature concentrating solar thermal power (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. CSP plant operating temperatures greater than 700 °C have the potential to reduce the cost of CSP systems by increasing the efficiency of the plant. There are 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 create a cost-effective and reliable integrated solution.

On May 15, 2018, the U.S. Department of Energy announced it would provide US$72 million in funding for this effort, which included US$62 million for the Gen3 CSP competitive solicitation and US$10 million for additional national laboratory support for the Gen3 CSP selectees. On May 31, 2018, the Energy Department announced an additional US$7 million for five projects selected as alternates.

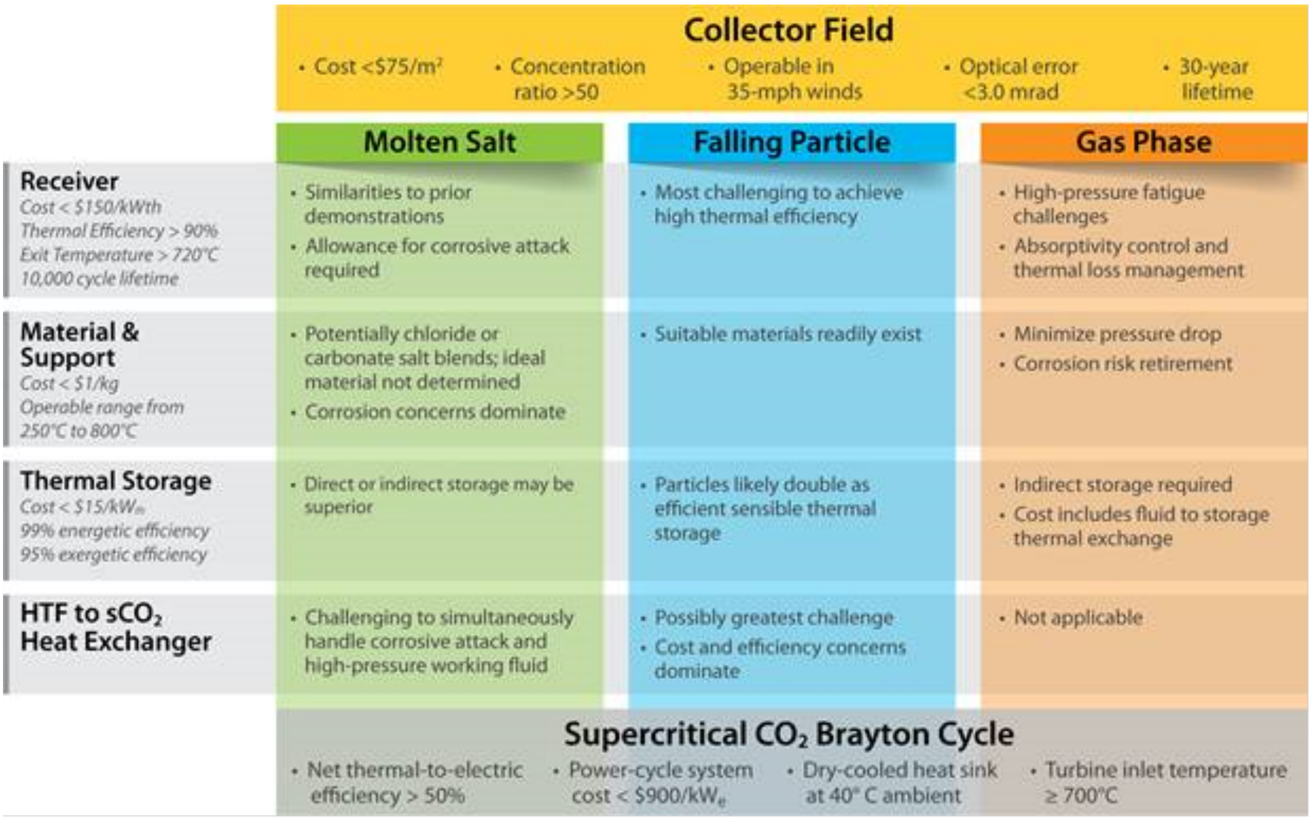
US DoE Gen3 Approach

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 °C.

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.



DoE Gen3 Awardees

BRAYTON ENERGY

Project Name: Gen3 Gas-Phase System Development and Demonstration

Location: Hampton, NH

DOE Award Amount: $7,570,647

Project Summary: In this project, a commercial-scale gas-phase concentrating solar thermal power (CSP) system will be developed in the first two Gen3 phases and, if selected for the third phase, developed into a test facility. The megawatt-scale test system will absorb energy from a heliostat field and deliver it into a thermal energy storage system, storing nine megawatt-hours of heat at a temperature of 750 °C for a minimum of ten hours. The energy then moves into a working fluid that could have a round-trip efficiency of 99 percent, creating a CSP solution that enables on-demand renewable energy.

