Australian Solar Thermal Research Institute (ASTRI)
Public Dissemination Report 2022

Prepared By: The Australain Solar Thermal Research Institute March 2023

DIRECTOR'S MESSAGE

Australia's transition to a low emission economy continued to evolve over the course of 2022. Influenced by domestic and international events, including a change of government, the situation in Ukraine, higher emission targets and increasing energy costs, interest in low-emission technology solutions in rapidly increasing.

Investment in renewables is increasing, with uptake of PV and wind accelerating in 2022. This increased uptake has seen increased government and industry interest in technology solutions that can store renewable energy. While the main focus has been on short term energy storage systems, there has been increased awareness of the need for longer duration (10-15 hours) intra-day renewable energy storage to provide firm capacity overnight. Governments have acknowledged that investment incentives for longer duration intra-day storage will be required if Australia is to reduce its reliance on emission-intensive coal and gas applications, particularly at night.

While markets and governments continue to focus on renewable power, there has also been increasing awareness of the role of renewable heat in Australia's future energy systems. Renewable heat has three primary end-use outcomes. Firstly, it can be used to generate utility scale power. For this application, the renewable heat can be stored, and then used, on demand, to generate firm power. The application is identical in operation to a coal-fired power station, using steam turbines, but without the coal.

Secondly, renewable heat can be captured, stored, and used for industrial process heat applications in temperatures from 50C to 1000C.

Lastly, renewable heat can be used for combined heat and power applications, which is of growing relevance for a range of industrial applications, particularly the emerging renewable fuels market.

While renewable heat can be created through a range of technology pathways, Solar Thermal is the technology solution that is best suited to larger scale, higher temperature, renewable heat applications (power generation, industrial process heat, renewable fuels). It is also the technology solution best able to meet Australia's longer duration, intra-day renewable energy storage needs.

Given Australia's exceptional solar resources, Solar Thermal has the potential to be a cost-effective technology solution for the provision of multiple hours of renewable power and/or heat.

In 2022, the Australian Solar Thermal Research Institute (ASTRI) has continued to highlight the role of Solar Thermal in Australia's future energy systems. The focus has been on the role of Solar Thermal in the key end-use markets including remote area power systems, utility scale grid-connected power generation, renewable fuel production and industrial process heat applications.

Solar Thermal continues to be deployed internationally in high solar radiation countries as a renewable solution for the provision of firm, dispatchable energy. Almost 7GW of Solar Thermal capacity is now in operation with an additional 10GW of capacity being constructed or proposed over the next 10 years. Installation is occurring in the Middle East, China, Spain, South America, and Africa. China has committed to 28 new combined PV/Wind and CSP plants (3GW/25GWh of storage) by the end of 2024. Spain is also in the process of adding an additional 5GW of Solar Thermal capacity by 2030.

While deployment is occurring overseas, domestic deployment has not yet occurred primarily due to Australia's reliance on low-cost coal and gas. However, this situation is changing with rising energy costs and increased interest in Solar Thermal technology solutions for power generation and industrial process heat applications. To this end, it is anticipated that new domestic Solar Thermal systems for power generation (Vast Solar), industrial process heat applications (Mars Petcare) and green methanol production (Vast Solar) will commence in 2023.

In 2022 ASTRI continued to progress activities to promote and enhance the value proposition that Solar Thermal can provide across different energy end-use markets. This includes activities focused on technology enhancements, a detailed technoeconomic analysis of the Australian CSP value proposition, and on renewable heat projects to demonstrate the real-world application of Solar Thermal and Thermal Energy Storage systems within Australia's industrial process heat sector.

This Annual Report highlights much of this work, including developments in higher temperature thermal capture and thermal energy storage systems, industrial process heat applications, high temperature material interactions, and operations and maintenance cost reductions. It also includes ASTRI's commercial engagement, communications, and advocacy activities.

Domestically, one of the most important drivers for the uptake of Solar Thermal will be the demonstration of an economically viable reference plant. Over the course of 2022, ASTRI has moved towards finalising a high-temperature demonstration system at CSIRO Newcastle. This demonstration system, utilising sodium as the high-temperature heat transfer fluid (in support of Vast Solar), will operate at temperatures between 600°C to 700°C. This will allow the operational and performance benefits of moderate increases in temperature, for Solar Thermal systems, to be clearly demonstrated.

Given increased industry and government interest in overnight renewable power generation and industrial process heat, ASTRI is confident that 2023 will be the year for Solar Thermal deployment to occur in Australia.

Dominic Zaal

Director, Australian Solar Thermal Research Institute, CSIRO

CONTENTS

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Front cover: Delingha 50MW – 7-hour storage – Cosin Solar
Above: NREL

Solar Research Facility Newcastle - CSIRO

ABOUT ASTRI

The Australian Solar Thermal Research Institute (ASTRI) is a consortium of leading Australian research institutions working with Australian and international developers to facilitate commercial interest in, and domestic uptake of, Solar Thermal technologies. The intent being to ensure that Solar Thermal is considered as an option in support of Australia's transition to a low emission energy future.

To achieve this objective, the ASTRI Program focuses on technology development and commercial facilitation. ASTRI's technology-based activities are aimed at improving the cost competitiveness, efficiency, and reliability of Solar Thermal technologies. This includes the use of multi-hour thermal energy storage (TES) systems as a cost-effective option to address Australia's emerging energy storage needs - for power generation, for industrial process heat applications, or both (i.e. combined heat and power).

As the Program has evolved, the focus of ASTRI's technology development activities has shifted from fundamental to applied research, and now includes a high level of direct industry support. In 2022, ASTRI's technology development activities are at Technology Readiness Level 5 and 6, with over 80% of activities directly supporting industry development and deployment.

ASTRI's commercial facilitation activities promote the value proposition that Solar Thermal systems can deliver within key Australian energy end-use markets. These activities involve close engagement with major energy users on commercial uptake opportunities across a broad range of end-use applications including power generation, industrial process heat, off-grid mining, and renewable fuel production.

As the Program has evolved, ASTRI has spent an increasing amount of effort on commercial uptake support. In 2022, over 80% of ASTRI's effort has been directed to advocacy, stakeholder engagement and direct support for industry. This has increasingly involved industry support for thermal decarbonisation, reflecting growing industry interest in renewable heat technology solutions.

ASTRI

What is Solar Thermal?

Crescent Dunes – NREL

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 (water, molten sodium or oil) that is then stored. The stored heat is then used to generate steam for power generation, or it is used directly for industrial process heat applications. Solar Thermal can also generate both heat and power, which could be used for renewable fuel production. Solar Thermal systems typically operate at temperatures between 300°C to 600°C.

Globally, over 90 Solar Thermal plants are operating commercially, mostly in countries with high solar radiation. However, even though Australia has some of the best solar radiation in the world, the technology is still in its early stages of domestic deployment. This is due to three factors. Firstly, it reflects our access to relatively cheap and abundant local coal and gas resources. Secondly, it reflects a lack of market signals for long-duration, intra-day energy storage. Lastly, it reflects the absence of an international pricing mechanism on carbon.

Solar Thermal can be applied as a Concentrated Solar Power (CSP) system for electricity generation, or as a Concentrated Solar Thermal (CST) system for process heat.

The key difference between systems is that CSP converts the thermal energy into power. This noted, some CSP applications use both power and heat (e.g. renewable fuel production).

Both systems use collectors to concentrate the sun's light onto a receiver where it is converted into thermal energy.

The thermal energy can be used directly or stored for use at a later time to produce electricity, process heat or a combination of the two.

The thermal energy can be stored on a daily basis for long periods (8 to 18 hours) and then dispatched, as required, at any time of day and night. As such, Solar Thermal is a technology that allows storage of energy during the day, which can then be used at night. In essence, Solar Thermal is solar energy at night.

Key components

There are several different Solar Thermal 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. Parabolic Trough and Linear Fresnel collectors are suitable for heat collection up to 400°C. Heliostats collect heat up to 600°C.

Thermal capture

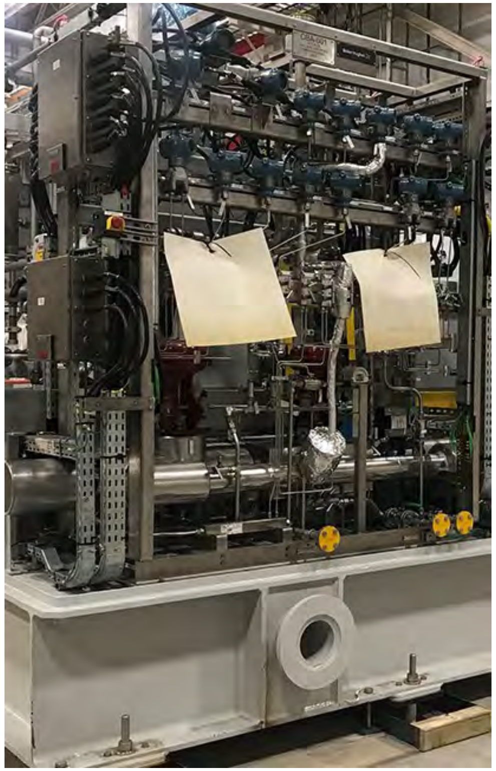
The mirror reflects sunlight onto a receiver, which converts the concentrated sunlight into high temperature heat.

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 involves the production of super-heated, 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 C02 are emerging as a pathway for smaller, more efficient power generation systems.



Main Compressor Skid - sCO2 STEP Demo – GTI

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 almost 7GW at the end of 2022. There are now more than 90 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. This may soon change with China planning to have 3.5GW of CSP operational by the end of 2024.

In the past few years, CSP plants have also been built in Morocco, China, South Africa, India and the Middle East.

There is another 5.5GW of large CSP plants under construction or under development across a number of countries including China, Chile, Spain Morocco and Saudi Arabia.

Countries leading the way with CSP all have high solar radiation, like Australia.

However, despite having the highest solar radiation in the world, there is only one commercial CSP system operating in Australia (Sundrop Farms). This situation will change with Vast Solar about to commence construction of a 30MW CSP plant in Port Augusta.

More CSP Plants will be deployed as coal fired plants retire and alternative low emission energy storage and generation technologies are required.

Operational Performance

How many CSP systems are there globally?

There are currently around 65 CSP plants that are 50 MW or larger and another 34 smaller plants. Installed capacity is increasing after a slowdown due to Covid19. This increase has primarily been driven by China, which has announced the construction of 28 new CSP plants (3GW/25GWh of storage) by the end of 2024. China has indicated plans for another 10GW by 2030. Spain has announced plans for another 5GW 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 10 years. The eight plants in the US have been operation for over five years. Another 20 plants locations have been operating for over three years.

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

The Challenge

To combat climate change and meet emission reduction targets, Australia must reduce its reliance on fossil fuels. This is a difficult challenge given our access to abundant, low-cost coal and gas. However, the need for action is being recognised by government.

The new Federal Government has adopted a more aggressive emission reduction target, which complements strong state government commitments and supporting policies to reduce emissions. Together, this increased focus on decarbonisation has provided the incentive for Australian households and businesses to invest in low-emission technologies.

However, emission targets are not the only reason Australia should be aggressively looking to decarbonise. With our abundant renewable resources and land, decarbonisation should be easier and more cost effective for Australia, in comparison with other countries. The quicker we move to renewable energy, the quicker we capture the productivity, sustainability and energy security benefits associated with reduced reliance on fossil fuels.

Power Generation: multi-hour, intra-day, firm capacity at night

Australia has the highest penetration of rooftop solar in the world and take up has continued to accelerate in 2022. Investment in utility scale PV and wind has also been the highest Australia has seen in many years. This noted, renewable energy represented 36% of our electricity in 2022, but only 10% of our total energy use. As such, there is still significant investment and action required to transition to a low-emission economy.

While there are many decarbonisation pathways, the use of renewable technologies to replace fossil fuels is the most effective and timely way to transition to a net-zero future. This is reflected in Federal and State government emission reduction targets, and their focus on policies and programs to promote investment in low-emission technologies.

Australia's move away from fossil fuels will be a significant undertaking. Our economic prosperity and high quality of life has been largely built on our abundant coal and gas resources, both as a valuable export commodity and as a low-cost source of energy (power and heat).


Trough Field NREL

Large coal-fired power stations were built to support centralised energy networks. However, this centralised delivery model is not a good fit in a renewable-based energy system, comprising multiple, highly dispersed, and lower capacity or intermittent renewable energy assets.

