AUSTRALIAN SOLAR THERMAL RESEARCH INSTITUTE (ASTRI)
PUBLIC DISSEMINATION REPORT 2021

DIRECTOR'S MESSAGE

In 2021, the Australian energy market continued to face significant challenges as it transitioned to a low emission future. These challenges centre around the need to lower emissions while maintaining secure, reliable, and cost-effective energy solutions for Australian households and businesses.

Significant uptake of renewable energy in the form of PV and Wind has continued into 2021. While these technologies deliver affordable clean energy, their variable generation profile creates system stability issues. Firm generation capacity is required to address this stability issue. At present, firm generation capacity is provided by conventional coal fired power plants. However, with these plants scheduled to retire over the next 10 to 15 years, alternative forms of firm and dispatchable renewable generation capacity will be required.

Renewable energy storage is the best solution for firm generation capacity. It allows energy to be captured, stored and dispatched, at any time of day or night, to meet system and end user needs. It provides two critical functions. Firstly, shorter duration energy storage delivers firm and responsive capacity for system stability. Secondly, longer duration energy storage enables high renewable penetration by displacing conventional generation for evening, morning and overnight energy demand.

Long-duration renewable energy storage also has the potential significantly to lower Australia's emissions. It's importance to Australia's energy transition has been acknowledged in the 2021 update of the Government's Low Emission Technology Statement (LETS). It has also been identified as a key issue in AEMO's draft 2022 Integrated System Plan (ISP).

Concentrating Solar Thermal (CST) is a technology solution that can help meet Australia's long-duration energy storage needs. Given Australia's excellent solar resource and abundant land, Solar thermal can play an important role, in conjunction with other low-emission technologies, in providing 24/7 renewable power and heat solutions.

For the provision of power, CST is commonly referred to as Concentrating Solar Power (CSP). Internationally, CSP continues to be deployed in high solar radiation countries. Over 6.5GW of CSP generation capacity, across over 100 CSP plants is now in operation with an additional 5GW of capacity being constructed or proposed over the next 5 years. Installation is occurring in Spain, South America, Northern Africa, the Middle East and China.

The latest International Renewable Energy Agency (IRENA) Report (2020) on power generation costs identified Solar Thermal as having the sharpest cost reduction over the past several years. The same report indicated that with four or more hours of storage, Solar Thermal was more cost effective than PV with batteries.

However, contrary to international markets, domestic deployment of Solar Thermal at scale has not yet occurred. This reflects Australia's reliance on low-cost coal and gas for power and heat. It also reflects a lack of domestic market signals for multi-hour renewable energy storage, making Australia's transition to a renewable-based energy system far more challenging. This noted, emerging international carbon pricing mechanisms are creating market signals for trade exposed industry sectors, which is increasing commercial interest in longer duration renewable energy storage.

In 2021 the Australian Solar Thermal Research Institute (ASTRI) continued to progress a range of activities to promote Solar Thermal as a technology option to help meet Australia's low-emission energy requirements. This includes activities focused on technology enhancements, establishing the CST value proposition and on projects to demonstrate solar thermal applications within key Australian energy (power and heat) markets.

This 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 CST in Australia will be the successful demonstration of an economically viable reference plant. Over the course of 2021, ASTRI has continued to work towards a high-temperature technology demonstration system. This work has been undertaken in close collaboration with Australian Industry and will result in the on-sun demonstration, towards the end of 2022, of a high-temperature, sodium based, solar thermal system.

Internationally, ASTRI has continued to be recognised for its role in supporting next generation Solar Thermal technology enhancements and systems deployments.

Dominic Zaal
Director, Australian Solar Thermal Research Institute, CSIRO

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Front cover: Delingha 50MW – 7-hour storage – Cosin Solar
Above: Crescent Dunes 110MW - 10 hour storage - 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 technical improvements, commercial interest in, and domestic uptake of concentrating 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, ASTRI has two key focus areas. The first key focus area is on technology development and demonstration. This involves activities aimed at demonstrating the cost competitiveness, efficiency and reliability of next generation solar thermal technologies, and their application within Australia's future energy landscape.

These technology development activities seek to address the technical challenges in reducing the Levelised Cost of Energy (LCOE) and realising the next step change in system efficiency and reliability. This includes the use of multi-hour thermal energy storage (TES) systems as a cost effective option to address Australia's emerging energy storage need.