NATIONAL RENEWABLE ENERGY LABORATORY

Project Name: Liquid-Phase Pathway to SunShot

Location: Golden, CO

DOE Award Amount: $7,035,309

Project Summary: This team will test the next generation of liquid-phase concentrating solar thermal power 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.*

SANDIA NATIONAL LABORATORIES

Project Name: Gen3 Particle Pilot Plant: Integrated High-Temperature Particle System for CSP

Location: Albuquerque, NM

DOE Award Amount: $9,464,755

Project Summary: This project will design and test a multi-megawatt thermal falling particle receiver concentrating solar thermal power (CSP) 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 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.

Country	Program	International Partners	Objective	ASTRI Involvement	Comment
US	Gen3	NREL	Develop + test liquid receiver technology (Molten Salt, Sodium) + Storage	Sodium receiver design & demo	Work included in proposed ASTRI strategic plan (Sodium receiver is primary option for ASTRI)
US	Gen3	Sandia	Develop + test falling particle receiver with storage	Multi-stage receiver design, CFD analysis	Work included in proposed ASTRI strategic plan (Backup option to Sodium receiver)
US	STEP	GTI, GE, SWRI	Develop + test 10MWe sCO2 Brayton cycle	Partnering to drive CSP applicability testing	Not included in proposed ASTRI budget plan, benefits will be commercialization, recuperator design, system operability
Germany	none	DLR	Heliostat development;	Heliostat optimization software, Heliostat designs	Initial discussions held with DLR to discuss coordinated collaboration, currently CSIRO, ANU connection to DLR
		DLR	DLR rotating particle receiver test	Provide test site for DLR's particle receiver	
		KIT	Sodium safety and materials	KIT have provided design and materials for ASTRI sodium lab at ANU	KIT personnel have unique experience in high temperature sodium and should be involved in ASTRI sodium R&D.

Key R&D relationships have also been developed with other institutes and research organisations, as follows:

INTERNATIONAL PARTNER INSTITUTION	TOPIC
University of Colorado, Boulder	Supercritical water gasification and Fischer Tropsch synthesis
University of Arizona	Water splitting
NREL	Determination of thermos-physical properties and stability testing of high temperature phase change materials for CSP applications; Experimental study of crosswind effects on the performance of small cylindrical natural draft dry cooling towers
University of Montpelier II	Optics modelling for CST
CIEMAT (Spain)	Develop open source DNI forecasting tools
CAS (China)	Economic analysis of thermal energy storage (TES) for concentrated solar power (CSP) systems
Loughborough Uni (UK)	Economic analysis of thermal energy storage (TES) for concentrated solar power (CSP) systems
GREA Innovació Concurrent, University of Lleida (Spain)	Reliable low-cost phase change material thermal storage systems for CSP
Universitat de Barcelona (Spain)	Reliable low-cost phase change material thermal storage systems for CSP
Institute for Fluid Dynamics, ETH-Zurich (Switzerland)	sCO2 Systems – Power Block - Advanced heat exchangers for cooling tower
Karlsruhe Institute of Technology (Germany)	sCO2 Systems – Power Block - Supercritical flow modelling and comparison of energy storage options compatible with sodium receivers
Centre for Electromechanics, University of Texas at Austin	Design of a supercritical CO_2 turbo-generator
Von Karman Institute for fluid dynamics (Belgium)	sCO2 Systems – Power Block - Spray nozzle for air cooling
Universidad del Norte (Colombia)	Development of control strategies for solar tower systems
ETH-Zurich (Switzerland)	Vortex reactor
University of Miguel Hernandez (Spain)	Power Block - Sensitive paper for evaluating spray nozzle effects on air cooling
University of Padua (Italy)	Power Block - Advanced condensers for thermal power plants
Technische University Delft	Power Block – Design and optimisation of radial inflow turbine plenums and diffusers.

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.

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.

AEMO projects Australia's 2030 emissions reductions target will be met mostly by large-scale renewable generation replacing coal generation as it withdraws from service. GPG will be required to support intermittent renewable generation unless alternate technologies become cost-competitive[1].

[1] AEMO National Transmission Development Network Plan 2015 p4

Partners

CSIRO

Australian National University

Flinders University

QUT

The University of Adelaide

University of South Australia

The University of Queensland Australia