As we move to a renewable energy system, a key challenge is how best to integrate renewable assets in a way that delivers a reliable 24/7 outcome. The challenge is not renewable generation, rather it is about how best to manage what is generated, when and where.

Australians have access to secure and reliable energy, day and night, under-pinned by coal power plants that run 24/7. During the day, PV is taking an increased share of generation away from coal-fired plants. At night, coal plants, supplemented by gas generation (and wind), still provide most of our power needs. Together this mix of technologies ensures that there is sufficient firm capacity to meet Australia's 24/7 demand.

However, Australia's fleet of aging coal-fired power stations will retire over the next 10 years. This creates a need for replacement technologies that provide the same level of firm capacity, day and night, but with zero emissions.

Gas-fired power generation provides an interim solution. However, the use of gas still creates emissions, and its long-term use will not allow Australia to meet its emission reduction targets.

If Australia is to move to a low-emission economy, we need technologies that can reduce our reliance on coal and gas, 24/7. This will require technologies that can capture and store renewable energy during the day, for dispatch, on demand, at night. To this end, renewable energy storage technologies will be a critical enabler of Australia's transition to a low emission economy.

The Federal Government recognises the importance of energy storage and has announced a number of potential mechanisms to increase investment in long duration (8 to 24 hours), intra-day renewable energy storage. These mechanisms recognise that while batteries are a good solution for short duration energy storage, different technology solutions are required to address our longer duration intra-day storage needs. These storage solutions must be capable of providing firm, fully dispatchable capacity for at least 8 hours each day, and are particularly important for meeting overnight power requirements.

Solar Thermal is a technology that meets all of these needs. It captures heat during the day, which is then stored for use at a later time (typically at night). This stored heat is used to generate steam to run a turbine, just like a coal-fired power plant (but without the coal). Solar Thermal is able to store up to 24 hours of thermal energy, making it an ideal technology solution to provide firm capacity for 10-15 hours over night.

Industrial Emissions: mid to high temperature industrial process heat with storage

While markets and governments continue to focus of renewable power, there has been increasing awareness of the need to decarbonise Australia's transport and industrial sectors. This is important given that industrial emissions (including stationary power) will exceed those for grid-connected electricity generation within the next year. For transport, the focus is on electric vehicles and on renewable fuel production. For industry the focus has been on renewable power and renewable heat solutions.

Renewable heat for industry is focused on three primary end use outcomes. Firstly, it can be used, to generate renewable power. The heat can be captured and stored, and then used, on demand, to generate power through a steam turbine (like a coal fired power plant).

Secondly, renewable heat can be captured, stored, and used for industrial process heat applications . Lastly, renewable heat can be used for applications that require both heat and power, which is relevant to the emerging renewable fuels market.

For industry the primary focus is on renewable heat to displace gas for industrial process heat applications. Renewable heat can be generated in three main ways. Renewable electricity to heat, solar thermal, and bioenergy.

For low temperature applications (< 120°C), electricity-based renewable heat technologies are a good fit. However, for mid-temperature applications (150°C to 600°C), renewable heat technologies with storage are required. For applications over 650°C, more complex, higher temperature renewable heat systems are required (particle-based).

Solar Thermal for heat and power applications is also of increased interest. The main focus area here is mineral processing and renewable fuel production. For larger scale applications where both mid-temperature heat and power are required, and land is available, Solar Thermal is an ideal technology.

Australian Solar Thermal Value Proposition

Jemalong Vast Solar

The Australian energy market involves a complex interaction between key energy use sectors. While most people view the energy market as the electricity market, more energy is used in Australia in non-electricity markets. Specifically, the Australian manufacturing, mining and transport sectors account for over 60% of Australia's energy use.

Significant change is occurring in all energy use sectors. For electricity, the amount of renewable generation continues to increase, representing 36% of total generation. For transport, electric vehicles sales are rapidly increasing and are expected to represent 50% of all new vehicle sales by 2030. For industry, rising gas and power prices have resulted in many companies now looking for alternative renewable heat solutions. For mining, significant investment in renewable technologies and renewable fuels is continuing.

Consumers are also more engaged in energy markets. Rooftop PV is increasing at a rapid pace, and sales of residential batteries increased by 55% in 2022 (almost 50,000 new installations).

All of these trends, coupled with higher energy prices, more aggressive government policies, increased climate change risk, and rapid technology advancements are creating some significant integration challenges for Australia's energy system. Central to these challenges is the need to deliver clean energy outcomes that provide secure, reliable, and affordable access to energy for all Australians.

One of the key challenges in moving towards a renewable energy system is how to deliver renewable energy across a 24-hour time period. Solar PV and wind are intermittent energy technologies. They generate when the sun is shining, and the wind is blowing. At night, and when wind resources are low, it is impossible to deliver a secure and reliable renewable energy solution.

Conventional fossil-fuel systems (coal and gas) are currently used to ensure that we have access to secure and reliable energy on a continuous 24/7 basis. However, Australia is moving away from fossil fuel generation and a replacement solution is required. This solution will likely involve renewable technologies that can store and dispatch energy when required (in the form of power, heat, or both), at any time of day or night.

Solar Thermal can meet this requirement and is well suited to Australia given our high solar levels. It uses sunlight to create thermal energy, which can be used or stored, for end-use applications, in the form of power, heat, or both. Thermal energy plays an important role in Australia's energy system, with well over 85% of Australia's current energy requirements (electricity, transport and industry) using a thermal energy process. This includes 65% of our electricity, over 90% of our industrial process heat applications, and over 95% of our transport requirements.

Solar Thermal is yet to reach the point where it is cost competitive in the Australian market. This reflects a range of factors including the low cost of other renewable technologies, the higher up-front cost of Solar Thermal systems and the operational risk of integrating renewable heat into existing power and process heat applications.

However, this situation will change with the focus on multi-hour renewable energy storage. As decarbonisation efforts intensify in response to emission reduction imperatives, solutions to quickly displace fossil fuel power generation and heat production will be required. Solar Thermal can deliver that outcome, particularly in countries like Australia with high solar radiation.

Solar Thermal's main value proposition is its multi-hour energy storage. The ability to store thermal energy, which can then be dispatched on demand (as power or heat) has significant value. Energy storage provides firm capacity, which will also increase in value as the level of variable generation increases. Thermal energy storage can also be used for arbitrage, to store excess renewable energy (PV and wind).

In essence, Solar Thermal is a renewable replacement for coal-fired power generation. It uses an identical thermal process, at the same temperature ranges, involving the production of high temperature steam, through a steam turbine to create power. The only difference is that, for Solar Thermal, the thermal energy comes from the sun not from the combustion of coal or gas.

Benefit to Australia of Solar Thermal

Solar Thermal is a technology that captures, stores, and then utilises thermal energy. The use of thermal energy in Australia's energy mix is not a new concept. Conventional power generation using coal and gas converts thermal energy into power. Gas is also used in industry for process heat applications. Over 85% of Australia's current energy requirements use thermal energy processes.

Given Australia's high solar irradiance levels, Solar Thermal is a renewable energy option that has the potential to provide low-cost, utility-scale, firm and fully dispatchable energy in the form of heat or electricity. When coupled with thermal energy storage (TES), Solar Thermal systems can generate firm power or heat at any time of day or night, over multiple hours.

In addition to utility scale power generation, there is also an emerging market interest in smaller Solar Thermal systems (<30MW) at remote locations. Such systems are viewed as a means to increase the level of renewable uptake, particularly for evening/night time loads, to displace high-cost diesel generation, and to hedge against future fossil fuel energy price volatility.

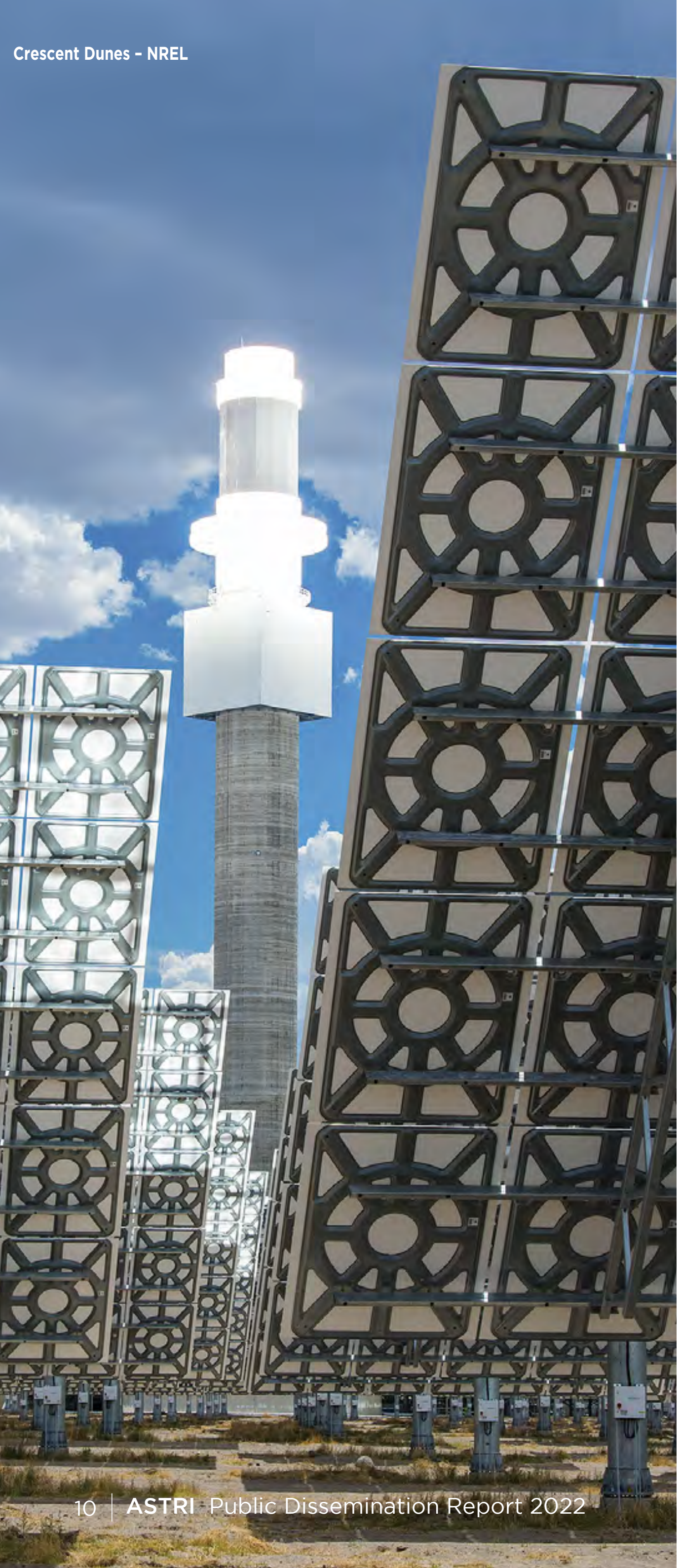
As Australia moves to a low-emission future there is also a need and emerging market for renewable process heat. Over $16 billion is spent annually by Australian industry on process heat. Our decarbonisation journey will need to address emissions from industry, which currently use a third of Australia's total energy. Thermal energy from solar thermal can be stored or used directly for industrial process heat applications at temperatures from 150°C up to 1000°C.

Australia is keen to position itself as a major global player in the production of clean hydrogen. This will require large amounts of renewable electricity. To maximise production, renewable power will be required night and day. Solar Thermal can meet this need, particularly in Australia's high solar resource areas. When coupled with PV and wind, Solar Thermal can provide night-time power to achieve a higher capacity factor for clean hydrogen production in response to export demand. Solar Thermal can also be used to support high temperature solid oxide electrolysis, which produces higher hydrogen yields.

Solar Thermal can provide a technology solution for low-emission mineral processing. Specifically, the ability of Solar Thermal to provide power and/or heat at any time of day or night makes it a good technology option to enable high renewable levels for 24/7 mineral production. The carbon liability associated with Australian mineral exports will inevitably need to be accounted for. This liability will reduce the competitiveness of Australian mineral exports unless effectively managed. Solar Thermal can be used to provide renewable heat and power to lower the carbon liability and improve the value of Australian mineral exports (e.g. beneficiation).

A summary of the Solar Thermal benefits to Australia are summarised below.

