# AUSTRALIAN SOLAR THERMAL RESEARCH INSTITUTE (ASTRI)
# PUBLIC DISSEMINATION REPORT 2019

# DIRECTOR'S MESSAGE

As Australia's electricity market transitions to a low carbon future we are seeing a significant uptake of renewable energy in the form of photovoltaic and wind. While these technologies have immense value, they also bring challenges.

Specifically, they only generate electricity when the sun is shining or the wind is blowing, resulting in variable or intermittent supply. The electricity network finds it difficult to manage large amounts of variable generation and addressing this problem requires access to firm capacity, which can be quickly dispatched on demand.

At present, coal and gas fired generation meets this need, however, Australia also requires renewable energy technologies that can be stored and dispatched with the same level of reliability as today's conventional fossil fuel systems.

High temperature concentrated solar thermal (Solar Thermal) is a technology that provides low cost, utility scale, dispatchable renewable energy. The technology involves the capture and concentration of sunlight which is then stored as high temperature heat. This heat is then used for electricity generation or for process heat applications, any time of day or night.

In essence, Solar Thermal works in a similar fashion to a coal fired power plant. Both technologies use thermal energy and a steam turbine to generate electricity. However, instead of burning coal, solar thermal plants use concentrated heat from sunlight and are 100% renewable. Solar thermal plants also provide more flexible capacity, enabling them to better respond to demand changes.

Alongside photovoltaic with batteries and pumped hydro, solar thermal can also provide multiple hours of energy storage. This stored energy can then be used on a daily cycle, when the sun goes down, to power Australian homes and industry. By using Solar Thermal, to power Australia at night, the transition to a 100% renewable energy is within reach.

Worldwide, over 80 commercial Solar Thermal power plants have now been installed. There are plants in Spain, North America, South America, Northern Africa, Southern Africa, the Middle East and China. More plants are being constructed in countries including, China, Chile, Morocco and Saudi Arabia. Solar thermal systems are very well suited to countries like Australia with high levels of direct solar irradiation. While Australia does not yet have commercial solar thermal plants, as Australia's coal fired power plants continue to retire, Solar Thermal will provide a competitive, low cost and fully renewable replacement option.

The Australian Solar Thermal Research Institute (ASTRI) was established by Australian Renewable Energy Agency (ARENA) to help facilitate commercial uptake of concentrated solar thermal technologies and systems. As a consortium of leading Australian research institutions, ASTRI researchers are developing next generation technologies and systems suited to Australia's unique geographical and operational requirements. Working closely with Industry, ASTRI looks forward to establishing Solar Thermal as a viable component of Australia's future renewable energy landscape.

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Cover: SolarReserve, Crescent Dunes
Left: Abengoa, Solucar

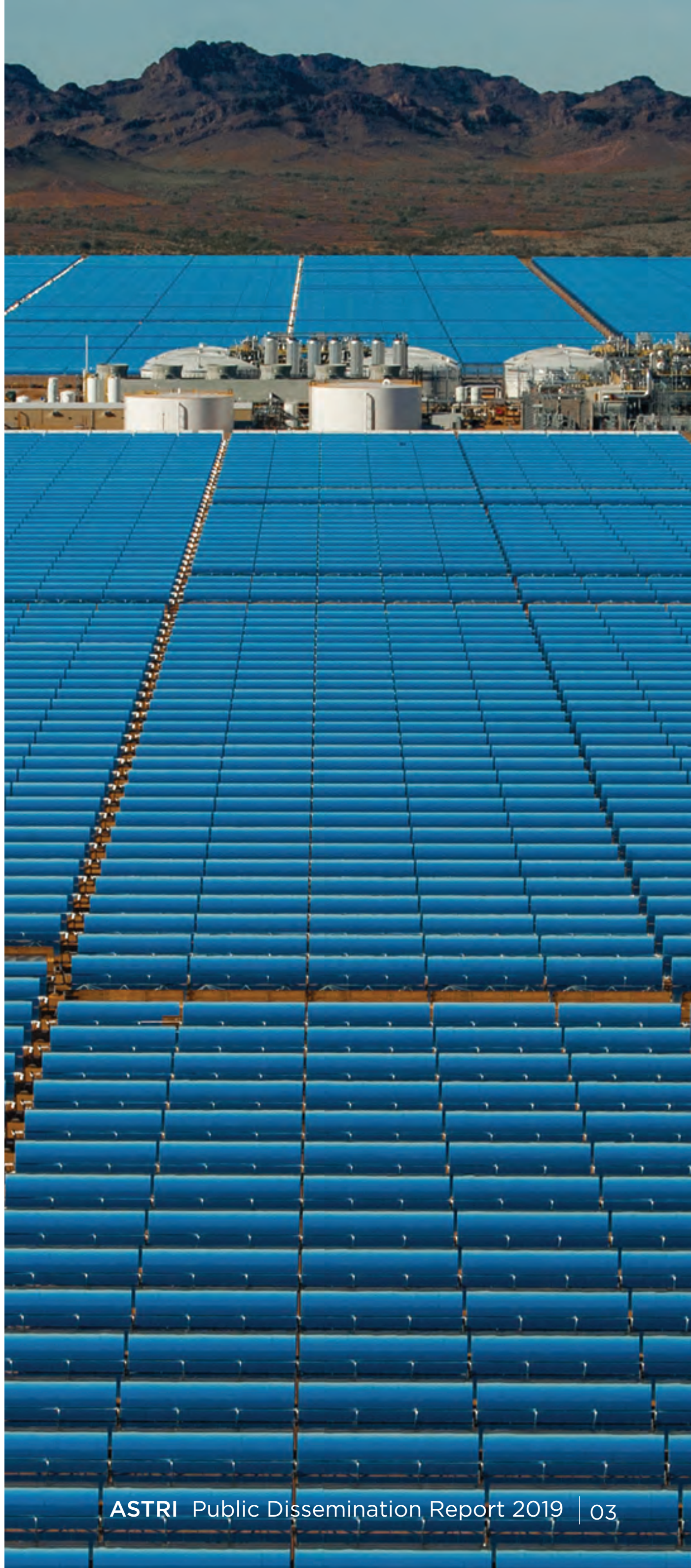
# CONTENTS




ASTRI acknowledges its funding partner: ARENA — Australian Government, Australian Renewable Energy Agency

ASTRI Members: CSIRO, Australian National University, Flinders University, QUT, The University of Adelaide, The University of Queensland Australia, University of South Australia

US Collaborators: Sandia National Laboratories, ASU Arizona State University, NREL National Renewable Energy Laboratory

| Abengoa, Solana

# ASTRI AT A GLANCE

ASTRI is an unincorporated joint venture with the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Queensland University of Technology, University of Queensland, The Australian National University, University of South Australia, Adelaide University and Flinders University.

ASTRI was established in 2012 through a contractual arrangement between the Australian Renewable Energy Agency (ARENA) and CSIRO. Under this arrangement, ASTRI's primary objective is to facilitate the commercial uptake of more efficient, higher temperature solar thermal technologies in the form of:

- concentrated solar power (CSP) systems for electricity generation or
- concentrated solar thermal (CST) systems for process heat applications.

To reach this objective, ASTRI is:

1. Developing technologies that improve the performance of next generation CSP and CST systems through increased efficiency and lower risks and costs.
2. Closely engaging with major industry players to identify and support commercial uptake opportunities for current CSP and CST systems within the Australian energy market.

## Leading the way for solar thermal deployment

In 2018, the *Australian Concentrating Solar Thermal Industry Roadmap*, funded by ARENA, highlighted pathways and timings for commercial deployment of concentrated solar thermal systems in Australia. Consistent with these pathways, ASTRI is working with key industry, research and government stakeholders, both domestically and internationally, to deliver technical, cost and performance outcomes required for commercial domestic uptake of solar thermal systems.

ASTRI's efforts are important for ensuring that the Australian market has timely access to viable solar thermal systems in support of Australia's transition to a low-emissions energy future.

In seeking to facilitate commercial uptake, ASTRI recognises the importance of establishing the value proposition of Solar Thermal technologies and systems across a range of applications, including:

- utility scale power generation and storage;
- smaller site-specific power generation and storage in remote mining, community and fringe of grid locations; and
- Industrial process heat applications.

| CSIRO Solar Field Newcastle

# WHAT IS SOLAR THERMAL

Solar thermal uses the sun's light to generate heat that can be used in industrial processes or to generate electricity. It uses high quality mirrors to concentrate sunlight, which heats a liquid (e.g. water or oil) to produce steam to drive a turbine. The technology is currently in its early stages of development in Australia, however it is used more extensively overseas.

Solar Thermal can be applied as a concentrated solar thermal (CST) system for process heat or as a concentrated solar power (CSP) system for electricity generation. Both of these systems use a field of mirrors to concentrate the sun's light energy onto a receiver and convert it into heat (i.e. thermal energy). The heat can be used directly, or stored for use at a later time. The heat can be used for solar fuel production or for process heat applications (CST systems). Alternatively, the heat can be used to produce electricity (CSP systems). The heat can be stored for long periods of time and dispatched day and night, meaning that CSP can dispatch electricity in a similar way to coal fired generators.

## Key components

There are different solar collection configurations – troughs, dishes, linear Fresnel and towers – ASTRI is primarily investigating solar towers (central receivers) which work as follows:

### Solar collection

Solar energy is collected through curved or flat mirrors (heliostats) that track the sun and reflect the sunlight onto a receiver.

### Thermal capture

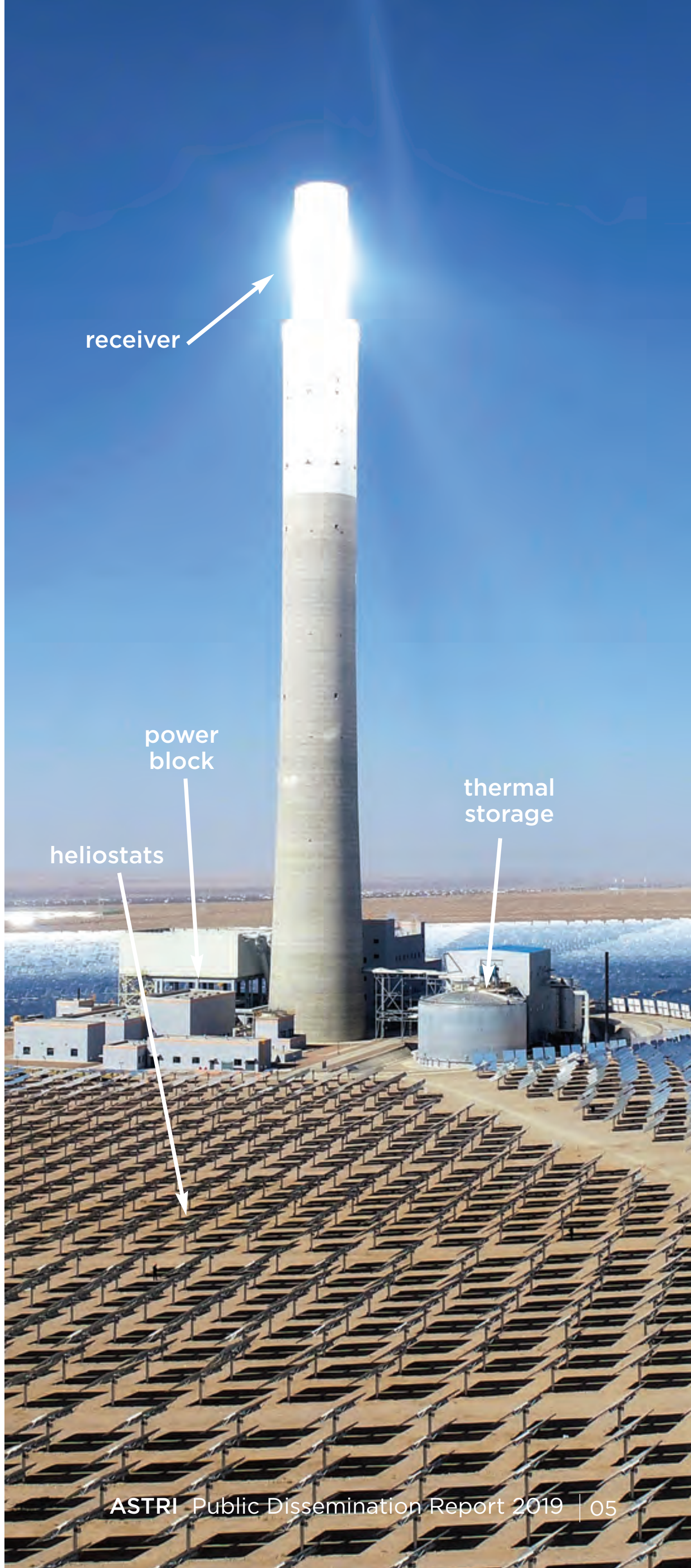
The mirror reflects sunlight onto a receiver, which converts the concentrated sunlight into high temperature heat.