Feature of solar thermal systems	Benefit to Australia
Carbon-free, utility-scale, dispatchable generation.	A fully flexible supply of renewable based electricity to meet daily system demand profiles.
Scalable energy storage and generation for remote areas.	Reliable, low-cost, renewable supply of electricity for remote mining and communities, reducing reliance on diesel generation.
Mineral Export – decarbonisation and value adding.	Lower the carbon liability and improve the value of Australian mineral exports.
High temperature industrial process heat.	Low-cost supply of industrial process heat to improve industry's cost competitiveness.
Low-cost, multi-hour, energy storage.	Low-cost supply of firm renewable energy.
Firm capacity on demand.	Improved system reliability and stability and a greater proportion of load firming.
A 100% renewable energy solution.	Reduced CO_2 emissions.
A broader renewable energy generation mix.	Providing improved flexibility and redundancy in the system.
Complementary with other technologies.	These integrate with other energy technologies and allow for greater uptake of intermittent renewable energy (i.e., PV & wind).
Grid support services.	Provide critical grid support services such as firming, inertia response and frequency control, once coal fired generators retire.
Low-cost local grid-connected or standalone generation.	Savings on network augmentation and remote area subsidies. Ideal complementary technology within Renewable Energy Zones.
Renewable Fuel Production.	Increase the capacity factor and yield of clean hydrogen production in response to export demand.



Crescent Dunes - NREL

ASTRI'S ROLE IN SUPPORTING SOLAR THERMAL UPTAKE

ASTRI has established itself as a trusted adviser to government, energy providers, technology developers and energy end-users on the application and commercial uptake of solar thermal systems and technologies. ASTRI has also continued to function as a leading collaborative research institute working closely with industry and other research entities on technologies to enhance the performance and reliability of concentrated Solar Thermal systems.

Over the past year, ASTRI has sought to promote and increase commercial interest in the use of solar thermal technologies as a cost competitive energy storage, power generation and process heat solution.

ASTRI's commercial support activities were focused on deployment and uptake of current solar thermal systems and technologies. These activities have focused on direct technical and commercial uptake support to industry.

This includes direct support to technology developers to help de-risk their technology from both a technical and operational perspective.

It also includes direct support to energy end-users. Specifically, support to companies who are seeking advice or assistance on deployment of conventional Solar Thermal systems and technologies.

In terms of technology development, ASTRI has also continued to focus on de-risking solar thermal applications through the demonstration and integration of higher-temperature Solar Thermal systems and technologies.

ASTRI support for Solar Thermal uptake has focused on the following four areas:

- **Improving System Performance:** the development and demonstration of next generation, higher temperature solar thermal technologies specifically designed to increase the performance and market competitiveness of concentrated solar thermal systems (heat and/or power) through lower cost and improved efficiency;
- **Focus on End-Use Application Areas:** more active engagement with end-use application areas including power generation, process heat, remote area power systems (i.e. mining and mineral extraction activities) and production of clean hydrogen;
- **Thermal Energy Storage as an Enabler:** promoting the critical role of Thermal Energy Storage as a means to provide firm power at heat generation capacity and at any time of day or night.
- **Solar Thermal Advocacy:** the provision of support to solar thermal technology developers and energy end-users to improve awareness, investment and uptake of solar thermal technologies and systems in Australia.

Improving System Performance

Solar Thermal systems comprise integrated technologies that together convert thermal energy into dispatchable electricity or heat. These component technologies include solar collection, thermal capture, thermal energy storage and a power block (if the system is used for power generation).

In 2022, ASTRI's technology development activities were focussed on a smaller number of higher Technology Readiness Level (TRL) projects in areas of strong commercial interest. These activities were designed to increase/support commercial uptake through the delivery of more efficient, cost effect and lower-risk solar thermal system outcomes.

For ASTRI's specific technologies, the focus has been on commercial uptake of particle receiver systems, and higher temperature sodium and TES systems. The particle receiver system is now being commercialised through a joint venture arrangement. The sodium loop is being progressed in collaboration

with Vast Solar. TES systems are being examined through international collaboration.

ASTRI has also been working closely with a number of companies on renewable heat technology pathways for industrial decarbonisation. These renewable heat pathways include active consideration of solar thermal for mid temperature process heat.

The technology development focus areas included the following activities:

- higher temperature, higher efficiency receivers;
- higher temperature, more efficient thermal energy storage systems;
- improved heliostat cost and performance;
- advanced high temperature materials; and
- lower cost operations and maintenance strategies.

Over the final year of the Program, ASTRI's focus is on operating the high temp sodium loop, to establish the performance benefits of higher temperature solar thermal systems.

Delingha – Cosin Solar, Delingha

Focus on End-Use Application Areas

When established in 2012, ASTRI was primarily a researcher driven program for emerging technology development. Under this initial construct, commercial uptake was a secondary consideration. The focus was on research of Solar Thermal technologies to improve the performance of next generation systems.

However, this focus changed in response to the 2017 Mid-Term Review which recommended that ASTRI become more involved in commercial deployment. As a result, ASTRI sought to undertake more collaborative activities with industry, in direct support of commercial uptake.

These commercial support activities are closely aligned to key end-use application areas for Solar Thermal. Understanding how solar thermal can be applied across different energy end-use sectors, and the value streams that can be derived from different applications has played a key role in ASTRI's transition to a commercially oriented program.

These end-use application areas focus on deployment of conventional Solar Thermal Systems. As such, they do not readily fall into ASTRI's 'next generation' high temperature technology pathway. However, from a commercial uptake perspective, deployment of conventional Solar Thermal systems in these sectors will be an important catalyst for future market uptake of next generation technologies. Once industry understands how solar thermal operates, can see the benefits, interest and deployment of next generation systems will follow.

ASTRI's activities traditionally focused on Solar Thermal for power generation within large power networks. However, the Program has evolved to other end-use markets. This includes Solar Thermal for remote area power systems and for industrial process heat applications. The use of Solar Thermal for renewable fuel production is also being explored.

ASTRI's focus on end-use application areas is also aligned with government's strong policy and program focus on real world deployment. This includes support for multi-hour energy storage, dispatchable power generation, clean fuels production and industrial process heat applications.

Consistent with government policy, ASTRI is also involved in a range of international collaboration activities, with a focus on bilateral engagement with key strategic partners.

As ASTRI moves into its last year of operations, the approach is to focus is on technology demonstration and deployment, and the development of a strong value proposition for Solar Thermal technology solutions across the following key energy end-use markets:

- utility scale power generation;
- remote area power systems;
- industrial process heat; and
- clean hydrogen production.

Utility Scale Power Generation

Globally, there is almost 7.0GW of Concentrated Solar Power (CSP) plants operating commercially.

CSP requires good levels of direct normal irradiation (DNI) and thus is best suited to hot dry climates. Over 60 CSP plants are now operating in utility scale power generation markets. CSP is typically cost-effective at large scale, where its multi-hour storage can provide markets with firm and fully dispatchable clean power.

Most of the global deployment has been in Spain, USA, South Africa, Morocco, China, and the UAE. In China, 28 new CSP/PV hybrid systems are currently under construction. These new integrated systems utilise PV during the day, and CSP with multiple hours of storage at night. By combining PV and CSP, these integrated systems are able to provide firm power generation 24/7.

The three largest CSP plants (DEWA – UAE 700MW; Noor Midelt – Morocco) 380MW CSP Project and the proposed Likana – Chile 390MW) have a stated LCOE of $73 (USD), $70 (USD) and $40 (USD)/MWh respectively. All of These projects include multi-hours (10+) of storage. What this indicates is that large CSP Plants, with good DNI and multiple hours of storage, can deliver extremely cost effective utility scale solutions into electricity networks.

It is important to note that CSP's large scale comes at a high initial capital cost. This makes it difficult to compete with conventional utility scale power generation systems (i.e., coal and gas fired plants), especially where markets do not value long duration renewable energy generation. Accordingly, deployment of CSP typically requires policy measures and incentives that value long duration (8 to 15 hours), intra-day clean power generation that can be

ASTRI'S ROLE IN SUPPORTING SOLAR THERMAL UPTAKE

displaced on demand at any time of day or night. This will change as markets and consumers start to shun fossil-fuel powered generation assets, and the need for firmed night time renewable energy increases.

Remote Area Power Systems

Australia has a large demand for energy for remote mining operations. Australian mining operations used over 720 Peta-joules of energy in 2018, representing almost 12% of Australia's total energy end use. Over 55% of this energy was used to support oil and gas, with 45% used to support mineral extraction/ processing. The mining sector consumes over 4.5 billion litres of diesel per annum for transport and electricity production. Gas is also used in mining and Liquefied Natural Gas (LNG) production to generate heat and electricity.

Energy price volatility and upstream carbon pricing risks (Scope 3 emissions) are forcing mining companies to examine options to reduce emissions. If these risks eventuate, mining companies with lower fuel usage and emissions will have a competitive cost advantage in the international marketplace.

Mining companies are now looking at renewable technologies to address these risks. There are numerous PV + battery systems being installed but such systems are not currently cost-effective for multiple hour energy storage (i.e. 4+ hours). This will create challenges for Australia's mining companies, which require long-duration energy storage to support 24/7 mining operations. Solar Thermal can address this challenge. Solar thermal systems are a good 'utility scale' renewable energy option for mining, particularly in hot, dry areas. They can provide both electricity and heat (if required for mineral processing / beneficiation). Solar thermal systems are currently cost competitive against diesel for electricity generation (diesel generation cost is approximately $350/ MWh). They are also competitive against PV with multi-hour battery storage.

For future mining operations, solar thermal systems can also be used to provide heat and power for on-site clean hydrogen production. Low-cost on-site hydrogen production will be of increasing interest to mining entities as they transition their transport fleets to hydrogen fuel cell drive-trains. The ability of solar thermal to provide heat and power for clean hydrogen production, and other mining applications, is also of increasing interest.

Industrial Process Heat

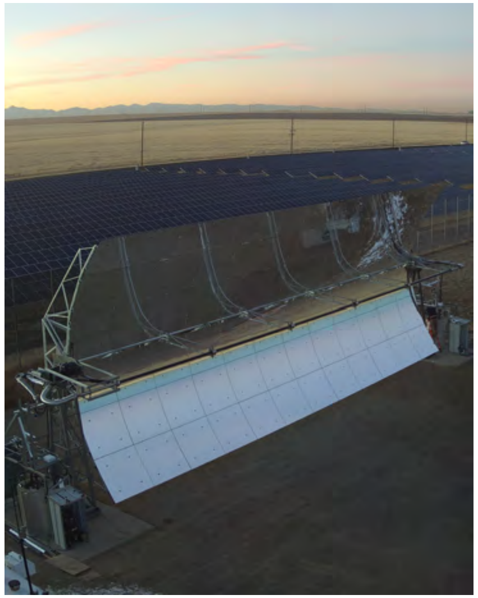
Industry is responsible for over 40% of Australia's total energy consumption. Of that, 50% involves the use of fuels for process heat. The dominant fuel is gas (46%), with coal (22%) the next largest. The actual heat used is less than the fuel consumed (more heat is produced than is utilised), with process efficiency estimated at 80% (20% of thermal energy is lost). Industrial process heat applications can be categorised by temperature, which ranges from less than 150°C to over 800°C.

At an indicative price of $20/GJ for gas, the annual cost to Australian industry for process heat supply is around $16 billion. Approximately 50%, or $8 billion/year is estimated for process heat applications in the temperature range 150°C - 500°C.

Solar thermal applications are ideally suited to process heat applications above 150°C. In the 150°C - 500°C range, Solar Thermal linked to Thermal Energy Storage (TES) systems, can provide cost effective process steam and hot air solutions. For such systems, the inclusion of higher temperature TES (up to 500°C) allows for significant displacement of gas for night-time process steam operations.

It is important to note that, while ASTRI advocates the use of Solar Thermal for process heat applications, it recognises that TES systems can be charged with renewable heat, renewable electricity, or both. To this end, ASTRI views TES systems as an adjacent market opportunity that could be used to enable Solar Thermal uptake. Ultimately, a range of factors including available on-site land and solar resources will determine the best renewable technology (solar thermal, PV, wind, bioenergy) to charge a TES system.

Solar thermal for process heat applications has a range of benefits including, lower energy costs, lower emissions, lower risk of energy price shocks and improved energy productivity. In essence, it provides companies with greater control over their energy inputs, at a lower cost with less emissions. This, in turn, can improve the competitiveness of Australian industry, which will become increasingly relevant as Scope 3 emissions become an important consideration for exports.



| Parabolic Trough – Solar Dynamics

Renewable Fuel Production

Renewable Fuel production is an emerging focus area for the replacement of carbon-based fossil fuels. Given our large amount of land, our excellent solar resources and our high quality regional export infrastructure, Australia is well positioned to become a world leader in the production of renewable fuels.

There are four main pathways for the production of renewable fuels. These include the use of renewable electricity, renewable heat (solar thermal), bioenergy or light.

ASTRI'S ROLE IN SUPPORTING SOLAR THERMAL UPTAKE

| Solid Oxide Fuel Cells – OxEon Energy

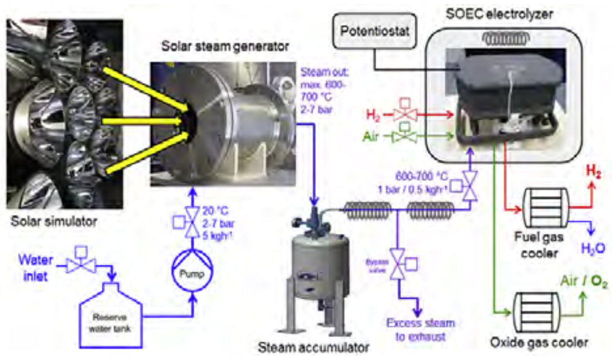
| Solar Thermal Dish at Lucas Heights Facility - CSIRO

Where Solar Thermal can dominate in the renewable fuel production market, are those pathways that require both heat and power. Green methanol is one such renewable fuel that requires both power (hydrogen production) and heat (methanol synthesis). Preliminary analysis undertaken by ASTRI suggest that Solar Thermal can produce green methanol at a 30% lower cost than any other renewable technology. Green Methanol is also a large end-use market. In addition to its use as a maritime and aviation transport fuel, it is also a key consumable for plastics manufacture.

In 2022, ASTRI worked with Vast Solar, Fichtner Engineering and DLR on a joint Australian-German HyGate Proposal. The proposal was successful and the aim is to build a CSP Green Methanol Plant, in Port Augusta, South Australia. Methanol requires hydrogen, CO_2 and heat. The CSP system will provide both power and heat. The power will be used for electrolysis based hydrogen production, with the heat used for the methanol synthesis process (320°C).

Hydrogen production is another key renewable fuel production area. The current clean energy focus is on hydrogen production using PV-supplied low-temperature (80°C) electrolysis. However, high temperature (800°C) solid oxide electrolysis (SOE), using solar thermal, can produce higher yields of renewable hydrogen with less renewable electricity. This needs to be weighed against the high upfront capital cost of Solar Thermal systems.

As Australia looks towards future hydrogen / renewable fuel export markets, consideration needs to be given as to what is the right technology mix to produce bulk renewable fuels at an internationally competitive price. The use of PV/wind with solar thermal systems might be the best technology mix to achieve this high-yield / low-cost outcome. The solar thermal system would provide the heat for high temperature electrolysis, with the electricity provided by PV/wind. If thermal energy storage is added to the solar thermal system, electricity and heat could also be provided at night, which would significantly increase the hydrogen production capacity factor.



| High Temperature Solid Oxide Electrolysis solar – DLR

The Importance of Thermal Energy Storage

Solar Thermal's main value proposition is its multi-hour energy storage. The ability to store thermal energy, which can then be dispatched on demand (as power or heat) has significant value.

ASTRI views TES as a key enabler for its targeted end-use application areas (remote power systems, grid connected systems, industrial process heat and renewable fuels production). ASTRI's focus on TES systems is consistent with the Federal Government's interest in mechanisms to encourage investment in multi-hour, intra-day renewable energy storage. The aim being to promote early investment in long duration energy storage as an enabler for peak and night-time renewable energy use and to firm increasing levels of variable renewable energy generation. CSIRO has also commenced work on a Renewable Energy Storage Road Map, expected for completion in early 2023.

While there is wide range of short-term (up to 4 hours) renewable energy storage solutions, the choice for longer-duration (4+ hours) renewable energy storage is somewhat more limited. At present, pumped hydro, clean hydrogen and thermal energy are the best available technologies for long-duration renewable energy storage.

| Molten Solar Storage – Cosine Solar

While the future mix of these storage technologies is yet to be determined, it is expected that all three technologies will be required, with deployment based on a range of geographic, resource availability, technical, commercial and policy factors.

Over 85% of Australia's current energy use involves a thermal combustion process. Most thermal energy is currently generated through the combustion of fossil fuels. That includes power generation (coal & gas), industrial process heat applications, and transport (combustion engines). However, the use of fossil fuels is unsustainable and there have been significant efforts to reduce the emission intensity of thermal energy applications through the use of renewable heat technologies. This has resulted in the increased use of renewable thermal energy storage (TES) systems as a means to lower emissions, improve operational efficiencies and reduce energy costs.

High temperature renewable TES systems have been of commercial interest for over 20 years. Renewable technologies, including Solar Thermal, PV, wind, geothermal and bioenergy are all being used for high temperature renewable TES. The primary application for these TES systems is power generation – allowing renewable energy to be stored and then used at a later time, for firm, fully dispatchable power generation.

These TES systems are typically based on the use of steam power generation technologies at temperatures between 400°C to 600°C. Recently, there has been strong interest in higher temperature TES as an enabler for advanced power generation systems (supercritical CO_2). These advanced power cycles, operating at temperatures over 700°C, have the potential to enable more efficient, reliable and cost-effective power generation. They can also be used efficiently for smaller power generation units (5MW-10MW), which would be ideally suited to remote location applications in Australia (mining, remote communities and fringe of grid).

Over the past 10-years there has been increased commercial interest in the use of high temperature (>300°C) renewable TES for industrial process heat applications. These applications can use different forms of renewable energy (wind, PV, solar thermal, geothermal, bioenergy) to create thermal energy, which is then stored and used, as required, to offset the use of fossil fuels. The use of renewable TES is viewed by industry / commercial users as a key enabler for more sustainable operations and to mitigate the impact of rising energy costs.

High temperature renewable TES has also been identified as a potential enabler for low cost renewable fuel production. Solid Oxide Electrolysis (SOE) is a high temperature process that has potential to produce larger volumes of clean hydrogen at costs significantly lower than that of current electrolysis technologies. Other clean hydrogen technologies that will benefit from TES include green methanol production and photocatalysis.

Crescent Dunes – NREL

Solar Thermal Advocacy

One of the largest barriers to Solar Thermal uptake in Australia is that there are no domestically deployed systems. While there is 7GW of Solar Thermal CSP being dispatched on a daily basis around the world, the lack of a large Australian operational system is a barrier. Creating awareness and understanding of these operational systems, and the benefits they bring to the Australian energy landscape, is a critical role.

With its international relationships and close industry engagement, ASTRI is in a position to play a strong Solar Thermal advocacy role. Key to undertaking this role is establishing the solar thermal value proposition with key Australian end-use markets. To this end, ASTRI has commissioned a detailed techno-economic analysis of the Australian CSP value proposition in key end-use markets. This information will be used to inform market participants. It will also be used to support evaluations such as the Integrated System Plan (AEMO and CSIRO's GenCost).

Other advocacy activities include: the provision of advice for federal and state energy system planning documents (e.g. Low Emission Technology Roadmap), preparation of case studies (based on international deployments) and installing and maintaining a network of DNI sensors to provide access to the resource data needed for investment.

ASTRI will also work with solar thermal companies to develop a communication strategy to increase stakeholder awareness and understanding of the value that Solar Thermal can provide within the Australian energy market. This would include the use of Solar Thermal for energy storage, power generation and/or process heat

ASTRI'S ROLE IN SUPPORTING SOLAR THERMAL UPTAKE

utility scale power generation

remote area power systems

industrial process heat

renewable fuel production

Australian CST Value Proposition – Technoeconomic Analysis

ASTRI has funded an independent technoeconomic analysis of the Australian CSP value within the following key markets:

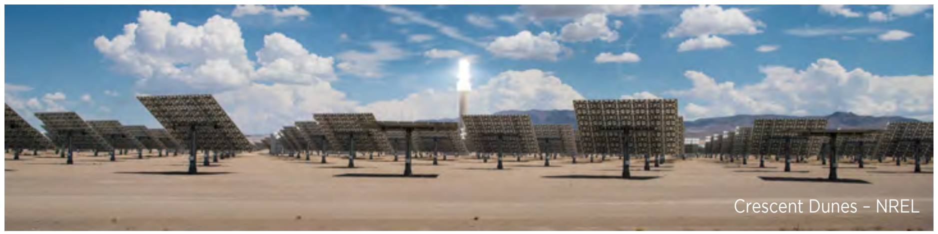
- utility scale power generation;
- remote area power systems;
- industrial process heat; and
- renewable fuel production.

The techno-economic analysis is a critical enabler for solar thermal uptake. End-users need to fully understand the cost and value streams of different solar thermal applications. The analysis will provide this information and allow ASTRI to better target key stakeholders and decision makers. It will also allow ASTRI to prioritise its activities at those areas that offer the greatest commercial uptake potential and value to Australian energy users. The specific outputs include:

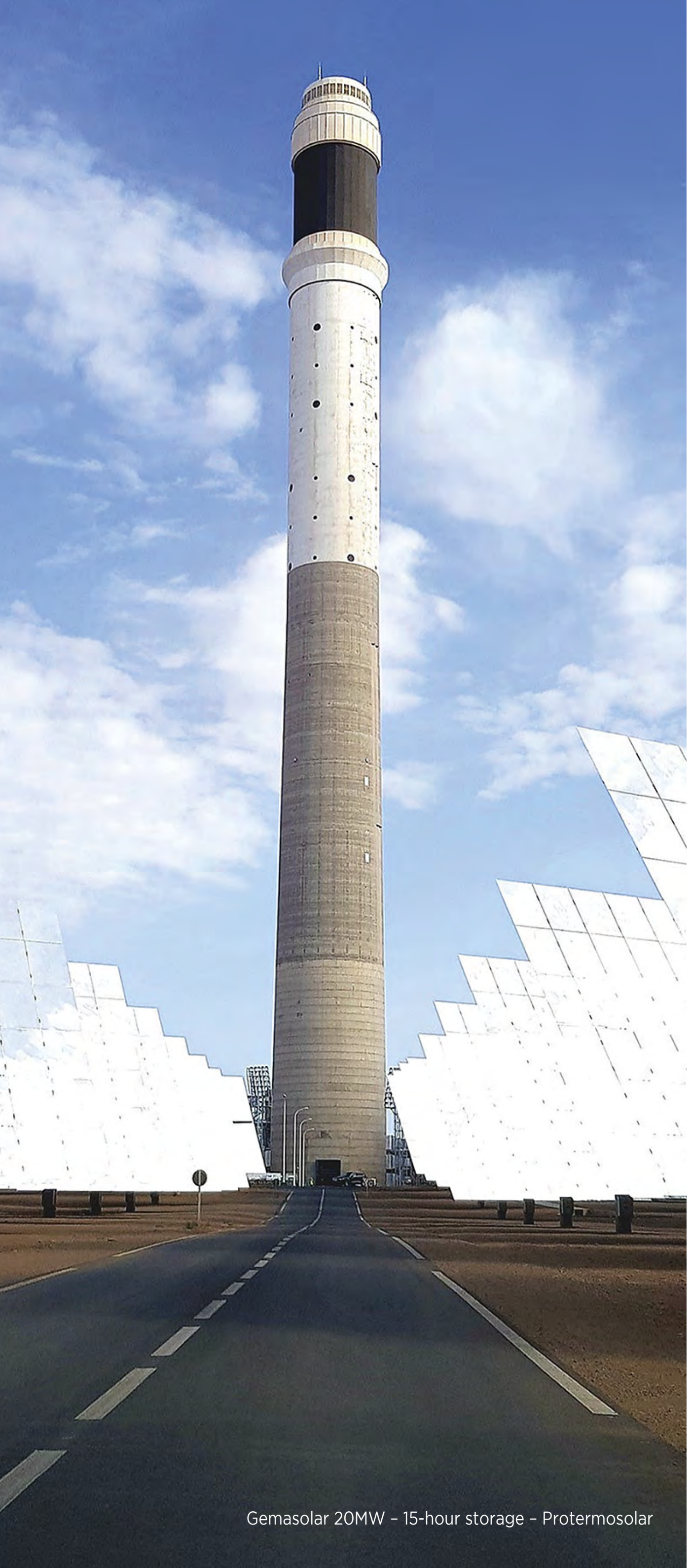
- defining the role and value of CST within key Australian energy use sectors
- examining key CST system outputs (i.e. power and/or heat) as:
  - a stand-alone system;
  - part of hybrid renewable solution (i.e. solar thermal integrated with other renewable technologies); or
  - part of a reduced emission solutions (i.e. solar thermal integrated with fossil fuel technologies).
- examining the role and value of TES as an integral component of CST systems and applications.
- comparing CST against competing low emission technologies in key CST markets and end-use applications

The techno-economic analysis will enable ASTRI to:

- better inform stakeholders about the role and value of CST technologies and systems in different energy use sectors and end use applications;
- provide information to Australian CST technology developers on what is required to be cost competitive in key energy end-use markets;
- inform the Australian Energy Market Operator (AEMO) about the role that CST, for power generation, can play in Australia's future electricity markets;
- inform ARENA about the role that CST, for industrial process heat, can play in decarbonising Australian industry;
- inform mining sector stakeholders about the role that CST, for power and/or mineral processing, can play in reducing mining sector emissions;
- inform key decision makers on the role that CST, for power and heat, can play in the production of clean fuels;
- prepare stakeholder engagement strategies in key end use markets (i.e. utility power, remote area, process heat, clean hydrogen); and
- refine its ongoing technology development and commercial deployment activities.