### Thermal energy storage

Concentrated solar thermal systems typically incorporate energy storage. Heat concentrated at the receiver is then stored in tanks typically using molten salts or other heat transfer gases, liquids or solids.

### Power block

The power block is used within CSP systems to convert thermal energy (directly produced or stored) into electrical energy. Identical to coal fired power plants, this conversion typically occurs through the production of superheated, high-pressure steam which spins a turbine to generate electricity. While steam turbines are the current technology choice for CSP systems, new advanced power cycles using supercritical $CO_2$ are emerging as a smaller, more efficient power generation technology pathway.




Key components of a CSP tower receiver system (Photo: Supcon)

# SOLAR THERMAL INTERNATIONALLY

Globally, the installed capacity of CSP systems has grown steadily over the last two decades. CSP had a global total installed capacity of 6,128 MW at the end of 2019, an increase in over 1,000 MW from 2018. There are now more than 80 commercial CSP plants around the world. Most new plants have multiple hours of storage to allow for renewable energy use at night.

Most of the early development of CSP occurred in Spain and the USA, and they remain the countries with the largest installed capacity. These two countries alone account for over half of the global capacity. In the past few years, CSP plants have also been built in Morocco, China, South Africa, India and the United Arab Emirates.

There is another 1.5 GW of large CSP plants under construction across a number of countries including China, Chile, Morocco, Israel and Saudi Arabia.

Countries leading the way with CSP all have high levels of solar radiation – just like Australia.

Despite having high levels of solar radiation, there is only one small commercial CSP system operating in Australia (i.e. Sundrop Farms). This situation will change as coal fired plants retire and alternative low emission technologies are required as a low-cost replacement.

## Operational performance

### How many CSP systems are there globally?

There are currently around 64 CSP plants that are 50 MW or larger and another 32 or so smaller plants. Installed capacity is increasing, with a range of industry studies estimating growth of over 25% annually, primarily driven by China, and the Middle East. Spain has announced plans for another 5 GW by 2030. China has indicated plans for another 10 GW of CSP by 2030.

### How long has CSP been operational?

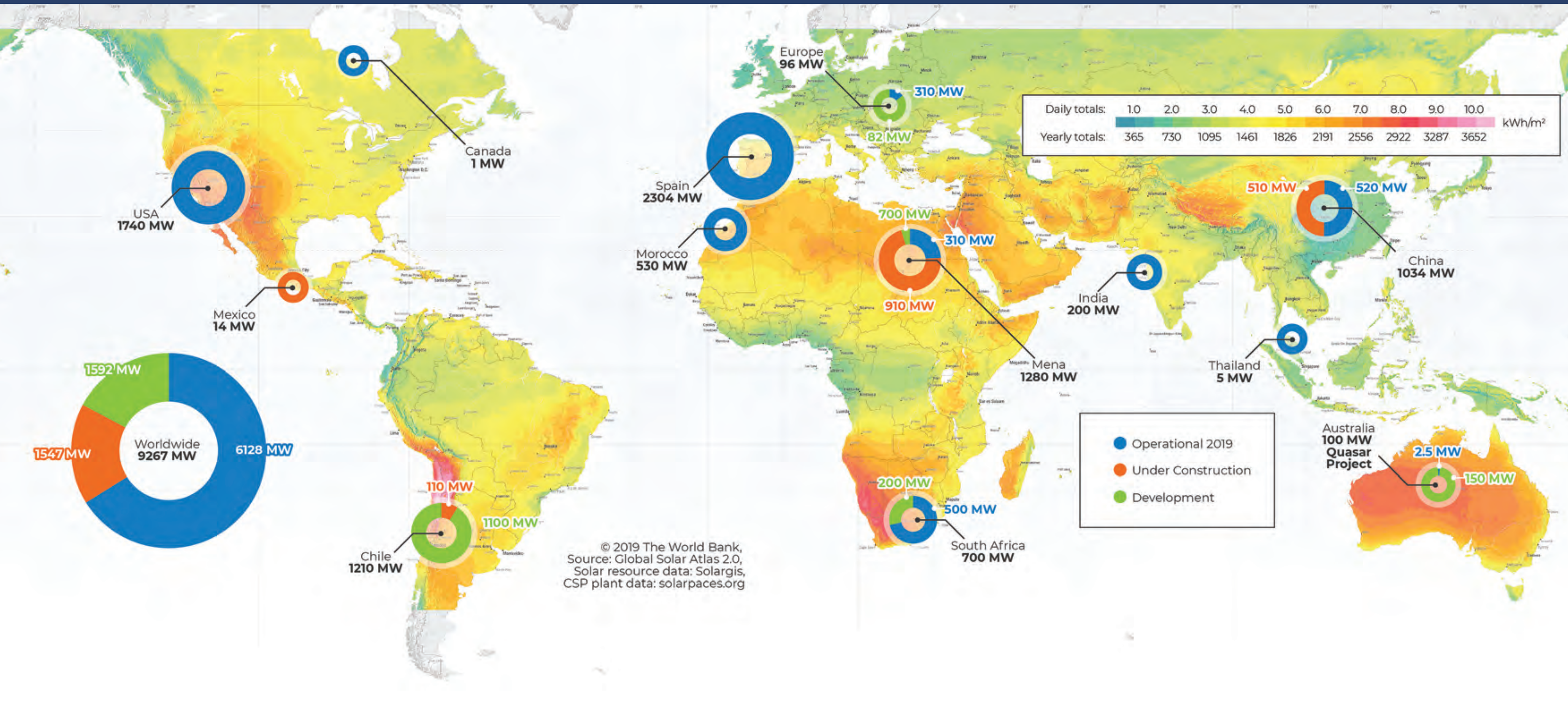
Commercial utility scale CSP systems have been operational since the mid-1980s. The 27 commercial CSP plants in Spain have been operating for almost 10 years. The eight plants in the US have been operation for over five years. Another 20 plants in other locations have been operating for over 12 months.

These CSP plants provide clean, reliable and sustainable power to large numbers of households and industry, providing on-demand energy both day and night.

> Countries leading the way with CSP all have high levels of solar radiation – just like Australia.

| Abengoa, KaXu solar field

# SOLAR THERMAL CAPACITY AROUND THE WORLD 2019



# HOW CAN SOLAR THERMAL HELP AUSTRALIA'S ENERGY TRANSITION

Cost competitive Solar Thermal has the potential to contribute over the longer term to an overall reliable, affordable electricity system with a high share of renewable energy. It has a particular advantage ahead of other renewable energy technologies in that it can store large amounts of energy, that can then be quickly dispatched as heat or electricity, any time of day or night.

## The energy market is changing

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, a changing energy mix, and rapid technology advancements will create some unique integration challenges for the Australian energy market. Central to these challenges is the need to supply secure, reliable, affordable and sustainable energy solutions to consumers.

Solar Thermal provides utility scale energy storage that provides firm capacity and on demand dispatchable generation. This will become increasingly important in energy markets that need to address the challenges of secure, reliable and affordable energy in a renewable energy future.

## The problem with intermittency

Solar photovoltaics and wind are intermittent generators, which means they only generate when the sun is shining or the wind is blowing. This generation variability creates significant reliability and capacity management challenges within the Australian National Electricity Market (NEM), especially as more PV and wind is introduced.

Generation variability is currently managed through conventional fossil-fuel power plants that can generate and dispatch electricity 24 hours a day. These power plants provide a firm, reliable and predictable supply of electricity able to balance system requirements, any time of day or night. However, Australia's coal-fired plants are aging and most will retire in the next 10-20 years. In this same time period, increasing levels of solar photovoltaics and wind generation will see increasing generation variability and reliability problems.

New renewable energy technologies are required that can provide the same firm capacity, reliability and resilience of a coal fired power plant, at similar or lower cost. These new technologies also need to be able to accommodate future energy systems with a high level of intermittent renewable energy assets.

Solar Thermal with energy storage is a technology solution that does everything that a coal-fired plant does, but with zero-emissions and with much greater operational flexibility.

Solar Thermal also accelerates the uptake of PV and wind by providing the firm capacity and system strength required to manage generation intermittency problems associated with high amounts of PV and wind.

| Vast Solar, Jemalong

## Renewable energy storage allows for electricity 24 hours a day, 7 days a week.

Australia's energy transition to a renewable future will require an energy system based on the generation and supply of secure and reliable renewable energy; 24 hours a day; 7 days a week. Renewable energy storage, through the flexible capacity it provides, is the key to achieving this outcome.

Renewable energy storage improves the availability, resilience and utilisation of renewable energy. It also balances out frequency and system strength fluctuations associated with variable renewable energy technologies (i.e. photovoltaics and wind).

Lithium batteries are emerging as a valuable solution for the storage of renewable energy. Batteries are currently a good option for short term storage (30 minutes – three hours) of renewable energy. They also provide an important system balancing role through the provision of fast response frequency control and ancillary services (FCAS).

While great for short-term storage, for utility scale systems with over six hours of storage, batteries are prohibitively expensive. The two best forms of utility scale renewable energy storage are Pumped Hydro and Solar Thermal. Pumped Hydro uses renewable energy to pump water into reservoirs which is then released through a water turbine to create electricity.

Pumped Hydro and Solar Thermal have their pros and cons in terms of cost, utility, resource availability and scalability. Pumped Hydro is a good option where you have lots of available water and suitable reservoirs. However, in areas that are flat, dry and hot, Solar Thermal is a better option.

There is no singular renewable energy storage solution for Australia. All options need to be assessed and deployed where they deliver the best value to Australia's electricity networks and energy users, based on cost, technical performance, geographical considerations and resource availability (i.e. wind, solar and water).

Large utility scale renewable energy storage systems, such as Solar Thermal, are the most cost-effective option to provide firm night-time generation capacity on a day to day basis.

| Supcon, Delingha

> Solar Thermal provides utility scale energy storage that provides firm capacity and on demand dispatchable generation. This will become increasingly important in energy markets that need to address the challenges of secure, reliable and affordable energy in a renewable energy future.