Crescent Dunes – NREL



Gemasolar 20MW – 15-hour storage – Protermosolar

TECHNOLOGY ACTIVITIES

ASTRI's technology activities focus on technology development and technology support. For technology development, ASTRI's activities are designed to improve commercial viability of solar thermal systems through enhanced performance, reliability and cost outcomes. For technology support, ASTRI's activities focus on cost, risk and performance improvements for industry-developed systems and technologies.

Over the course of 2022, ASTRI consolidated its technology activities to six key projects. These included three technology development projects and three technology support projects. The six projects are as follows:

- Technology Development
  - Particle Receiver
  - Thermal Energy Storage (TES)
  - High Temperature Sodium Loop
- Technology Support
  - Heliostats
  - Advanced Materials
  - O+M Technologies

Technology Development Project Activities

ASTRI's technology development activities have been designed to help ensure ASTRI meets it key objective of improving the commercial viability of solar thermal systems through improved performance, reliability, and cost outcomes. The key focus areas are high temperature receivers and supporting TES systems. A summary of ASTRI's technology development projects, covering 2022 activities, are provided in the following section.

Technology Support Project Activities

ASTRI's technology support activities are designed to assist industry in improving the performance and lowering the cost and deployment risk associated with their specific system and component technologies. The key focus areas are heliostats, advanced materials, and O&M. A summary of these support projects, covering 2022 activities, are provided in the following section.

Jemalong – Vast Solar

Thermal Energy Storage – Graphite Energy

ASTRI Technology Development Activities

Delingha- Cosin Solar

Particle Receiver

Commercial tower based CSP systems currently use liquid-based receivers which can only operate at temperatures up to 565°C. To increase market competitiveness of solar thermal systems and to improve performance, higher temperature receiver technology solutions are required: particles offer this. Particles also offer a storage medium, in that the irradiated particles also become the storage medium.

This project has developed a multi-stage falling particle receiver. Small particles are released (dropped) in a controlled manner through the use of a series of staged capture points. As the particles fall, they are irradiated by the sun where they are rapidly heated. The heated particles are capture below the receiver where they are stored.

The ASTRI particle receiver is designed for operation at high temperature (>800°C) and high efficiency (~90%), and has been tested on-site at CSIRO Newcastle. Under this project ASTRI has developed a system to store these particles at higher temperatures and test the system on-sun.

The advantages and disadvantages of particle receivers (including ASTRI's particle receiver technology) will be examined as part of the USA's $72 million (USD) Gen3 program. The Particle Receiver Project has demonstrated the on-sun operation of a multi-stage falling particle receiver and integrated sub-components. The project will also provide performance analysis of material degradation.

Key Achievements

Receiver

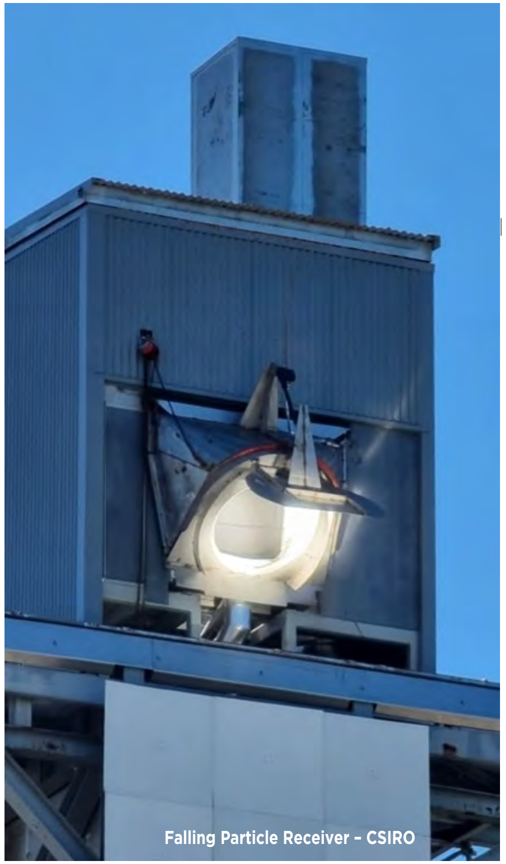
- On-sun test of multi-stage falling particle receiver has been successfully carried out at various temperature and solar input conditions along with a close monitoring of equipment behaviour, regular inspections of receiver material, and particle sampling as the test progresses.
- Combination of various test modes have been demonstrated based on the condition of system and operating strategy. Test modes included receiver-only operation with continuous particle circulation, receiver operation with two bins for thermal storage, and hot to cold bin particle transfer through (or bypassing) particle heat exchanger.
- To date, 100hrs of test operation data has been accrued with demonstration to 700°C of the receiver outlet temperature. Temperatures above 800°C are proposed (is dependent on the heliostat field at Newcastle).

Heat Exchanger

- 500kWt particle-water heat exchanger embedding the newly developed design concept has been integrated to the receiver test system, completing the cooling water connection and thermal insulation.
- The particle heat exchanger has been successfully commissioned and tested at various operating temperatures proving its functionality as designed.

Modelling

- Receiver performance model has been completed and was used for analysing and reviewing the test data. The predicted and measured performance showed a good agreement within the range of combined errors related to optical performance of solar field.
- Particle attrition modelling has been completed, providing an estimation of annual reduction of particle diameter caused by attrition while falling in the multi-stage particle receiver.



Falling Particle Receiver - CSIRO

Technology Development Activities: Particle Receiver

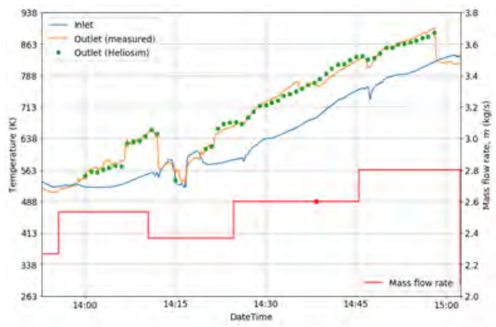
Key Challenges

Since the particle receiver system is the first of its kind in CSP technology and also new to the research team, a number of minor engineering and operating challenges were encountered and had to be resolved while installing, commissioning and testing the system. The issues include:

- particle clogging due to water infiltration and humidity. (Resolved).
- particle leak though unknown gaps. (Resolved).
- thermal damage of insulation material inside the receiver cavity. Regular replacing done as the issue is related to the solar field with unusual geometry.
- contamination of insulation surface inside the receiver cavity causing reduced internal reflection / regular replacing done as the issue is related to the solar field with unusual geometry.
- contamination of particles by debris (from both fabrication and operation) / screened and removed.
- thermal expansion of screw conveyor creating unexpected physical impacts to other components / resolved, proven to be caused by a mistake during the installation not according to the design.

Key Learnings

- The multi-stage falling receiver concept has been successfully proven to work as intended. This includes providing a stable and high-opacity falling particle curtain, provide effective protection of the receiver wall and maintaining high durability for the catch-and-release trough material.
- Direct absorption of solar energy by particle curtain demonstrated immediate temperature response to solar flux change.
- Thermal expansion of the components and chutes was able to be properly accommodated by using slip joints as designed. This is one of the key benefits of using particles as the heat transfer fluid.
- Flow rate measurement by using feed bin weight is inherently slow and intermittence. Development and use of an in-line flow measurement is strongly recommended.
- Receiver performance study and the test result revealed that the advective heat loss is higher than the convection heat loss from typical cavity receivers. This is as expected and is in accordance with US research group's study. Further study and design modification will be worth trying to minimise the advective heat loss.
- Additional learnings related to the challenges addressed above are:
  - Sound water proofing of the system is crucial.
  - Installation of heater or air injection port is recommended in the area where particle clogging is potentially likely (such as narrow valve area).
  - In the design of a receiver cavity, extra attention needs to be taken to minimise exposure of any material (expect for particles) to solar energy.
  - Installation of a device to screen out any debris (of which the size is bigger than the smallest gap for particle flow such as the constriction zone of particle heat exchanger) is important.



example of test data shown with estimated receiver outlet temperature from Heliosim performance simulation.

Opportunities

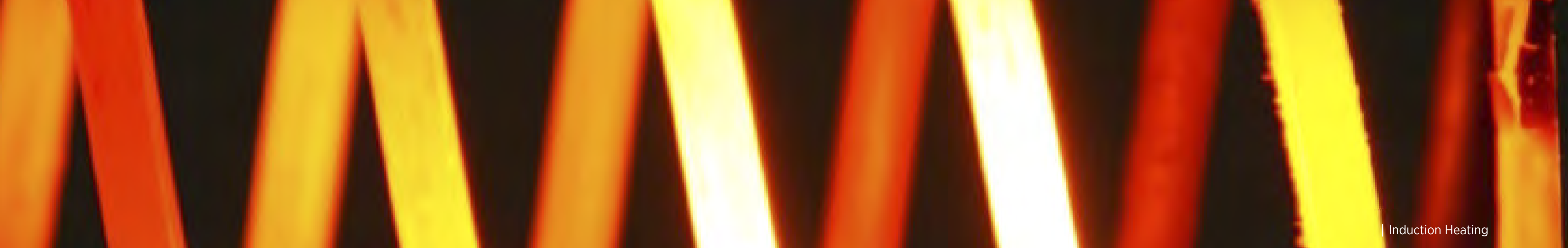
Particle receiver technology was invited to provide a funded bid for a Heavy Industry Low-carbon Transition Cooperative Research Centre (HILT CRC) stage 2 project proposals (for energy saving in iron ore processing). This bid is still under consideration.

Commercialisation Pathways

Activities for commercialisation of particle technology has actively progressed. Activities include preparing for the establishing a new particle technology-based CSP/CST company (tentatively named as Solstice Energy) managed by RFC Ambrian Ltd, and CSIRO.

Preliminary planning has commenced for an R&D project aiming at demonstrating a 50MWt pre-commercial system and there have been technical meetings with various potential customers.

Newcastle High Temperature Particle Receiver - CSIRO



Induction Heating

Thermal Energy Storage (TES) Integration and Evaluation

Thermal Energy Storage (TES) can significantly increase the capacity of high temperature solar thermal systems. TES can also be a key enabler of cost competitive renewable energy solutions for electricity generation or process heat at industrial and mining sites. The primary aim of this project is to facilitate the commercial uptake of TES systems in Australia.

The project includes a pathway to improve the Technology Readiness Level (TRL) of candidate TES solutions and perform a techno-economic assessment of prospective TES systems for next-generation CSP systems using liquid sodium as the receiver heat transfer fluid.

In addition to solar thermal systems, there are strong adjacent market opportunities for TES to store renewable heat. The project actively engages businesses to support the decarbonisation of their industrial processes and to promote interest in the potential commercial uptake of TES systems.

Key Achievements

- Sodium-compatible TES technologies for CSP systems
  - Demonstrated charging and dis-charging processes of the Graphite Energy storage up to 640°C using liquid sodium as the heat transfer fluid on the lab-scale sodium loop at ANU.
  - Performed a preliminary techno-economic analysis of modular sodium-based CSP tower systems based on a cluster of 10 MWth towers and solid media TES configurations. The analysis identified significant performance, cost, and operational benefits of a modular tower system.
  - Undertook an investigation of charging/discharging performance and estimated potential cost of electric-charged TES (eTES) options from alternative renewable sources of electricity (versus the cost of grid-connect electricity).
  - The analysis indicated that eTES systems, using lower cost variable renewable energy inputs, were cost competitive with grid-connected electricity, and are likely to be significantly cheaper in the future with high expected night time prices.
- Renewable heat industrial decarbonisation via TES integration (end-use focussed, 150°C to 600°C applications).
  - Prepared an overview of the TES integration opportunity in Australian energy systems and industrial processes, targeting mid to high temperature applications above 150°C.
  - Currently engaging >10 businesses to assist/provide input in industrial decarbonisation through renewable heat and facilitate the potential commercial uptake of TES solutions.
  - Completed a preliminary energy balance for a meat processing plant at Wodonga. An initial renewable heat option analysis (with TES integration) for the abattoir was performed with the aim of decarbonising steam used for the rendering process.

Key Challenges

While the industry waits to gain a better understanding of high temperature solar thermal systems, there is growing interest in the corresponding high temperature TES systems. To convert it to commercial reality, the project faces challenges in developing/sourcing low-cost TES technologies compatible with sodium above 700°C to meet the cost target of < $20/kWhth. Currently, the potential cost of commercial high-temperature TES options is estimated to exceed the target, whereas alternative low-cost solutions are still at the early TRL stage.

Two-Tank Molten Solar Storage - Protermosolar

Technology Development Activities: TES Integration and Evaluation

Key Learnings

- A stable experimental setup with improved heaters has been established, which allows a continuous charging operation of the TES using sodium at elevated temperatures above 700°C. This enables us to test sodium-compatible TES solutions in the future.
- Pursuing an advanced sCO_2 power cycle with turbine inlet temperatures above 700°C can increase the capital cost of TES based on the existing technology. The project has been able to explore different configurations, which could offer an effective solution for balancing between cost, energy density and optimal energy utilisation at a suitable temperature range.

Commercialisation pathways

- The commercialisation strategy aims to work with energy-end users that require a thermal energy solution (for power and/or process heat) and to create awareness and interest in the use of renewable-based TES systems.
- Successful demonstration is vital, and the project plan includes a pathway from lab-scale prototype testing and then integration at CSIRO at pilot scale.

The project team has established collaboration/commercialisation arrangements with a number of industrial process heat users, including Mars, Kimberly Clark, and Coca-Cola. Six more arrangements are proposed to be established by mid 2023.

Solana - Molten Salt Thermal Storage System - US DoE

Graphite Energy TES Unit at Mars Petcare Wodonga - Graphite Energy

MGA Thermal TES Pilot Demonstration Unit - MGA Thermal

Vast Solar Jemalong – Vast Solar

Sodium Receiver

This project aims to develop and build infrastructure for the scale-up and demonstration of sodium receivers for solar thermal applications to be installed at the solar thermal test facility at CSIRO Energy Centre Newcastle. This facility will utilise ASTRI technologies based around high temperature sodium-based solar receivers and systems and will develop and demonstrate a high temperature sodium-based test loop.

The project specifically targets components that have been developed over the past five years from the ASTRI program that fit within the ASTRI CSP proposed plant design and operating philosophy. It gives priority to operating individual components at their design point through operation of the entire system in an optimised manner. There is a strong focus on learning, de-risking, and applying best practices for designing, constructing, maintaining, and operating a high temperature sodium test loop at up to 740˚C for solar thermal application.

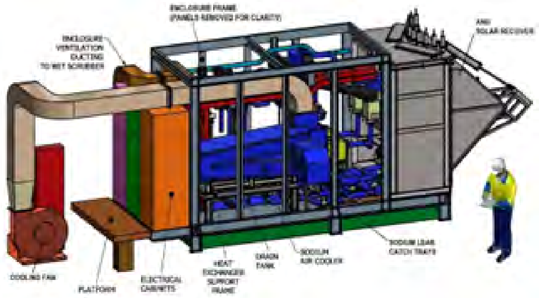
It is expected that this project can be used to integrate other key components of CSP into the sodium loop, such as alternative receiver designs, heat exchangers, thermal storage, and energy transfer to power cycles like the supercritical CO2 Brayton cycle.

The project involves the construction of a high temperature experimental test loop for circulating sodium as the heat transfer fluid in the solar thermal application. The test loop has a rated maximum receiver outlet temperature of 740˚C but, realistically, will be used to test performance and safety management systems to 650˚C. This lower temperature is applicable to current industrial demand for high temperature solar thermal systems.

Key Achievements

During 2022, the project focussed on executing packages of work for successful completion of the process design, and plant design for the sodium test loop and safety management systems. Vast Solar was engaged to convert the preliminary design by CSIRO into a fully designed and engineered system. Specific achievements include:

- At the conclusion of stage 1, engineering design awarded to Vast Solar in 2021, extended the existing contract with Vast Solar to undertake the stage 2 construction phase during 2022 including commissioning at Vast Solar's Jemalong site scheduled for early 2023.
- Awarded an extension to the design contract for stage 2, with a CSIRO Project Agreement with Vast Solar, as the project partner. Having Vast Solar join CSIRO through ASTRI on this project is a great achievement.
- Completed two Hazard and Operability (HAZOP) studies on the process design, at 30% and 100% design complete.
- Took delivery of additional remaining long-lead equipment, the sodium to air cooling heat exchanger designed by Uniquip Pty Ltd, and fabricated by MCM Manufacturing Pty Ltd. Took delivery of the Sodium Solar Receiver from the ANU, fabricated by Performance Engineering Group Pty Ltd.
- Project budget and delivery schedule adjusted to accommodate the higher cost realised as a result of completing the engineering, and further de-risking the system. Market conditions in the construction industry post Covid19 have driven up costs of materials and labour.



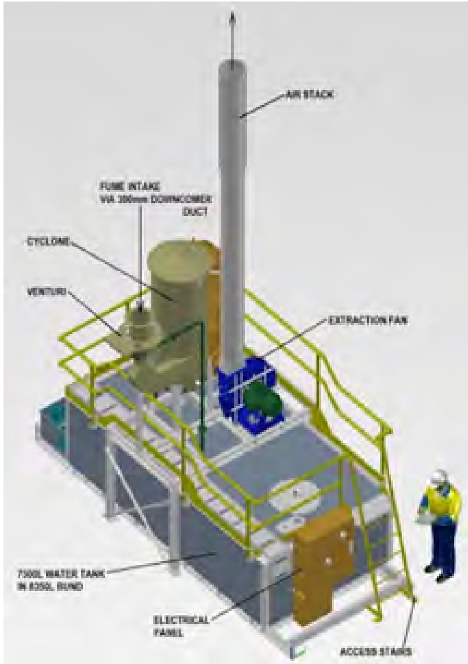
Final Design of the Sodium Test Loop Module - CSIRO

Sodium Test Loop Module under construction, Dec 2022 - CSIRO

Technology Development Activities: Sodium Receiver

Key Challenges and Learnings

- The resultant design produced a system that performs two key functions. Firstly, it provides a high temperature circulating sodium loop as a test bed for a range of CST technologies and applications. Secondly, it provides a system designed to detect a sodium leak using temperature, smoke, and inventory control. With safety being the highest priority the system is designed to be intrinsically safe.
- In the event of a sodium leak, the system shuts down the sodium flow and returns the sodium to a central storage vessel. This system prevents a further sodium leak by intentionally letting the small amount of leaked sodium combust, with a scrubber operating to extract and neutralise the sodium oxide smoke.
- Dangerous material handling up to 250kg of Sodium is under safety review by CSIRO management.
- This placed a larger requirement on the fire management and safety system. To address this, the system is designed with the likelihood that a leak will occur with a resulting fire. The system has an automatic detection, management, and system shut-down to extinguish the fire and be intrinsically safe. The need to have two systems has increased the cost and the challenge is to manage these costs.
- Developing this system has been a challenge because two independent systems (linked to function in parallel with each other) will be tested together. The sodium loop can operate if the safety management system says so. The fire management system operates independently on the sodium test loop.



Final Engineering Design: Fume Scrubber System - CSIRO

Key Opportunities and Commercialisation Pathways

ASTRI believes that liquid sodium, as a heat transfer fluid with outstanding thermal properties, offers a cost-effective solution for current and future CSP systems and would allow operation at higher temperatures than present.

This is why ASTRI is developing this infrastructure that will progress to full-scale testing and integration with other CSP technologies. ASTRI will start commissioning this system in April 2023.

Completed Fume Scrubber System by Fowlerex - CSIRO

ASTRI now has a strong collaboration with Vast Solar as a project partner. Vast Solar have gained directly from this opportunity. They have increased their knowledge in high temperature and fire safety systems for sodium. Since shutting down their Jemalong demonstration field, the Vast Solar team have been working on new projects but the ASTRI sodium project has provided their team with the opportunity to further develop their skills in designing and building next generation CSP plants. The knowledge and IP generated from the ASTRI project will be utilised in future CSP projects.

Recently, CTP Advanced Composites from the USA have been exploring the possibility of testing a ceramic tube based solar receiver on a sodium test loop. The CSIRO facility is currently the company's preferred choice. Currently CSIRO is working with CTP in utilising CSIRO's propriety software package, Heliosim, to help advance CTP's current design.

ASTRI Technology Support Activities

Crescent Dunes - NREL

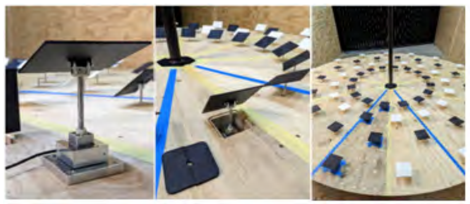
Heliostats

Heliostats are a key component of high temperature solar thermal systems, as they allow capture and concentration of sunlight for the production of heat. The solar thermal industry needs low-cost and high-performance heliostats, so ASTRI is working on key technologies and research to enable lighter, smarter and more bankable heliostats to be developed and commercialised. While ASTRI's work is targeted towards smaller heliostats, the results will provide outcomes that can be used in CSP plants with both small and large heliostats.

In parallel with developing technologies for cost reduction, team members are working with industry (directly, and through SolarPACES and HelioCon activities) on measuring and improving performance, to ensure predictable and controllable performance of heliostat fields. This will ensure yield is as expected and that receivers are not damaged during operation. Direct engagement with Australian heliostat developers is a key goal of this project.

Key Achievements

- Developed extensive and detailed Technoeconomic Analysis (TEA) tools for evaluating LCOE impact of novel concepts and sensitivity of heliostat performance parameters
- Publication of open state-of-the-art characterisation data for wind loads:
  - Dynamic load analysis for heliostats of different aspect ratios;
  - Dynamic wind loads on operating and stowed heliostats in tandem configurations; and
  - Impact of mesh structures (wind-fences) and edge-devices on turbulence field approaching and trailing heliostats
- Construction and commissioning of Atmospheric Boundary Layer measurement facility at University of Adelaide. This facility characterises the incoming atmospheric boundary layer conditions, and sense loads using instrumented full-scale heliostat comprising a differential pressure sensor array and an integrated 6-axis load cell, for comparison with wind tunnel results.
- Scale-up and demonstration of a novel concept for a lightweight single-component focussing facet on an operating heliostat. This concept is now subject of a Patent Application and has attracted commercial interest
- Network demonstration of an energy storage system for heliostat power and field wiring cost reduction
- Undertaken extensive external engagement, particularly through Raygen and Vast Solar's heliostat program, SolarPACES Task III working group, and the US DoE Heliostat Consortium "HelioCon", through which ASTRI is enabling overseas entities to adopt ASTRI-generated knowledge and heliostat innovations.



University of Adelaide indoor wind load testing - UOA

Key Challenges

At the start of 2022, ASTRI's Institute Steering Committee (ISC) and Technical Advisory Committee (TAC) recommended that effort be focussed on TEA tools to ensure that the business case for all technologies being developed remained strong. This required significant change to expected schedules and skill sets, with a stronger focus on simulation capabilities. The focus on these new activities slowed progression of Technology Readiness Levels (TRL) of the technologies. Despite a lower effort contribution, all technologies were progressed to demonstration (TRL 6) or above.

University of Adelaide outdoor wind load testing - UOA

Technology Support Activities: Heliostats


Crescent Dunes - NREL

Key Opportunities

In 2022 ASTRI joined the US Department of Energy Heliostat Consortium "HelioCon". HelioCon will see the National Renewable Energy Laboratory (NREL), Sandia National Laboratories, and ASTRI work closely with CSP developers, component suppliers, utilities, and international experts to pursue heliostat cost reductions and improvements to heliostat component performance.