# AUSTRALIAN SOLAR THERMAL APPLICATIONS

While Solar Thermal is not being deployed at the same level of uptake as other renewable technologies such as solar PV and wind, this will change in the coming decade as the importance of renewable energy storage increases. Solar thermal has three key applications of value in Australia: large scale electricity storage and generation, remote mining and communities, and industrial process heat.

## Large-scale energy storage and electricity generation

CSP provides a firm and flexible supply of renewable based electricity to meet daily demand.

Solar photovoltaics and wind technologies are variable renewable energy generators. This intermittent supply does not provide market operators with a reliable and resilient source of energy 24 hours a day, 7 days a week. This creates a gap in Australia's future low emission energy system. Renewable-based energy storage is required to provide firm capacity, and to enable the supply and transmission of energy around the clock.

Large-scale deployment of renewable energy technologies is needed to drive Australia's transition to a low emission future. This will require a commensurate increase in renewable-energy storage. While there is debate about exactly how much energy storage is optimal, there is consensus that the amount is significant and that both small- and large-scale renewable energy storage solutions will be needed.

> CSP provides reliable, low cost, supply of renewable-energy storage and electricity for remote mining and community locations, reducing their reliance on diesel generation.

Lithium batteries are emerging as the preferred form of short-term energy storage to support renewable generation.

CSP offers an alternative large-scale (utility) energy storage solution.

## Remote mining and community locations

CSP provides reliable, low cost, supply of renewable-energy storage and electricity for remote mining and community locations, reducing their reliance on diesel generation.

| Abengoa Mojave

| Protermosolar, NOOR complex

| Solar thermal technologies can help in transitioning industry to a low emission future.

Australia's remote mining and mineral processing operations rely heavily on diesel generation systems. These systems allow for good operational reliability but are very expensive to run and are emission intensive.

The mining sector is committed to reducing emissions and many mining entities have set a 50% renewable energy target by 2030. However, these entities recognise that a 50% target is difficult to achieve using intermittent renewable energy technologies such as photovoltaics and wind. Accordingly, these entities are looking to energy storage as an enabler for higher levels of renewable energy.

CSP provides mining and remote community locations with a cost-effective option to store energy and then convert it to electricity, with a significant reduction in diesel fuel costs and emissions. In fact, some mineral processing companies might only be interested in the high temperature heat that CSP can provide. Recent ARENA funded studies have identified near-term domestic opportunities for CSP systems at fringe-of-grid and remote mining locations.

## Industrial process heat

CST can supply low cost industrial process heat, either directly or in the form of a solar fuel, to improve industry's cost competitiveness.

Australia's only commercial CSP plant, Sundrop Farms, generates heat and electricity to grow large quantities of greenhouse tomatoes.

Australian industry accounts for more than 40% of the nation's end use energy and 52% of that is process heat, with an indicative value of $8 billion per year (ITP, 2019). Heat is predominantly provided by gas combustion with coal the second biggest source; both with notable contributions to carbon emissions.

There are opportunities for CST systems to supply high-temperature industrial process heat, either directly or as a solar fuel, to either complement or replace the use of natural gas.

“CST can supply low cost industrial process heat to improve industry's cost competitiveness.”

# INCREASING SOLAR THERMAL'S COMPETITIVENESS

When it comes to the uptake of Solar Thermal, there are two key challenges to overcome. First, accurately accounting for the value that Solar Thermal with energy storage can provide; and second, improving system performance in relation to cost, efficiency and reliability.

## Lowering cost

The cost of electricity from CSP systems is currently higher than that of existing fossil fuel and renewable energy technologies such as solar photovoltaics and wind. However, when the cost and value of multi-hour storage is taken into account, CSP systems are a more cost effective option.

The problem is that the future value of renewable energy storage is not captured in current markets where there is an excess capacity of low-cost, fossil-fuel generation. This will change when coal-fired plants retire and renewable energy storage becomes an economic and political imperative. However, until such time, and in the absence of strong pricing signals for firm renewable energy, CSP systems will struggle to be deployed at large scale.

This noted, cost reduction opportunities do exist for CSP systems, driven by learning curve benefits from the increasing number of international deployments. Significant cost reductions of over 25% have been achieved over the past five years. Based on expected international uptake, CSP system costs are expected to reduce by almost 50% over the next 10-years. At such a cost point, CSP would be extremely competitive in markets with high quality solar radiation resources, such as Australia.

The cost effectiveness of CSP systems is further increased due to the larger amount of energy that these systems can make available over a given period of time. This is referred to as the 'capacity factor'. CSP plants have a much higher capacity factor compared with other renewable energy technologies. Typical CSP Plants with storage have a capacity factor of between 50% to 70%, which is double that of PV.

CSP systems can allow you to generate revenue over a longer time period on a daily basis. If a capacity market was to be introduced, the ability of CSP plants to generate on demand during evening and morning peak load periods would further enhance daily generation revenues.

> Significant cost reductions of over 25% have been achieved over the the past five years.

| SENER, Noor Quazazzale

## Optimising system performance

The performance of solar thermal systems is a function of cost, efficiency and reliability. Specifically, what is the cost to reliably deliver a fixed amount of energy, on demand, over a given time period.

While costs can be lowered through scale, utilisation and learning curve benefits, system efficiency and reliability require a more technology driven solution.

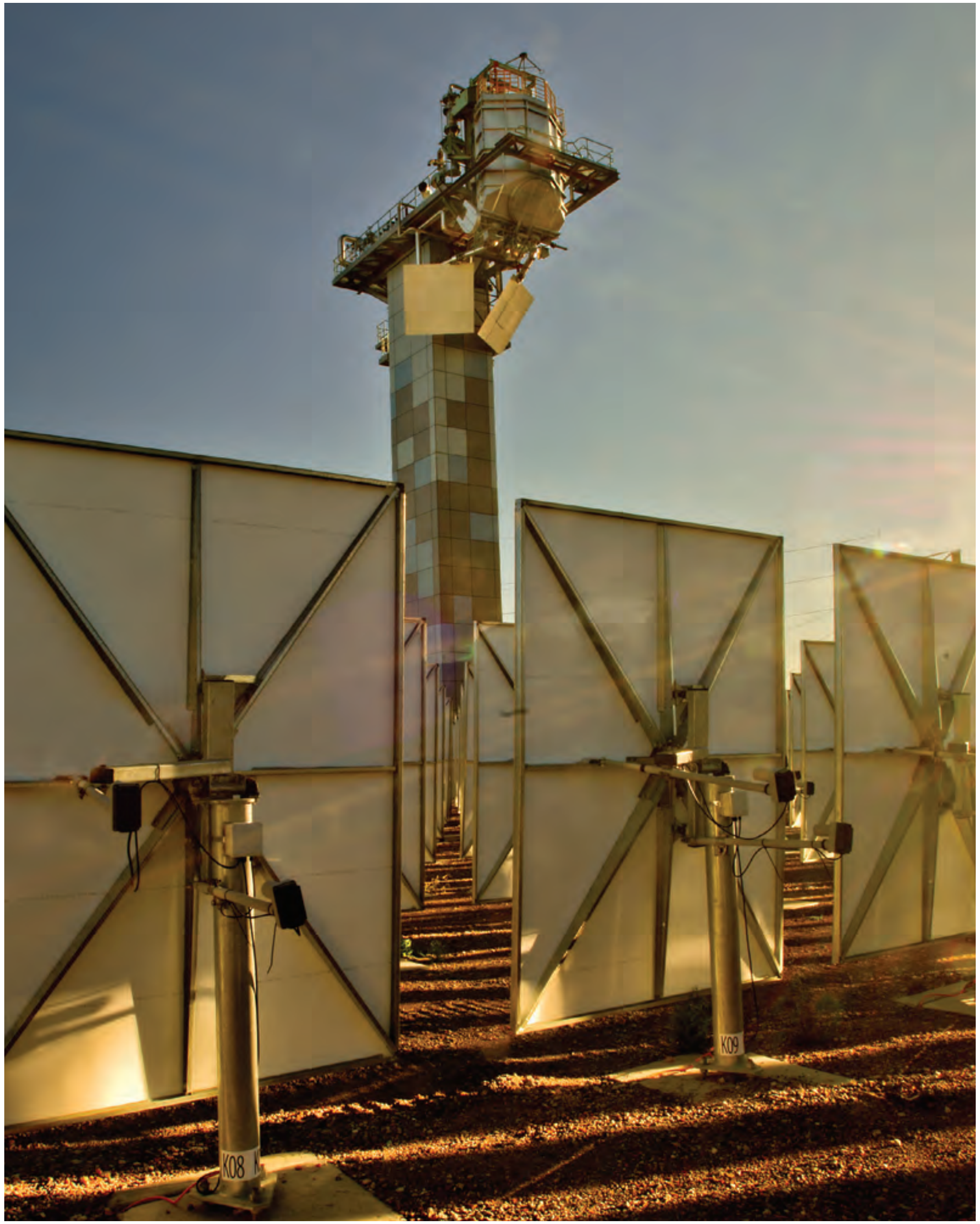
The overall efficiency of a solar thermal system is driven by the component sub-system efficiencies. These include the:

- optical efficiency of the heliostats;
- thermal efficiency of the receiver;
- thermal efficiency of the energy storage; and
- generation efficiency of the power block.

While there has been significant industry and research efforts to improve the efficiency of all of these sub-systems, the power block is emerging as the sub-system with the greatest potential to deliver significant system efficiency and performance gains.

Current solar thermal systems operate at temperatures up to 560°C, dictated primarily by the upper temperature for nitrate molten salts. This upper temperature reflects the performance limits of the steam power block used in CSP systems. New advanced power cycles operating at higher temperature (i.e. up to 720°C) have the potential to improve overall system efficiency by 20%. This is a game changer for solar thermal systems. However, the increased power block temperature requires higher receiver and energy storage temperatures and this, in turn, creates its own set of material and system reliability issues/challenges.

There are well coordinated international efforts by governments, researchers and industry to address the challenges of developing and deploying next generation, high temperature solar thermal systems. These efforts reflect the importance of ensuring that markets and energy end users have timely access to the low-cost energy storage, firm capacity and dispatchable generation offered by Solar Thermal.



| CSIRO Solar Field Newcastle

| Supcon, Delingha

# ASTRI'S ROLE IN SUPPORTING SOLAR THERMAL UPTAKE

ASTRI is addressing commercial uptake of Solar Thermal through two primary approaches:

- the development and demonstration of next generation, higher temperature solar thermal technologies specifically designed to increase system performance and market competitiveness through lower cost and improved efficiency and reliability; and
- the provision of support to commercial Solar Thermal technology providers and system developers to improve Australian market awareness and uptake of solar thermal technologies and systems.

In alignment with these uptake mechanisms, ASTRI has two parallel, yet closely integrated activity areas. The first of these activity areas involves **Technology Development**. This is by far ASTRI's largest activity area and involves over 120 researchers working on a range of technology development projects organised across seven programs:

**Program 1:** Thermal Capture

**Program 2:** Thermal Storage

**Program 3:** Power Systems

**Program 4:** Process Heat Technologies

**Program 5:** Advanced Materials and Operations & Maintenance

**Program 6:** Integrated System Modelling

**Program 7:** Integration Testing

The second of ASTRI's activity areas involves **commercial and stakeholder engagement activities**. This includes international collaboration, communications and knowledge sharing. The focus of this activity area is to ensure that the value proposition of Solar Thermal, and associated key messaging, is clearly articulated and targeted at decision makers within industry, government, investment bodies and research agencies.

## Technology development

ASTRI's technology development activity area seeks to fundamentally improve the performance of solar thermal component technologies and systems. The aim is to improve system performance through a 50% reduction in the levelised cost of solar thermal systems over 10 years – from 14c/kWh (AUD) in 2019 to 7c/kWh (AUD) in 2030.

### Component enhancement

Capturing these performance improvements requires component based technology enhancements that focus on cost reduction, improved efficiency and high reliability. The technology enhancements being pursued through ASTRI's technology development activities include:

- New cost effective and optically efficient heliostats;
- Higher temperature receivers with high efficiency;
- New operationally effective heat transfer fluids;
- New cost-effective thermal energy storage solutions; and
- New efficient, lower cost power generation cycles.

## Enabling activities

In support of these component technologies, ASTRI is also undertaking essential enabling activities including:

- Evaluation and testing of key durability, fatigue and transient creep characteristics of the advanced high temperature materials being considered for use in component technologies;
- Improved operations and maintenance technologies and strategies for component technologies to lower operation and maintenance costs over the life of plant; and
- System cost and integration modelling to understand component cost capability trade-offs within solar thermal systems, and how such systems will impact on Australia's future energy systems.

## End-use applications

With high gas prices on the East Coast, and increasing industry in environmentally sustainable operations, many industrial process heat users are looking at renewable energy options. For high temperature industrial processes the use of solar thermal systems for the production of process heat and/or solar fuels for process heat, has the potential to be a large market in Australia.

To this end, ASTRI has established a dedicated program to look at the end use application of solar thermal systems for industrial process heat. ASTRI has established seven projects with industry partners to demonstrate innovative solar thermal applications for high-temperature process heat.

Many of these projects are exploring options for integrated hybrid systems (i.e. Solar Thermal, fossil fuels and other renewables), which can be adopted as a transitional pathway to higher future uptake of solar thermal systems within Australian industry.

## Integration testing

Having developed and demonstrated individual component technologies, ASTRI has established a dedicated program to test the integration of the various component technologies. This includes the testing of heliostats with high temperature sodium and particle receivers. Further testing of ASTRI's preferred thermal storage solution and advanced power systems might also be undertaken depending on the successful completion of specific component technologies.

The ultimate outcome of component integration testing is to demonstrate to industry the operation, efficiency, reliability and cost effectiveness of solar thermal technologies and the expected performance of upscaled systems once deployed.

Above: Vast Solar, Jemalong

Right: Protermosolar, Almacenamiento Extresol

## Commercial and stakeholder engagement

ASTRI's role is to design, develop, enhance and demonstrate solar thermal technologies to a point where they are ready for commercial uptake. It is industry, not ASTRI, which will deliver commercial technologies and systems into the marketplace. As such, ASTRI's commercial and stakeholder engagement is solely targeted at collaborative activities to facilitate commercial uptake of solar thermal technologies.

ASTRI's engagement with industry stakeholders includes:

- solar thermal project developers, component designers and manufacturers;
- solar thermal engineering, procurement and construction entities;
- energy market participants including generators, retailers and network operators within the NEM;
- remote mining and fringe of grid operators; and
- industrial process heat users.

ASTRI has also increased its engagement with federal and state/territory government policy makers. The aim being to highlight the value of Solar Thermal in maintaining high levels of system reliability and security; delivering low-cost utility-scale dispatchable energy; lowering carbon emissions; and creating employment opportunities.

### International collaboration

In addition to its strong domestic engagement activities, ASTRI also actively engages with international industry and research entities. The aim being to establish mutual technology development activities to strengthen Australian capabilities and commercial uptake opportunities.

ASTRI's engagement with major CSP developers and component manufacturers include Sener, Abengoa, John Cockerill, Brightsource, Supcon, ACWA and Shanghai Electric. ASTRI's collaboration with overseas technology developers research entities includes: NREL Sandia, GTI and Argonne Research Laboratories (USA); DLR, KIT, Fraunhofer Institute (Germany); CIEMAT, PSA (Spain); Chinese Academy of Sciences (China); CORFO (Chile); and MASEN (Morocco).

The work ASTRI is doing today and into the future will form the basis for how Solar Thermal will evolve as part of Australia's renewable energy landscape. Given ASTRI's increasing recognition internationally, and its inclusion on key international projects like the US Gen 3 and STEP programs, ASTRI's international reputation and impact is also set to increase.

### Communication activities

ASTRI's communications framework seeks to increase stakeholder awareness and understanding of the value that Solar Thermal can provide within the Australian energy market. It also seeks to establish a greater appreciation for how Solar Thermal can be applied and implemented across different Australian energy market segments. This includes the use of Solar Thermal for energy storage, power generation and/or process heat for utility scale, mining, remote community, and industrial applications.

In highlighting the value that Solar Thermal can bring to in the Australian market, ASTRI focuses on the following four key enablers of Solar Thermal uptake:

**Technology**
Demonstrating that the technology works, is reliable and that associated integration and operational risks can be effectively managed.

**Economics**
Establishing the economic business case, including market impact/needs, revenue streams, financing and investor interest.

**Policy**
Keeping policy makers informed and encouraging policies that support timely and  support timely and cost-effective uptake, and reflect end user needs for secure, reliable and least cost energy solutions.

| Wes Stein (ASTRI CTO) presenting a conference paper.

**Community**
Ensuring that social awareness and expectations of renewable energy include an understanding of the role that dispatchable renewable energy technologies, such as Solar Thermal, provide in delivering a reliable energy system.

### Knowledge sharing

ASTRI places high importance on knowledge sharing. Throughout the year, ASTRI has given over 70 presentations and published over 30 articles and reports on topics ranging from heliostats, receivers, thermal energy storage, advanced power cycles, advanced materials and system modelling.

Where commercial arrangements allow, ASTRI actively seeks to share information on its technical development and commercialisation activities and has processes in place for capturing and publicly sharing information and lessons learnt.

ASTRI works closely with Australian solar thermal companies including project and technology developers such as Vast Solar (Jemalong site pictured here).

# KEY TECHNOLOGY DEVELOPMENT AREAS

ASTRI's technology development areas aim to improve the commercial viability of solar thermal systems through improved performance, reliability and cost outcomes.

ASTRI's technology development program seeks to improve the individual performance of these component technologies, as well as their overall performance as part of an integrated solar thermal system.

Abengoa, Xina 2

## Heliostats

Heliostats are a key component of solar thermal tower technology systems that capture and concentrate sunlight to produce heat. Heliostats are high quality mirrors that accurately track the sun and are aligned to reflect and focus sunlight at a fixed target, typically a tower mounted receiver.

ASTRI is working on key heliostat technologies and research to enable lighter, smarter and more bankable heliostats to be developed and commercialised. With heliostats comprising a significant portion of capital expenditure for solar thermal plants, lowering the CAPEX, OPEX and risk associated with heliostat systems is a key focus of this project.

### Key achievements and highlights

In 2019, the team made good progress, with prototyping completed in all work streams.

Key achievements included:

- Demonstration of lightweight single component focussing facets and rapid prototyping using single point incremental sheet forming;
- Publication of state-of-the-art characterisation of wind loads;
- Subsystem testing of Closed Loop Tracking using retroreflectors; and
- Proof of concept of LIDAR as a rapid commissioning and verification method.

### Collaboration

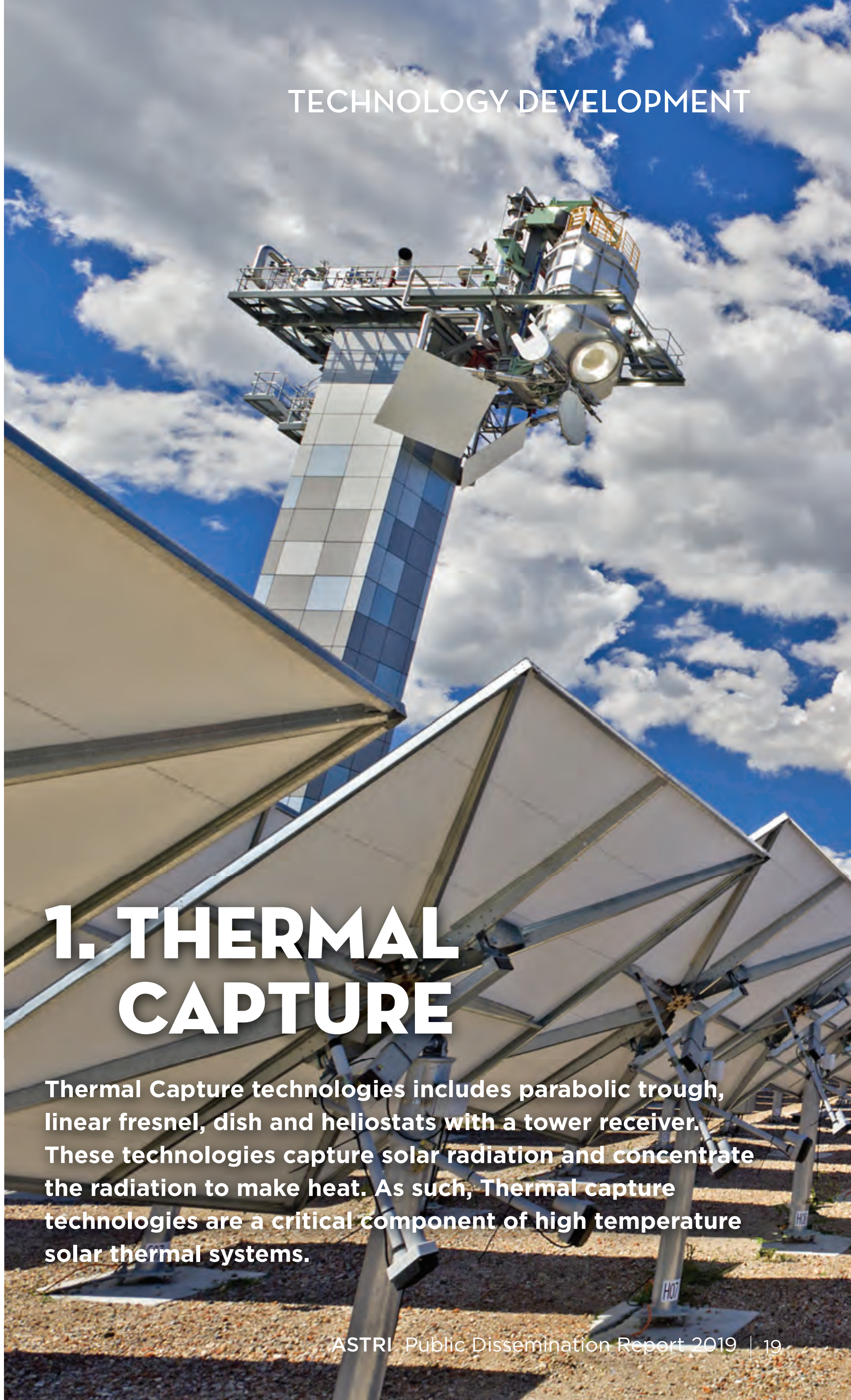
- Engagement on the project has been excellent. Key activities have included: supporting Australian technology company Vast Solar with its heliostat development program, including providing state-of-the-art wind load data; and
- Introduction of wind load guideline working group at SolarPACES, through which ASTRI is enabling overseas entities to adopt ASTRI generated knowledge and heliostat innovations.