ASTRI Heliostats has contributed to the development of world-class simulation tools for TEA of heliostat systems. These tools have been used to contribute directly to the HelioCon Road-mapping Report, which will guide DOE and ASTRI research into 2023. ASTRI's Heliostat Project is well placed to operate alongside Heliocon in 2023.

TEA tools developed in 2022 have reinforced the requirement for high performance heliostats for CSP facilities. ASTRI will be able to focus on these technologies in 2023. Conversely, other TEA results have shown marginal value for some heliostat technologies. Effort on these technologies can now be reduced and the knowledge disseminated through publication.

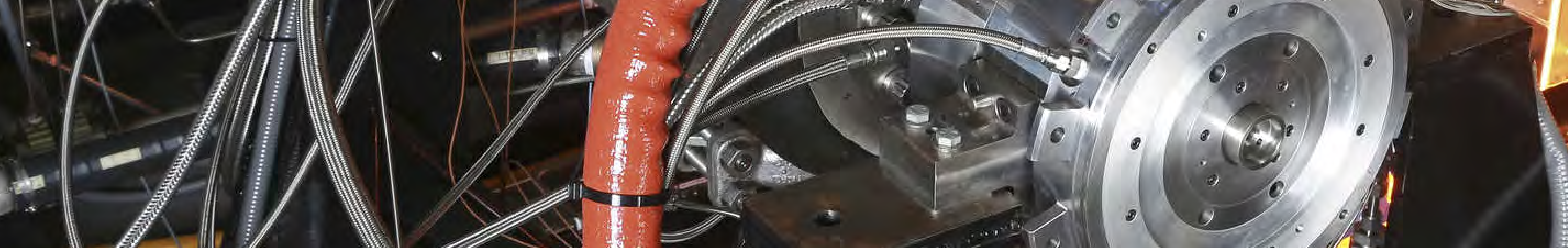
University of Adelaide, through ASTRI, is now positioned as a global leader on heliostat wind loads. Disseminating information about wind-loads will have broad-reaching impact across the global CSP community, including ASTRI's contribution to a wind-load guideline/standard. This should reduce costs and decrease risk to CSP projects.

Commercialisation Pathways

From a domestic perspective, ASTRI's challenge lies in the current low level of activity in Australia's solar thermal industry. The team is working hard to develop meaningful collaboration with Australian heliostat designers and prospective projects to explore opportunities to get ASTRI heliostat technologies into Australian heliostat projects.

Internationally, ASTRI is working to create a sufficient value proposition to generate commercial interest, while minimising barriers to integrating ASTRI technologies into commercial heliostat systems (important as most international heliostat technology developers and manufacturers have their own complete commercial heliostat products).


Delingha- Cosin Solar



Advanced Materials

The 30-year design life of a solar thermal system (CSP and CST) requires full understanding of material compatibility and associated characterisation of material degradation. This allows for more informed/adequate design decisions, material selection and cost estimates. Across the energy industry, project delays, cost overruns, shortened asset life and injury have been attributed to poor material selection.

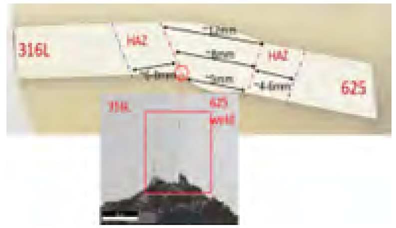
The materials program is providing specific answers to many material issues and closely associated research gaps for ASTRI's solar thermal technologies. Examples include providing engineering material degradation test data to identify corrosion, cycle fatigue, and other material issues for specific alloy and thermal energy storage media, for specific alloy and sCO2 and for alloy and sodium compatibility.

This project has already had a direct impact on the materials choices being made with ASTRI and for CSP industry partners and will continue to de-risk materials and the design choices leading to the full development and demonstration of an operational CSP system within Australia. The project team's approach involves several parallel activities including:

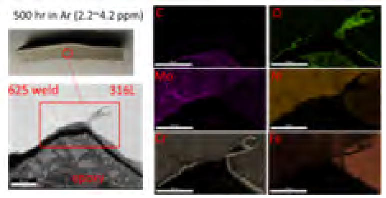
- international collaboration to tap into existing knowledge;
- design of components to include sample specimens and tubes for destructive exposure testing;
- static testing of samples under laboratory conditions;
- a dedicated sodium exposure test program; and
- degradation of priority alloys after exposure to enable a cost-benefit analysis of long-life expensive materials.

Key Achievements

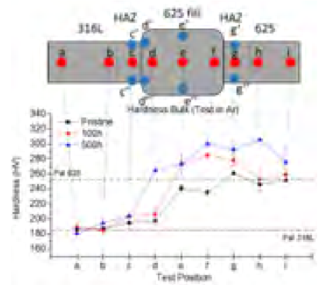
- Initial evaluation showed that the potential for liquid sodium to cause Liquid Metal Embrittlement on ASTRI alloys is not a high risk.
- Qualified the methodology to determine high temperature transient creep and mechanical strength test capability, which is unique in Australia and one of few in the world. It will allow evaluation of novel alloys under ASTRI conditions.
- Developed a protocol for obtaining low oxygen containing liquid sodium.
- Developed and implemented new test protocols for long term liquid:
  - Understanding of the mechanism of corrosion of stainless steel and Inconel in liquid sodium established.
  - Corrosion rates at low exposure times for ASTRI alloys in low oxygen containing liquid sodium are relatively low, but awaiting longer term exposure results.
  - Welded sections appear to have similar sodium corrosion rates as their parent metal.
  - Exposure of CTP graphite samples show minimal degradation.
- Built significant engagement with VAST Solar and Graphite Energy to identify and provide initial experimental results to de-risk their CSP work:
  - Measured friction coefficients for thermal energy storage tanks that was thought to be critical to prevent large (catastrophic) tank failures.
  - Developed & implemented research program to characterise carburisation potential of alloys used in CSP thermal storage for Graphite Energy.



Inconel 625 & 316L weld exposed at 750°C/500 hr - QUT



Analysis of 625 fill-316L weld boundary - QUT



Hardness profile: 316L to 625 across weld - QUT

Technology Support Activities: Advanced Materials

Key Challenges

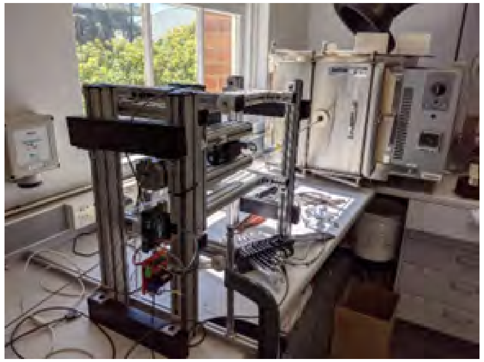
- Rapid development of new testing capabilities in Sodium and consideration of a new mechanical strength testing program.
- Meeting the needs and expectations of key industry partners advancing CST in Australia which have required the development of new test methodologies.

Key Opportunities

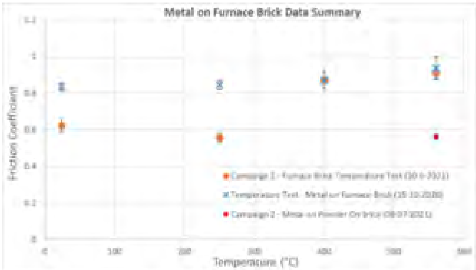
- The Materials group has established an international reputation in the properties of alloys at extreme temperatures and under harsh environments in CSP/CST. This achievement continues to position ASTRI as an expert advisor on CSP/CST system materials for domestic and international companies and organisations such as Vast, Gen3, NREL, DOE, Graphite Energy and John Cockerill. Some of this industry interaction has commenced.
- The next phase of the program will provide a knowledge bank on materials issues which go beyond "normal" engineering expectations. This will allow successful (proactive) operations and maintenance in CSP plants into the future.

Commercialisation Pathways

The commercialisation pathway for the Advanced Materials project is to provide exceptional and ongoing support to industry to de-risk system uptake from a technical, operational & cost perspective.

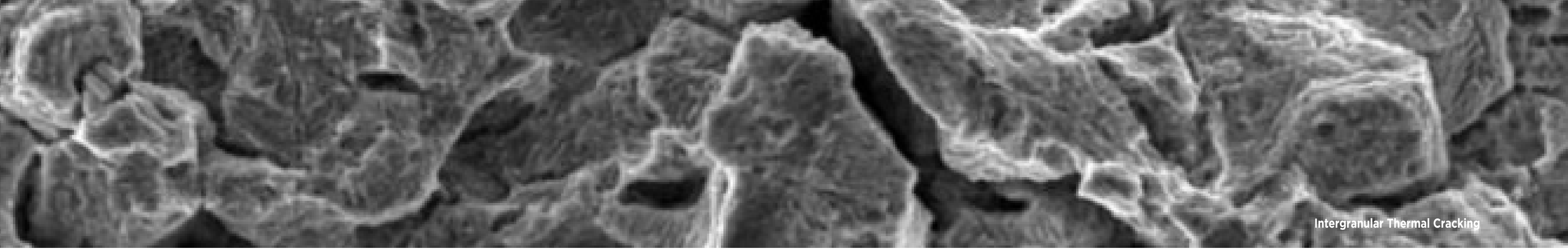


Experimental apparatus to determine friction coefficient between thermal energy storage tank material bottom and substrate tank foundation - QUT



Example of friction coefficient data for metal plate friction on furnace brick - QUT

Noor Ouarzazate – MASEN



Operations and Maintenance

The cost of Operations and Maintenance (O&M) for solar thermal, which includes the cleaning of heliostats, optimising staffing levels, and managing the failure risks of key equipment, are not well documented and not well understood. This is a critical factor in the de-risking of investment in CSP and CST. Furthermore, several unique aspects of solar thermal systems create significant uncertainty for O&M costs of future plants. Yet, despite their critical importance, optimal O&M strategies for the solar thermal equipment are poorly understood.

Project finance is usually contingent upon performance reliability, making O&M an even higher priority for operators of solar thermal systems. This is especially true in Australia given our unique grid requirements, potential remote locations, and high labour costs. This project seeks to develop engineering solutions to both predict and minimise O&M costs, helping to “de-risk” investments in solar thermal systems.

Key Achievements

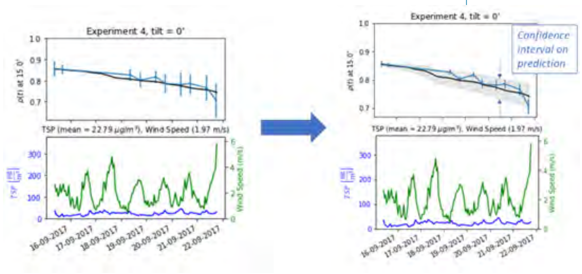
The project team has made progress in several areas, strengthening international collaborations with both industry and research institutions (Vast Solar, Mars Petcare, ACWA Power, NREL, Sandia, Politecnico di Milano). A key new collaboration was the leadership of the Heliostat Consortium Soiling Subtask. This activity includes leading the writing of the Soiling section of the Roadmap report and the planning of future activities based on feedback from industry and research institutions. This has deepened our collaboration with NREL researchers and their industry partners and led to the O&M team conducting a soiling study with a CSP operator together with NREL in late 2022.

Significant progress was also made in ongoing research thrusts for CSP O&M. Because of the large risks associated with uncertainties in degradation, the team had a significant focus on understanding the impact of uncertainties in 2022. Uncertainty assessment was developed for the soiling model and a Python library for CSP soiling analysis was released publicly via GitHub

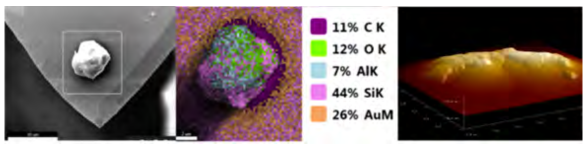
The dispatch optimisation methodology was refined and extended to include uncertainty in the optimisation. The receiver creep-fatigue lifetime predictions have been refined and methods to assess the creep lifetime uncertainty have been developed. The team also developed new nano-roughened anti-soiling coatings and tested them at an outback CSP site.