### Future research

ASTRI will continue to develop and improve heliostats to meet the increasing interest in their use for higher temperature processes. Smaller heliostats are ideally suited to site specific applications. ASTRI future heliostat research will focus on improved heliostat performance as part of smaller applications linked to advanced $sCO_2$ power cycles. These applications including mining, fringe-of-grid, reactions to produce hydrogen, and heat for high temperature industrial process heat applications.

**fact**

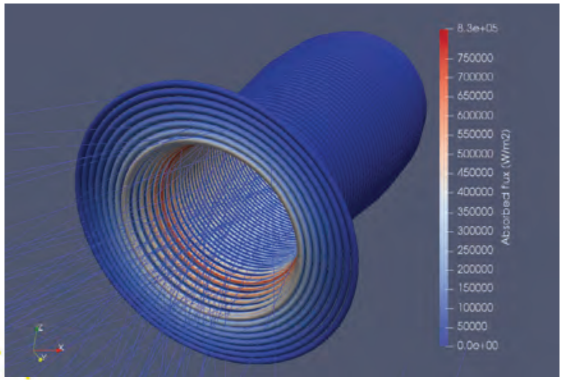
You can melt a hole through a 1/2 inch steel plate in under 10 seconds using mirrors.



| CSIRO Solar Field Newcastle

# 1. THERMAL CAPTURE

**Thermal Capture technologies includes parabolic trough, linear fresnel, dish and heliostats with a tower receiver. These technologies capture solar radiation and concentrate the radiation to make heat. As such, Thermal capture technologies are a critical component of high temperature solar thermal systems.**




Above: ANU Sodium loop

Leftt: ANU Receiver design

## Sodium Receivers

In a solar thermal system a field of heliostats reflects sunlight towards a receiver. There are many types of receivers and currently most tower-based systems use receivers with liquid-nitrate salts. While they have excellent thermal efficiency and heat transfer benefits, nitrate salts decompose above 600°C, making them unsuitable for higher temperature applications. Different receivers using liquid sodium or particles are being explored for higher temperature applications.

ASTRI's sodium receiver projects have explored new receiver designs that can operate at temperatures over 700°C. Higher temperature receivers are an important focus area because they can contribute to an 20% improvement in overall solar thermal system performance. ASTRI work has focused on liquid sodium as a heat transfer fluid, given its excellent heat transfer, low viscosity and other key advantages.

### Key achievements and highlights

The project team has achieved significant progress. Key achievements include:

- Completion of a concept design and down-selection for the 700 kW prototype receiver;
- Estimation of full-scale receiver cost, with industry input;
- Completion of structural integrity and materials selection reports;
- ANU sodium test loop piping and major components acquired; and
- Completion of initial round of coating durability testing (with tests up to 3000 hours duration).

### Collaboration

Project team members have increased engagement this year. Key activities include:

- Engagement on the US Gen3 Liquids pathway with NREL;
- Engagement with domestic technology developers including Vast Solar and Graphite Energy on working with ASTRI on higher temperature pathways; and
- Sodium safety and handling workshop at Argonne National Labs, Chicago.

### Future research

During 2020, the project will focus on activities to facilitate commercial uptake, including:

- Testing of sodium receiver to 740°C operation;
- Development of a commercial-scale version of cavity receiver concept;
- Lifetime estimations of sodium receivers using advanced structural integrity analysis;
- Exploring opportunities with mining and mineral processing entities for mid-sized, higher temperature CSP systems; and
- Exploring opportunities for the use of higher temperature receivers for high temperature processes to produce sustainable hydrogen and other industrial process heat applications.

**fact**

In solid state, sodium metal can be cut with a knife and has the consistency of a block of parmesan cheese.

## Particle Receivers

Tower based CSP systems can use liquid, solid or gas receivers. Particle receivers use solid particles that fall through a beam or concentrated solar radiation for direct heat absorption and storage.

Particle receivers could significantly increase the maximum temperature of the heat-transfer media, improving performance and increasing market competitiveness Particles have significant advantages in that they are cheap, don't melt until very high temperature and don't freeze like salts.

ASTRI's project will develop a multi-stage falling particle receiver designed for operation at high temperature (above 800°C) and with high efficiency. Under this project ASTRI will also develop a system to store these particles at higher temperatures and test the system at the CSIRO Newcastle site.

### Key achievements and highlights

The project team has achieved significant progress.

Key achievements include:

- Design of a 750kW particle receiver;
- Fabrication and indoor testing of particle receiver commenced;
- Development of a novel, scalable and high-performance particle heat exchanger concept;
- Design and development of various test systems including laser diagnostics, wind effect and water tunnel; and
- Development of a particle falling hydrodynamics model.

### Collaboration

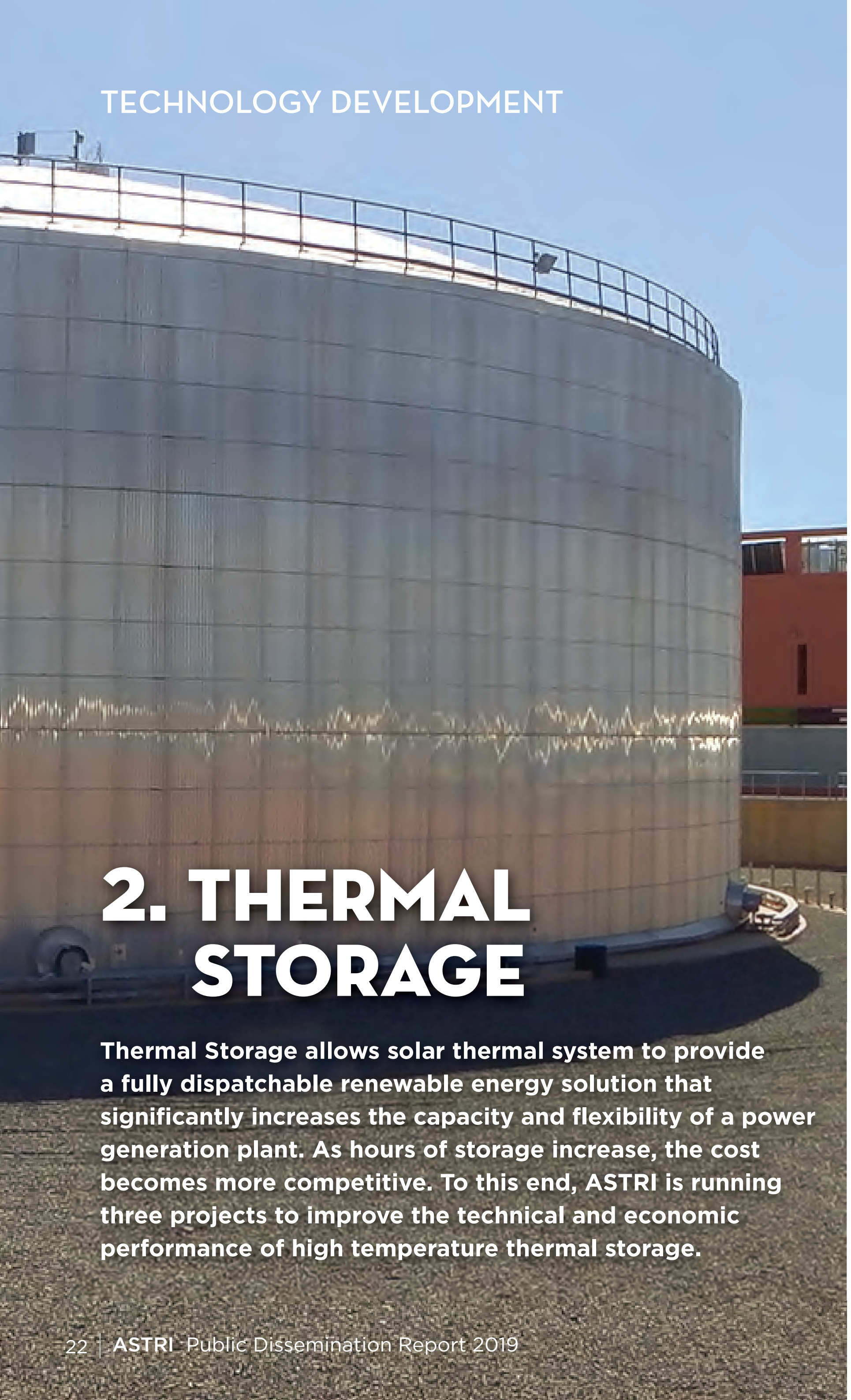
Key collaboration in 2019 included engagement on the US Gen3 particles pathway with Sandia.

### Future research

ASTRI will explore the use of higher temperature particle receivers for high temperature processes to produce sustainable hydrogen. Other applications could include additive heat for high temperature industrial process heat applications and providing "thermal battery" technology, where excess electricity from periods of peak PV and wind is used for charging.

**fact** Particle receivers can produce large amounts of thermal energy using trillions of particles similar to sands.

Particle receiver test rig.



# 2. THERMAL STORAGE

**Thermal Storage allows solar thermal system to provide a fully dispatchable renewable energy solution that significantly increases the capacity and flexibility of a power generation plant. As hours of storage increase, the cost becomes more competitive. To this end, ASTRI is running three projects to improve the technical and economic performance of high temperature thermal storage.**



## Cascaded PCM Storage

This project seeks to design, develop and test a cascaded phase change material (PCM) thermal storage system. This system seeks to exploit the increase in energy produced as materials change from one phase into another (e.g. water going from a liquid to steam). The use of cascading series of PCMs will deliver a system specifically targeted at efficient operation of high temperature $sCO_2$ cycles.

### Key achievements and highlights

- Experimental characterisation of key candidate storage materials (melting point, latent heat, heat capacity, thermal stability and density);
- Development of technoeconomic framework showing the predicted costs and cost reduction pathways; and
- Design and manufacture of a lab scale PCM storage system.

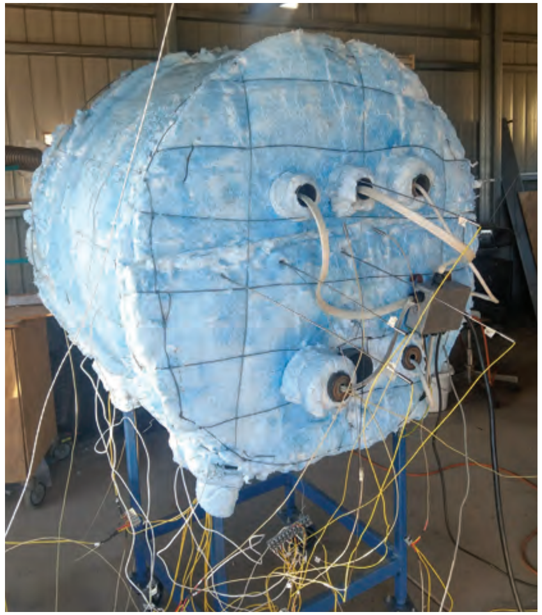
### Collaboration

- Discussion with national and international commercial companies to develop high temperature storage technologies, including CCT Energy Storage, MGA, Graphite Energy, Furnace Engineering and Buhler Group; and
- Creation of new partnerships with international universities and institutions, including Forschungszentrum Jülich and University of Illinois.

### Future research

ASTRI will continue to explore higher temperature thermal energy storage with lower cost materials, high energy density, high material durability (low degradation), more flexible charging and discharging storage systems, lower operational and maintenance costs, and lower volume/infrastructure requirements.

There will likely be significant growth in thermal energy storage being utilised within existing infrastructure to replace coal and gas boilers for power generation and process heat.



| Electrically charged PCM hybrid for production of heated air (up to 700°C) successfully tested at UniSA

**fact** Common materials similar to table salt could be the key to unlocking low-cost, high temperature reliable energy storage by taking advantage of their heating and cooling characteristics when they change phase, much like water and ice.

| ITP Thermal, Thermal Storage Tank

## Heat Exchangers

Heat exchangers indirectly transfer heat from one fluid/material to another. In a high temperature solar thermal system, the heat exchanger critically allows the separation between the Heat Transfer Fluid (HTF) and the working fluid for the power generation unit. While all heat exchangers operate on similar principles, they use different flow configurations, construction methods and mechanisms.

This project seeks to design new heat exchangers for next generation CSP plants that can withstand higher temperatures and associated higher pressures. ASTRI is working with international heat exchanger companies on an appropriate design for its system. It will demonstrate a small-scale Printed Circuit Heat Exchanger (PCHE).

### Key achievements and highlights

- Down-selection of project partners;
- Confirmation that Printed Circuit Heat Exchangers deliver a least cost heat transfer solution; and
- Identification of critical factors for Printed Circuit Heat Exchanger advancement.

### Collaboration

Links have been strengthened between ASTRI and PCHE developers including Clean Energy Systems (HEXCES), VPE, Comprex, Kelvion (USA) and Heatric (UK), which offer the greatest potential for development of a suitable heat exchanger.

### Future research

ASTRI will explore the use of higher temperature sodium/$sCO_2$ heat exchangers for other applications including heat for solar fuels (e.g. hydrogen) or for high temperature industrial process heat applications.

**fact** Compact plate heat exchangers can transfer large amounts of heat between two very different fluids with a separation of just a millimetre

## Emerging Storage Technologies

There are a number of thermal storage systems being designed for smaller modular applications (i.e. mining, fringe of grid). This project is about assessing technical, cost and integration issues for emerging storage technologies for ASTRI's large and small target applications.

### Key achievements and highlights

This year a range of sensible, latent and thermochemical thermal storage solutions have been explored. After assessing all options, project team members selected the most promising thermal storage options from a commercial uptake perspective to progress to development and testing. These options include phase change materials, particle storage, high temperature molten salt, graphite, miscibility gap alloys (MGAs) and sodium packed-bed with filler materials.

### Collaboration

The project team continues to engage with Australian commercial entities developing thermal storage solutions including MGA Thermal and Graphite Energy. Collaboration with overseas entities, including KraftBlock and SaltX (both from Germany) has also occurred.

### Future research

Energy storage has become a major focus of the energy industry worldwide The ability to charge thermal storage with either heat (Solar Thermal) or electricity (resistance heating) makes it an excellent energy storage option. ASTRI will explore adjacent markets for thermal storage systems as this will be a platform for consideration of Solar Thermal as the front-end charging solution.

HEXCES Printed Circuit Heat Exchanger being considered by the UniSA under the ASTRI Thermal Storage Program.

1Mwh thermal energy storage unit constructed by Graphite Energy

**fact** Thermal energy storage systems can not only enable Australia's use of renewable energy at night, but can also help mining companies lower their emissions and energy costs.

# 3. POWER SYSTEMS

**ASTRI is researching advanced power cycles, via the use of supercritical carbon dioxide ($sCO_2$) as an alternative to steam as the working fluid for power generation turbines. These $sCO_2$ power blocks can significantly increase power generation efficiency, are more compact and are ideal for small and large power generation applications.**

General Electric, Southwest Research Institute (SwRI)
Apollo Compressor (Photo: SwRI)

## Power Blocks

A power block converts thermal energy into mechanical energy by spinning a turbine shaft which creates electrical energy through a generator. In conventional solar thermal systems, superheated, high-pressure steam is used to drive a turbine to generate electricity. However, while steam turbines are predominantly used for large systems, as steam turbines reduce in size they quickly lose efficiency and cost effectiveness. This makes it difficult to develop smaller cost effective solar thermal systems.

An alternative that could significantly increase power generation efficiency and deliver more cost effective power block solutions for small and large power generation applications involves the use of supercritical carbon dioxide ($sCO_2$). These new power generation applications would replace steam with $sCO_2$ as the working fluid in the turbine, running in a closed loop.

This project seeks to explore the application of advanced $sCO_2$ power cycles within solar thermal systems. Working in collaboration with key industry and research stakeholders, ASTRI is providing expert support in the design, development, construction and demonstration of a small (1MWe) pilot scale power block.

### Key achievements and highlights

- Prepared detailed concept design of prototype 1MWe $sCO_2$ power block;
- Review of $sCO_2$ turbine prototypes globally;
- Review of Concept Design with invited independent experts;
- Testing of shaft cooling test rig (air only); and
- Assembly of the vertical wind tunnel as part of $sCO_2$ Heat Exchanger experiments.

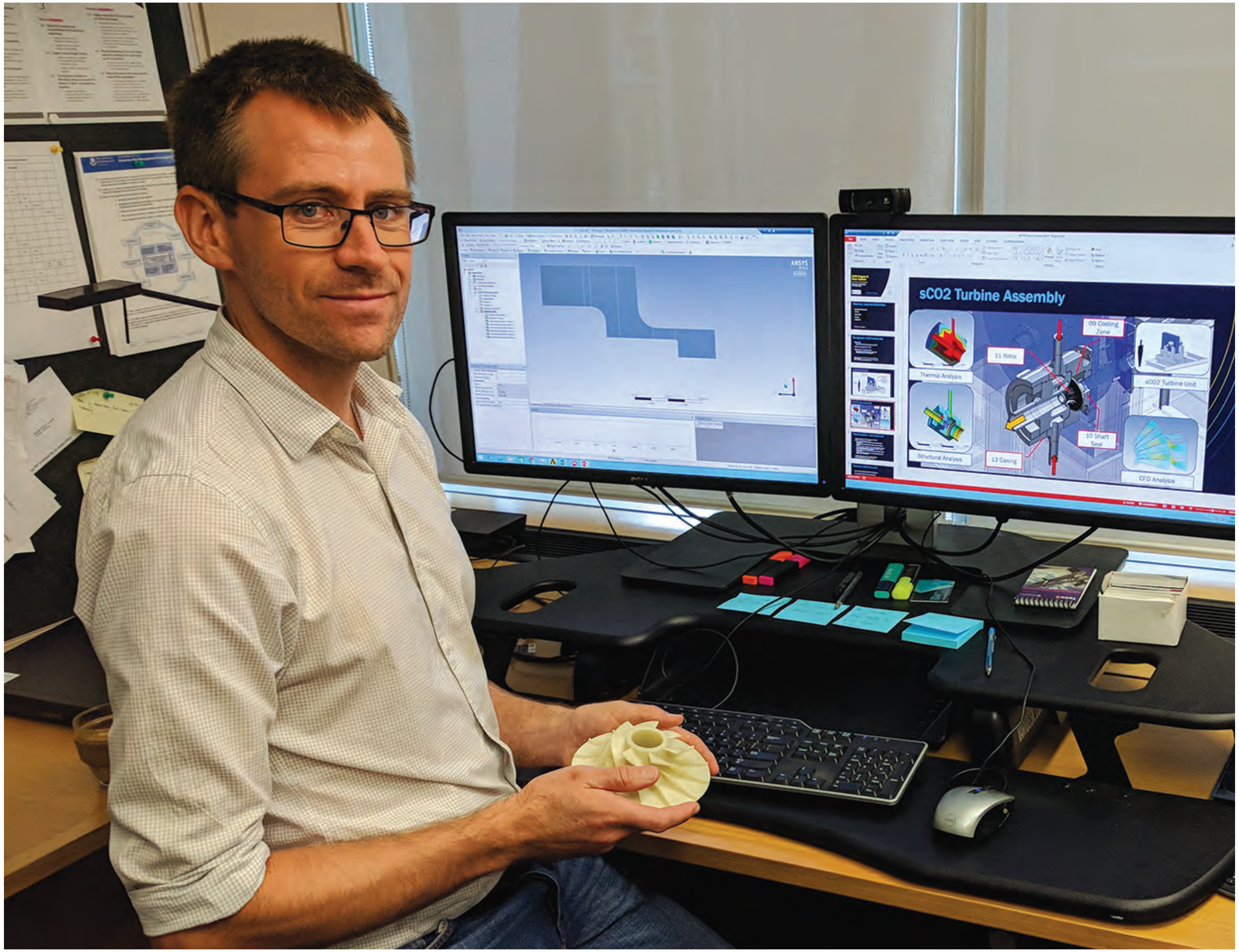
### Collaboration

- Australian participation as an Associate Member in the US DoE Supercritical Transformational Electric Power (STEP) Program, being managed by the gas technology Institute (GTI);
- In-person meetings with likely manufacturing partners (Harbine Turbine Company, Dong Fang Turbine Company, Shanghai Turbine Works Co Ltd) and test facility partner organisations (South West Research Institute, Chinese Academy of Sciences);
- Preliminary agreement with proposed manufacturing partner (Shanghai Turbine Works Co Ltd); and
- Preliminary collaborative agreement to establish the Chinese Academy of Science – Institute of Thermophysics as the power block test facility partner.

## Future research

ASTRI will focus its development efforts on an emerging market opportunity for smaller (5-30MW) power generation solutions in remote locations (mining, mineral processing, remote communities). At these locations diesel power generation is costly and emission intensive, and $sCO_2$ turbines linked to renewables offers a cost competitive, low emission alternative.

ASTRI is expecting to make a key down-select decision on its preferred $sCO_2$ power block solution in the first half of 2020. This decision will result in the development, acquisition or loan of a $sCO_2$ power block for testing with other key component technologies being developed by ASTRI in support of commercial uptake of solar thermal systems.




| ASTRI Project Manager Hugh Russell holding a 1-MWe supercritical rotor replica – one of the early designs by the University of Queensland

**fact**

Carbon dioxide could actually play a key positive role by being the next disruptor for the power sector, with next generation closed loop supercritical $CO_2$ turbines being more efficient and providing cheaper electricity than steam turbines.

# 4. TECHNOLOGY APPLICATIONS

**While significant effort has been placed on developing renewable energy technologies for electricity generation, there has been minimal investment in renewable energy solutions for high temperature industrial process heat applications. This is despite the fact that high temperature industrial process heat accounted for almost 15% of total energy used in Australia in 2016/17 and over 20% of Australia's $CO_2$ emissions. Researchers and industry are examining innovative ways to incorporate renewable energy into existing and future industrial process heat applications.**

| ITP Thermal, Noor Quazazzale

## Process Heat Technologies

The project aims to better define the value proposition for the commercial uptake of solar thermal technologies in support of high temperature industrial process heat applications.

ASTRI has narrowed its focus on the several 'high potential' industrial process heat activity areas that have strong industry interest, commercial viability potential, have high potential impact and are the strongest supported process heat applications.