The detailed 2022 achievements were:

- Leading the Soiling Subtask for the Heliocon Consortium, including leading the writing of the Soiling Subtask section for the Roadmap report;
- Planning work for 2023 - including soiling campaigns, development of a soiling database, benchmarking soiling prediction models;
- Delivery of a seminar entitled Soiling Losses for Concentrating Solar Power - Prediction, Assessment, and Mitigation for the Heliocon;
- New soiling campaigns: one in Mount Isa, Queensland and two in Wodonga, Victoria;
- Completed collaboration with ACWA power on optimised O&M practices. Results were presented and follow-up analysis for cleaning optimization was requested;
- Meetings with Solar Dynamics and RayGen to discuss soiling assessment of CSP sites;
- Visits to NREL and GECOS at Politecnico di Milano to discuss collaborative work on soiling modelling, dispatching & receiver O&M;



Predictions from the deterministic model (left) vs. the stochastic model - QUT



SEM image of dust particle on tip of AFM cantilever. Middle, EDX analysis of dust particle attached to AFM cantilever. Right, AFM image of topography of dust particle - QUT

Crescent Dunes Heliostat Cleaning – NREL

Technology Support Activities: Operations and Maintenance

- A new collaboration with Politecnico di Milano and Fraunhofer ISE (supported SFERA-III program) on understanding moisture effects on soiling losses; and
- Conducted a (currently confidential) soiling study with NREL and an industry partner.

Soiling modelling, nanoroughened coatings, and cleaning optimisation

- New experiments were performed (together with Politecnico di Milano) by C.B. Anderson and G. Picotti at Fraunhofer ISE to understand the effects of dew on soiling;
- The HelioSoil Python library was developed and released to the public. A publication on this was presented in SolarPACES 2022 and is expected to be published in 2023;
- Methods for evaluating prediction uncertainty were developed for the soiling model. A journal publication on the methods is expected in 2023;
- Adhesion of individual dust particles to a range of different coatings with nano-roughness shows using a novel atomic force measurements; and
- Dust accumulated on the mirror has been analysed to validate assumptions on source and size for adhesion models.

Dispatching and storage management:

- A stochastic optimisation model has been developed and refined in 2022 to optimise dispatching to maximise the expected profit attained from the CSP plant's operation under uncertain DNI trajectories.

Receiver Operations and Maintenance (O&M)

- The receiver thermal and lifetime estimation models were refined in collaboration with the GECOS group at Politecnico di Milano — particularly the jointly supervised PhD student Giancarlo Gentile;
- Methods for estimating uncertainty in creep lifetime prediction models were developed. A bootstrapping approach with available experimental data was used to understand the prediction error of two popular creep models. These errors are key to understanding failure risk of CSP receiver panels and therefore to plan their maintenance and renewal; and
- Lifetime estimation and maintenance policies were examined for central and billboard receivers to optimise their renewal times.

Key Challenges

While there is strong commercial interest in the adoption of new techniques to lower heliostat maintenance, monitoring and cleaning costs, the project relies heavily on engagement of industry players (and operating CSP plants) to share and evaluate experimental protocols and tools. The Heliocon project has alleviated this issue somewhat for heliostats. Industrial partners have been easier to engage in soiling studies due to this visibility, but this engagement still must be broadened due to the significant differences in economic and soiling conditions in different areas of the world.

Another key challenge is that equipment degradation models for new technologies are currently difficult to validate, as there is no available reliability data for some key subsystems. It will be necessary to partner with operators in these spaces as well to understand their real-world performance. However, there is currently no entity like HelioCon to foster this collaboration, so finding partners has been more challenging.

Key Opportunities

Numerous opportunities are arising from this project, and there is potential to establish ASTRI as an expert adviser for solar thermal system O&M. There is also an opportunity to share the developed software tools for soiling prediction and cleaning optimisation.

An unmet need is an integrated "solar station" that can be deployed at a potential solar site and provide specific local data on DNI, dust (particle size and number) for soiling models and moisture levels. Such a unit could provide greater confidence on the economics of investment and O&M costs in particular. This need has been confirmed by the experience of the team within HelioCon.

In addition to the collaboration with Vast Solar, the project is also providing opportunities to connect other industrial partners like Mars Petcare, ACWA Power, and HelioCon industrial partners. ASTRI's work on heliostat monitoring and cleaning is also of increasing commercial interest to the broader international community. The inclusion of thermally-induced receiver damage has increased the spectrum of potential collaborators both within industry and academia.

Key Learnings

- Soiling studies at Mount Isa and Wodonga have yielded a large amount of data on soiling, including dust storms, airborne dust distributions, and rain effects. In these locations, soiling tends to be low on average, but can have significant variation (dust storms, traffic).
- The soiling model has reasonable accuracy when tuned to local conditions and the newly developed uncertainty assessment appears to characterise prediction uncertainty well. However, the experiments have uncovered some conditions where the model predictions are poor. Further investigations and benchmarking are ongoing.
- Recent observations in Mount Isa showed that following rain events, the rain drops sheet off hydrophilic nano-roughened coatings while droplets remain. These droplets then dry leaving dust and mineral deposits for conventional uncoated mirrors. This offers valuable insights to a different mechanism of soiling in a real environment .
- Receiver O&M work has focused on creep-fatigue assessment of tubes and assessment of uncertainty of creep rupture model predictions. The main failure mechanism for CSP receivers appears to be creep. The uncertainty in creep lifetime predictions is high for CSP-relevant conditions, and understanding the prediction errors is crucial to informing O&M plans (which must consider the risk of failure, not just the average lifetime).

Commercialisation Pathways

The commercialisation pathway for O&M is to provide ongoing support to industry to de-risk system uptake from a technical, operational and/or cost perspective.

TECHNOLOGY COMMERCILISATION ACTIVITIES

| Industrial Process Heat

ASTRI's 2022 commercialisation objectives were as follows:

- Support commercial uptake of solar thermal systems and technologies in Australia through:
  - direct technical and commercial support to Australian technology developers;
  - where appropriate, commercial support to overseas technology developers.
- Support commercial uptake of conventional Solar Thermal systems, through technical evaluation, and operational deployment assistance to solar thermal end-users including mining entities and industrial process heat users;
- Work with international technology developers to promote commercial uptake of solar thermal technologies;
- Identify and promote adjacent market opportunities for solar thermal technology solutions as an enabler for broader solar thermal applications;
- Work with domestic and international EPCs to facilitate commercial uptake through improved system design and integration activities;
- Work with energy market participants to increase awareness and understanding of the role that solar thermal can play as a low-cost dispatchable generation option within Australia's future energy mix; and
- Work with industrial energy users to promote the role of solar thermal technologies in industrial process heat, storage, & power generation applications.

In support of these objectives, ASTRI has focused on commercial uptake of ASTRI developed technologies, and commercial support for more conventional solar thermal systems and technologies.

In 2022, ASTRI's technology development activities were focussed on a smaller number of higher TRL projects in areas of strong commercial interest. These activities were designed to increase/support commercial uptake through the delivery of more efficient, cost effect and lower risk solar thermal system outcomes.

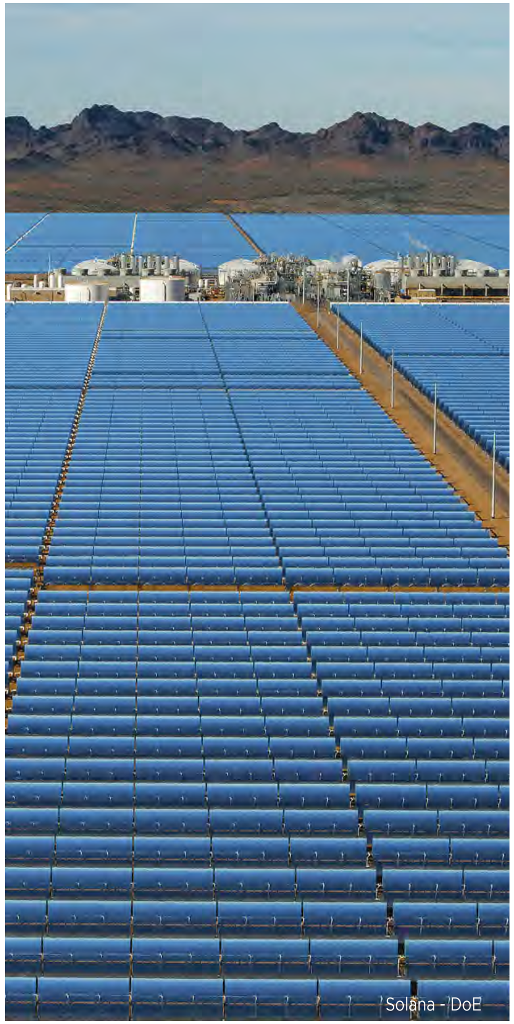
For ASTRI's specific technologies, the focus was on commercial uptake of particle receiver systems, and higher temperature systems. The particle receiver is now being commercialised through a joint venture arrangement. The sodium loop is being progressed in collaboration with Vast Solar.

ASTRI's commercial support activities in 2022 were focused on deployment and uptake of current solar thermal systems and technologies. Most of these activities have focused on direct technical and commercial uptake support to industry. The work in this area targeted two main industry stakeholder groups.

The first group is technology developers. ASTRI's activities have focused on direct support to developers to de-risk their technology from both a technical and operational perspective. Entities ASTRI has worked with include Vast Solar, Graphite Energy, MGA Thermal, Raygen, and ACWA.

The second group is industry end-users. Specifically, companies who are seeking support for assessment and deployment of conventional Solar Thermal systems and technologies. While not involving ASTRI developed technologies, deployment of current solar thermal technologies is vitally important to create awareness and acceptance of solar thermal as a technology solution. Companies that ASTRI has worked with include Mars Petcare, South32, CocaCola, Kimberly Clark and Fonterra.

Decarbonising Steelmaking



Solana - DoE

Crescent Dunes – NREL

ASTRI MOVING FORWARD

While ASTRI has made a significant contribution to enhanced technology outcomes, ASTRI's future centres around the support it can provide to industry (technology developers and energy end-users) and its ongoing commercial advocacy activities. Moving forward, ASTRI believes that its role should expand to include technical, economic and integration advice on current solar thermal technologies, and their deployment across a range of end-use application areas.

In terms of technology development, ASTRI believes that moderate increases in the operating temperature of Solar Thermal systems can deliver operational performance benefits and lower system costs. To this end, successful demonstration of sodium & particle receiver technologies, coupled with improved Thermal Energy Storage and advanced power blocks, will provide the foundation for next generation solar thermal systems.

The most immediate need for dispatchable power / heat generation is likely to be in the mining sector. Given their 24/7 operational requirements, rising diesel prices and increasing focus on scope 3 emissions, there is an increased mining sector interest in dispatchable, low-emission power generation solutions.

ASTRI believes that Solar Thermal can address this need, and ASTRI's advocacy focus over the course of 2023 will focus on the mining sector.

There is also a large emerging interest in renewable fuel production. In this regard, Solar Thermal's ability to provide both heat and power makes it an ideal technology for renewable fuels production, such as green methanol. ASTRI was involved in a successful HyGate submission in 2022 for the production of green methanol using CSP (Vast Solar). In 2023, ASTRI will continue to actively promote the role of solar thermal for large scale renewable fuel production (hydrogen, ammonia & methanol).

In terms of industrial process heat, there is significant commercial interest in renewable heat technologies, with Thermal Energy Storage (TES) systems, to displace process steam and heat in the mid-temperature range of 150°C to 500°C. Renewable heat technologies in this temperature range already exist, the issue for industry is which system best meets their operational requirements, based on available land and resources. Understanding and managing technology, operational and integration risk are also key considerations. ASTRI is well placed to provide this advice to industry.

Given this increased interest in thermal energy storage, power generation and process heat, ASTRI will ensure that its 2023 activities are clearly aligned to supporting markets in these key application areas. This includes:

- Demonstration of a high temperature sodium loop;
- Demonstration of a high-temperature particle receiver;
- Techno-economic analysis of TES systems for power generation and process heat applications;
- Demonstration of industrial process heat applications; and
- Demonstration of high-temperature renewable fuels production.

Communication and advocacy activities will be essential for targeting these markets. To this end, ASTRI will build on its 2022 advocacy activities to actively promote the value of Solar Thermal in these markets and end-use application areas.

In 2022, ASTRI commissioned a detailed techno-economic analysis of the value proposition of Solar Thermal in key end-use markets. In 2023, this information, coupled with operational risk profiles, will be prepared to establish the Solar Thermal value proposition within each of these end-use markets. This information will then be used to support demonstration projects.

The techno-economic analysis work will also be used to support evaluations such as the GenCost work and AEMO's 2023 Integrated System Plan activities.

AUSTRALIAN SOLAR THERMAL RESEARCH INSTITUTE (ASTRI)
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