### Key achievements and highlights

The following seven technology development projects with industry partners progressed to project agreement stage in 2019:

- Solar reforming of biomass feedstocks;
- Co-production of $H_2$, $O_2$ and $H_2SO_4$ from sulphur and CST in copper production;
- Solar fuels via thermochemical cycles;
- Identifying pathways to commercial application of beam-down particle technology in mining and off-grid applications in Australia;
- Photocatalytic production of methanol;
- Bagasse to liquid fuels; and
- Decarbonisation of steelmaking.

Two additional technology development projects with industry partners are expected to be finalised in 2020.

### Collaboration

ASTRI has been working with industry to ensure industry requirements and interest was a key driver in the research being undertaken. This has led to the development of multiple industry partnerships. The most recent round of projects based on this approach includes projects in the areas of copper processing, steel production, solar reforming of biogas, thermo-catalysis, agricultural waste and redox reactions.

### Future research

ASTRI sees a future for higher temperature hybrid systems incorporating: a mix of direct heat, solar fuels and conventional fuels, together with possible use of electrical energy; small heliostats; high temperature receiver designs; small radial $sCO_2$ turbine applications; low operational and maintenance costs; and solar fuels, with a strong focus on renewable hydrogen production and end use.

| Solar thermal could be used to drive down copper production costs

**fact** The key technologies expected to enable the transition to zero-emission aluminium, steel and cement are concentrated solar thermal heat, green hydrogen and green electricity.

## Advanced Materials

The 30-year design life of a solar thermal system (CSP and CST) requires full understanding of material compatibility and material degradation to make adequate design decisions, material selection and cost estimates.

This project will provide material degradation test data to identify corrosion, cycle fatigue and other material issues for metals and Phase Change Materials (PCMs).

### Key achievements and highlights

- Draft experimental protocols for testing candidate metals;
- Identification and procurement of candidate metals for testing;
- Testing of metals in various systems with various fluids;
- Characterised metal degradation, interaction and microanalysis; and
- Identified and purchased of high temperature transient creep test capability.

### Collaboration

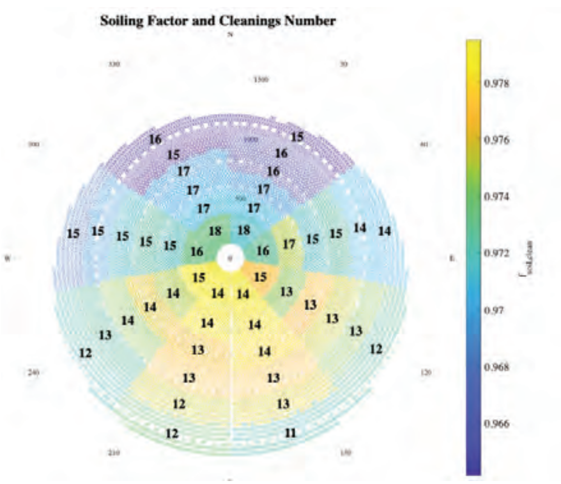
The project has enaged with a number of industry and research entities on material testing. This includes Vast Solar and the US Gen3 program, where similar testing with Gen3 salt/candidate metals is being conducted.

### Future research

ASTRI believes future opportunities exist to assist high temperature solar thermal component manufacturers with design and material selection.

**fact**

At normal operating temperatures, the steel commonly used in a CSP system will glow red hot, have increased reactivity and reduced strength and this, in turn, requires special considerations to ensure a long life.




Solar field with the number of cleanings from the optimal time-based schedule



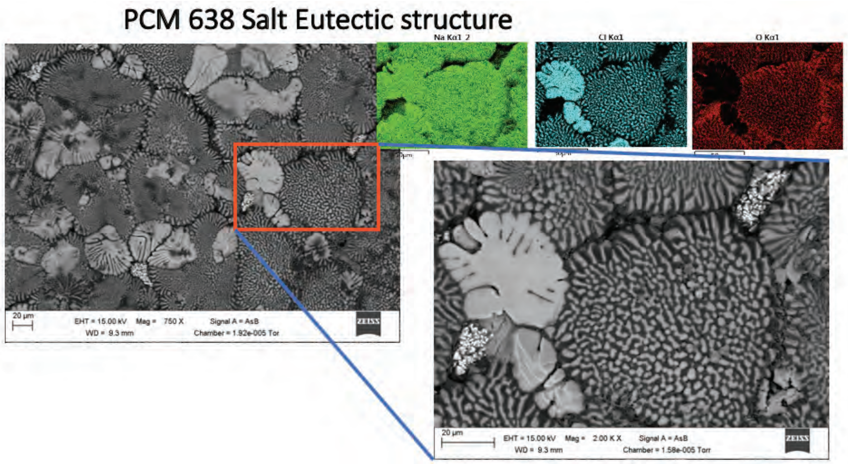
# 5. ADVANCED MATERIALS/ OPERATIONS & MAINTENANCE

**Material selection is critical to the successful design, development, building, commissioning, operation and long-term serviceability of high temperature solar thermal systems.**

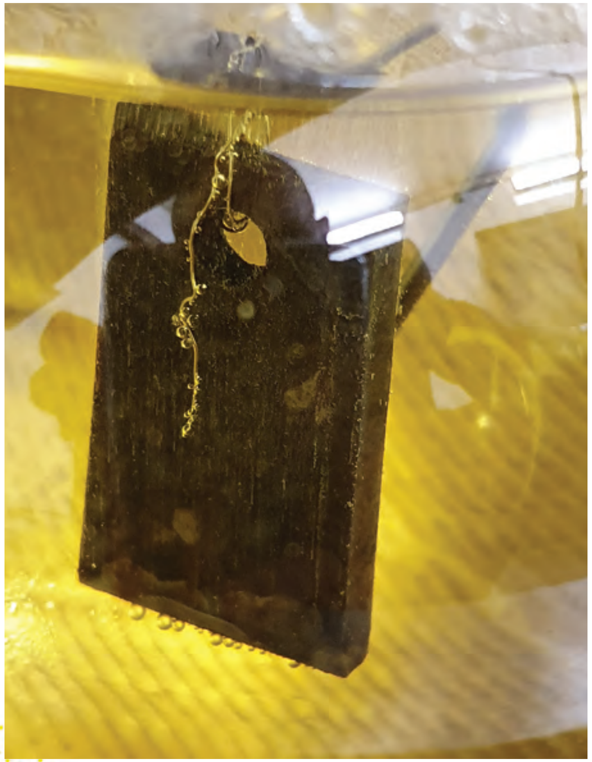
**ASTRI's materials program identifies suitable materials for high-temperature application and provide solutions to many of the materials issues associated with use and integration of high temperature components and different material interactions.**

**To accelerate the commercial uptake of solar thermal systems within Australia, more needs to be understood about the technology's operations and maintenance, as well as the effectiveness of the technology in the Australian energy mix.**

Vast Solar, Jemalong




Backscatter SEM/EDS images of 60wt% $Na_2CO_3$ : 40wt% NaCl (melting point 632°C) PCM solidified on Inconel 601 surface



Corrosion rate

## Operations and Maintenance

Some 15-25% of the costs of running conventional solar thermal systems come from operations and maintenance of key systems, including the cleaning of heliostats, optimising staffing levels, and managing the failure risks of key equipment. Unique aspects of solar thermal systems create significant uncertainty in terms of these costs going forward.

This project seeks to develop engineering solutions to both predict and minimise operations and maintenance costs, helping to "de-risk" investments in solar thermal systems.

### Key achievements and highlights

The project focus is on the evaluation, modelling, and mitigation of critical degradation modes of CSP equipment. Some of the major maintenance costs specific to solar thermal systems are associated with the solar field (e.g. heliostat cleaning) and the degradation of thermally cycled equipment (e.g. receiver, turbine). Yet, despite their critical importance, optimal O&M strategies for this equipment are poorly understood.

Key achievements have been:

- Staffing allocation model for heliostat field maintenance
- Mirror cleaning optimisation and soiling model refinement, with studies completed on:
  - Longitudinal natural soiling study; and
  - Initial evaluation of dust minimisation coatings.

### Collaboration

- Worked with Fraunhofer Institute for Solar Energy Systems ISE on validation of a soiling model;
- Increased engagement with domestic heliostat manufacturers; and
- Establishment of international collaboration arrangements with NREL and Sandia in the US, and DLR in Germany.

### Future research

Numerous commercial opportunities will stem from this project. There is potential to establish ASTRI as an expert advisor for solar thermal system O&M, as well as commercialise software tools for soiling prediction and cleaning optimisation. Additionally, ASTRI's work on heliostat monitoring and cleaning is of increasing commercial interest to the broader international community.

ASTRI will continue to engage industrial partners for staffing/cleaning cost studies; begin modelling of receiver degradation; and continue its $sCO_2$ turbine degradation modelling.

**fact** There are thousands of mirrors in a typical CSP plant and cleaning heliostats 1-2 times per month can improve efficiency by more than 20%.

## System Modelling

System modelling is critical for solar thermal system deployment. ASTRI is undertaking system modelling activities to understand the component cost interactions within solar thermal systems, and to understand the costs to the whole system of adding Solar Thermal to Australia's future energy mix.

This project provides system-level models for the ASTRI projects as well as the Gen3 Program. It involves development of suitable modelling capability and the collection of component cost data. Both should help ASTRI attract commercial interest in high temperature solar thermal components and systems.

### Key achievements and highlights

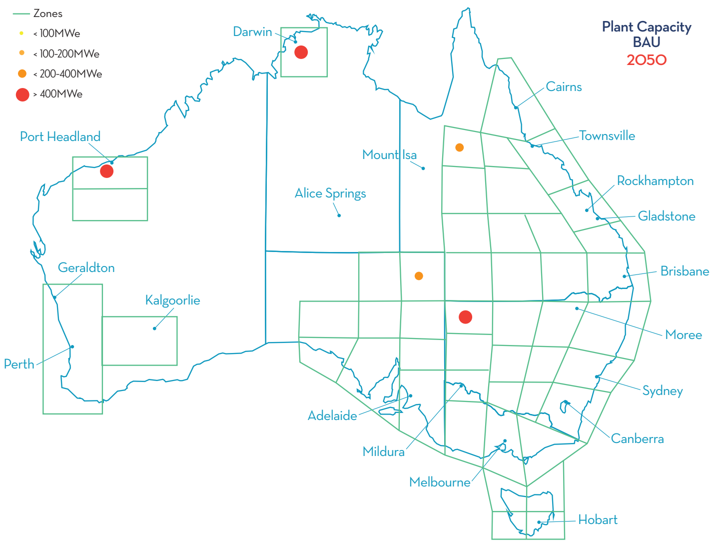
- Modelling of CSP plant designs (6, 9,12,15 hrs of storage & 3 hr peaking) optimised for 48 zones across Australia;
- Development of component models (field, receiver, HX, storage, power block);
- Assessment of receiver lifetime taking into account thermal stress; and
- CST uptake model developed for business-as-usual and stretch (low emission, high demand) scenarios.

### Collaboration

- Extensive collaboration with international research entities on key model inputs; and
- Institutions across France, Italy, Australia, Sweden, Germany, Spain, Cyprus and the USA participated in the evaluation and/or use of SolarTherm.

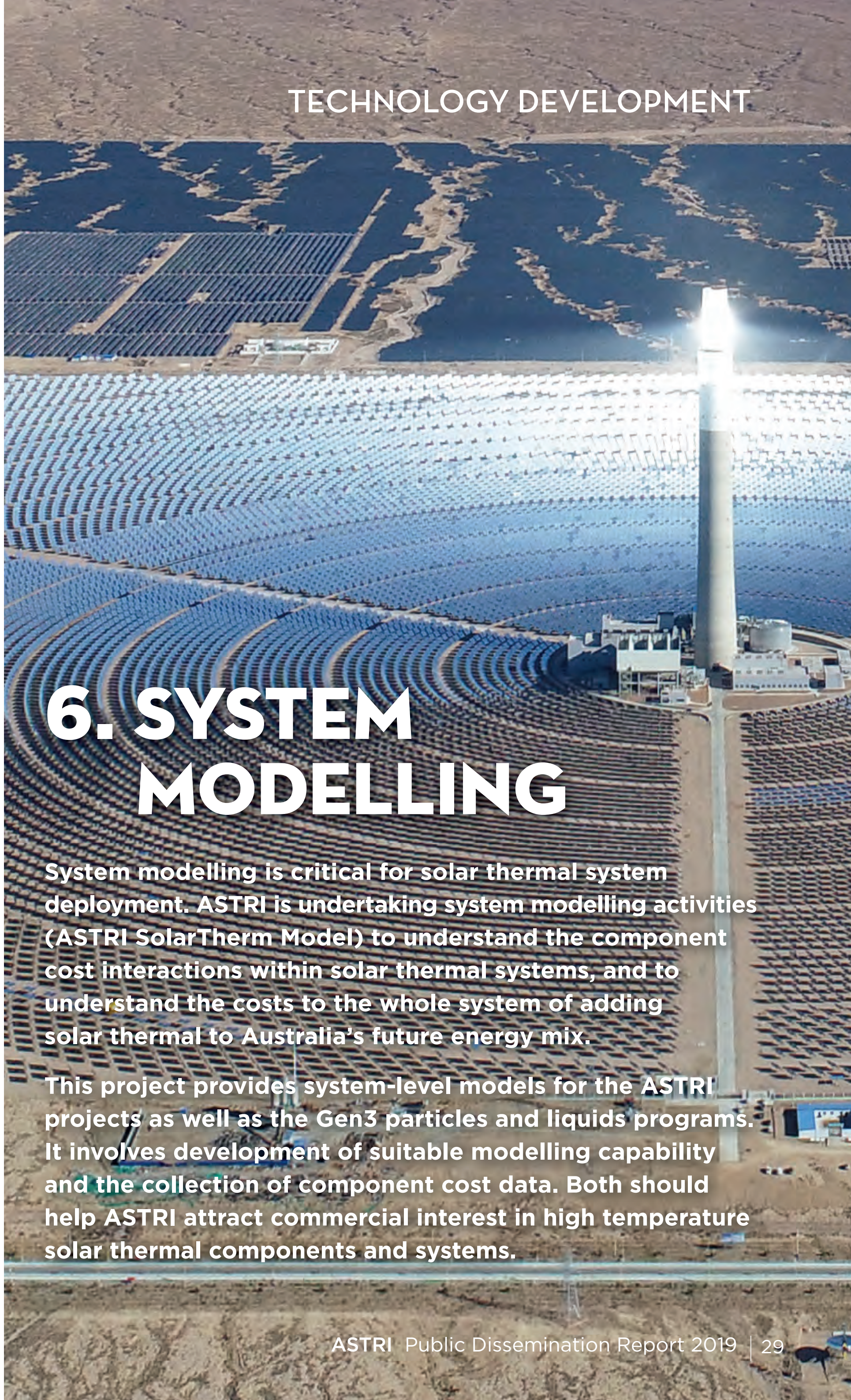
### Future research

In 2020 the project team will commence work on the Gen3 particles and liquids program down selection and begin work on the modelling for a full-scale ASTRI solar thermal system.




**fact**

Modelling shows that Australia will need 250 times more dedicated energy storage by 2050 than it currently has now.

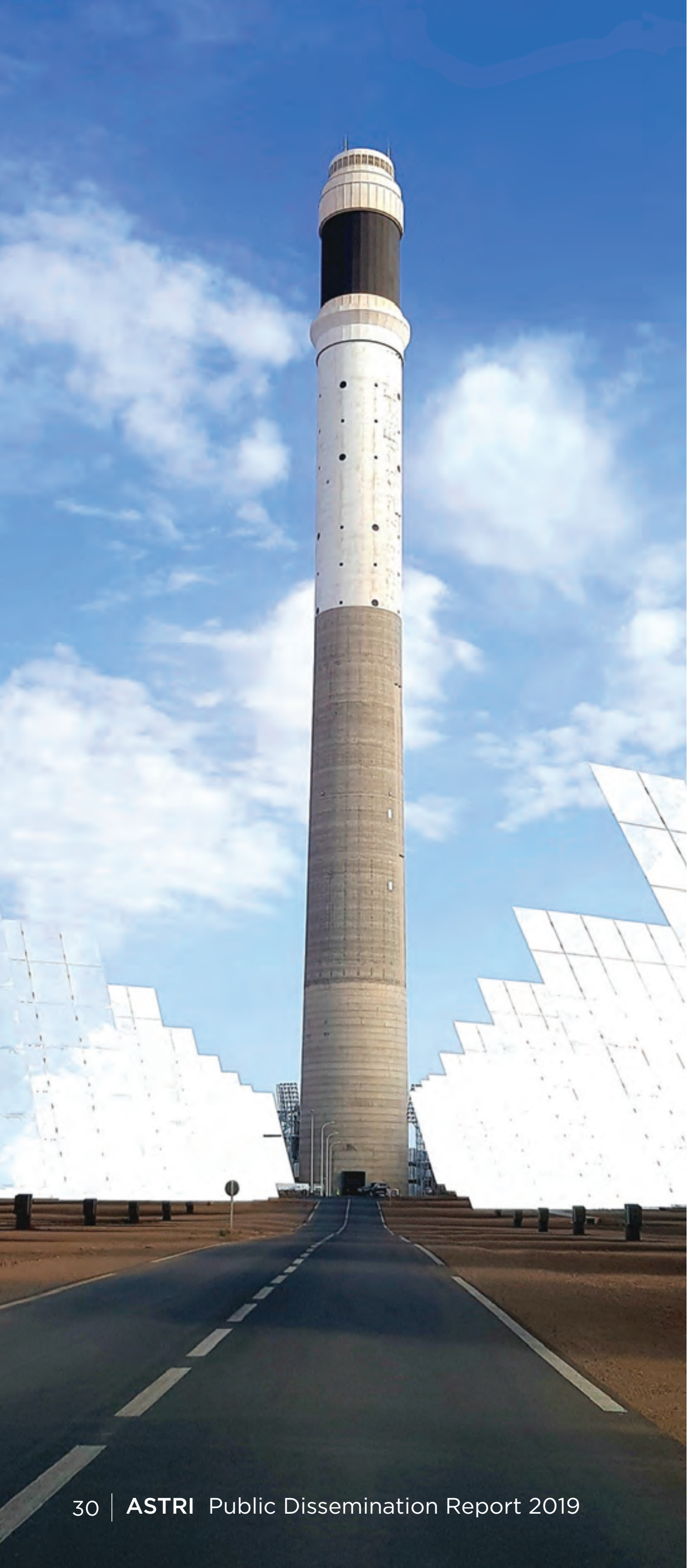


| Supcon, Delingha

# 6. SYSTEM MODELLING

**System modelling is critical for solar thermal system deployment. ASTRI is undertaking system modelling activities (ASTRI SolarTherm Model) to understand the component cost interactions within solar thermal systems, and to understand the costs to the whole system of adding solar thermal to Australia's future energy mix.**

**This project provides system-level models for the ASTRI projects as well as the Gen3 particles and liquids programs. It involves development of suitable modelling capability and the collection of component cost data. Both should help ASTRI attract commercial interest in high temperature solar thermal components and systems.**



# ASTRI MOVING FORWARD

ASTRI will continue to undertake research to facilitate the commercial uptake of solar thermal technologies and systems. ASTRI is focussed on the development of technologies that improve performance of solar thermal systems through higher efficiency, lower risk and lower costs.

ASTRI's technology projects are now moving from the development phase into the testing and demonstration phase. As a result, ASTRI is undertaking increased stakeholder engagement with both the solar thermal industry and the global research community to further the global interest in and uptake of solar thermal energy solutions.

The priorities for each program in 2020 are:

**Thermal capture** – continue to focus on lowering costs and improving performance of small heliostats, while exploring the use of optically improved heliostats for high temperature applications, like water splitting to produce sustainable hydrogen.

**Receivers** – sodium and particle receiver projects will focus on technology demonstration, commercial uptake, on-sun testing and opportunities with domestic and international industry partners for mid-sized, higher temperature CSP systems.

**Storage** – ASTRI will commence small-scale technology demonstrations in 2020. This will result in a down-select decision late in 2020 for ASTRI's preferred thermal energy storage solution. Once the down-select has been made, ASTRI will move quickly to de-risk (technical and economic) its preferred high temperature thermal energy storage solution for industry.

**Power blocks** – ASTRI is moving quickly towards a down-select decision (May 2020) on the design and potential development of a radial $sCO_2$ turbine. This decision may see a fast-track purchase or construction of a small $sCO_2$ radial turbine, to enable early, high temperature demonstration of the power cycle using solar thermal energy and thermal energy storage.

**Process heat technologies** – ASTRI will focus more on active small-scale testing and demonstration with its industry project partners. This work will seek to highlight the value of solar thermal technologies in the production of process heat, either directly or through solar fuels, and seed follow-on larger demonstration projects for promising technologies. ASTRI's direct engagement with industry project partners is expected to increase awareness and uptake potential for solar thermal process heat applications.

**Materials** – ASTRI will promote its role as an expert advisor on material design, selection and management for solar thermal technology components and systems (especially those used for high-temperature applications).

**Operations and maintenance** – ASTRI will offer existing technology developers and operators expert advice on options to reduce operations and maintenance costs.

| ITP Thermal, Gemasolar

| ITP Thermal, Crescent Dunes

**Modelling** – ASTRI will examine opportunities to integrate CSP into various energy-intensive industries. These could include pulp and paper, ammonia, cement and food/beverage sectors as well as greenhouse agriculture. Additionally, ASTRI will look to establish the role of solar thermal systems for large-scale hydrogen production.

**Commercialisation and stakeholder engagement** – In terms of commercialisation and stakeholder engagement, ASTRI will continue to actively work with technology developers to increase Australian market interest in solar thermal applications. ASTRI will also seek to work closely with energy market operators and regulators to ensure that solar thermal is actively considered as a technology option to provide firm capacity and system strength in support of Australia's transition to a low emission energy system.

ASTRI will work with Australian mining companies to understand how solar thermal technologies, particularily in Australia's hot dry mining areas, can be used to lower the emissions and improve the international competitiveness of Australia's resources sector. ASTRI's focus will be on thermal energy storage and advanced power blocks as an enabler for solar thermal systems.

In support of commercial uptake ASTRI will work with the Australian Solar Thermal Energy Association (AUSTELA) to improve investment sector interest in solar thermal systems. The investment sector is showing a strong interest in sustainable technologies and have actively moved away from investments in conventional fossil fuel. Technologies such as solar thermal that provide a 100% renewable solution are gaining increasing investment interest.

In support of all of its activities, ASTRI will continue to actively collaborate with international research entities, and share information and knowledge as an enabler for best practice international solutions.

| Back cover: Supcon, Delingha

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