In 2021, ASTRI focused on the following key technology development program areas:

- Program 1: Thermal Capture
- Program 2: Thermal Storage
- Program 3: Power Systems
- Program 4: Process Heat
- Program 5: Materials
- Program 6: Systems Modelling
- Program 7: System Integration

The second ASTRI key focus area is on commercial facilitation activities to establish and promote the value proposition that solar thermal systems can deliver within the Australian energy market for the provision of power and process heat.

These activities involve close engagement with system developers on the technical challenges facing deployment of solar thermal systems. It also involves engagement with major industry players on commercial uptake opportunities across a broad range of end-use applications including power generation, industrial process heat, remote mining and renewable fuel production (e.g. hydrogen, ammonia, methanol).

In 2022, ASTRI will increase its advocacy and communications activities, to ensure that Solar Thermal's value proposition, across Australia's key energy use sectors, is clearly understood and accepted.

ASTRI

WHAT IS SOLAR THERMAL?

Solar thermal uses the sun's light to generate heat that can be used in industrial processes or to generate electricity. To achieve high Temperatures, it uses high quality mirrors to concentrate sunlight, which heats a liquid (e.g. water, molten sodium or oil) that is then stored or used directly for power or heat production. Solar Thermal systems typically operate at temperatures between 300°C to 600°C. However, some Solar Thermal Dish systems can operate at temperatures over 3000°C.

Over 95 concentrating solar thermal plants are operating commercially, overseas, mostly in countries with high solar radiation levels. However, even though Australia has some of the best solar radiation levels in the world, the technology is still in its early stages of deployment within Australia. This is primarily due to weak domestic market signals for long-duration energy storage. International carbon pricing mechanisms, and new domestic policies and emission reduction targets will likely change these market signals.

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. Both of these systems use a field of mirrors to concentrate the sun's light energy onto a receiver and convert it into heat (i.e. thermal energy).

The heat can be used directly or stored for use at a later time to produce electricity to provide industrial process heat, or for the production of renewable fuels. The heat energy can then be stored for multiple hours of operation (typically between 8-18 hours). The stored energy is then used to generate power or to dispatch heat, as required, at any time of day and night.

From a power perspective, CSP is a technology solution that is almost identical in operation to conventional coal-fired steam power plants – but with zero emissions.

Key components

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

Solar collection

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

Thermal capture

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

Thermal energy storage

Concentrated solar thermal systems typically incorporate energy storage. Heat collected at the receiver is then stored in tanks typically using molten salts or other heat transfer medium (i.e. 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. These power blocks are similar, but more flexible, to those used in coal fired power plants. The conversion involves the use of solar thermal energy for the production of superheated, high-pressure steam, which spins a turbine to generate electricity. While steam turbines are the current technology choice for CSP systems, new advanced power cycles using supercritical CO_2 are emerging as a pathway for smaller, more efficient power generation systems.

| Crescent Dunes 110MW – 10-hour storage – NREL

SOLAR THERMAL INTERNATIONALLY

| Parabolic Trough – NREL

Globally, the installed capacity of Concentrating Solar Thermal (CSP) systems has grown steadily over the last two decades. CSP had a global total installed capacity of 6.5 MW at the end of 2021. There are now more than 95 commercial CSP plants around the world. Most new plants have multiple hours of storage to allow for on-demand dispatch of renewable energy, at any time of day or night.

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

There is another 4.5 GW of large CSP plants under construction or under development across a number of countries including Spain, China, Chile, Morocco and Saudi Arabia.

Countries leading the way with CSP all have high solar radiation levels – just like Australia. However, despite having some of the highest solar radiation levels in the world, there is only one small commercial CSP system operating in Australia (i.e. Sundrop Farms in South Australia). This situation will change as coal fired plants retire and alternative low emission energy storage and dispatchable generation technologies are required.

Operational performance

How many CSP systems are there globally?

There are currently 79 CSP plants that are 50 MW or larger and another 19 in the 10 to 50MW range. There are also 10 smaller (under 10MW) experimental test facilities/ plants.

Installed global capacity is increasing, driven by the construction of new plants in China and the Middle East. Moving forward, Spain has announced plans for another 5 GW by 2030 and China has indicated plans for another 10 GW by 2030.

The capacity factor of operational CSP plants is also increasing. The IRENA "Renewable Power Generation Costs in 2020" report indicated an average capacity factor of over 50% for CSP plants with eight or more hours of storage. The IRENA report also noted that CSP plants had the largest annual reduction (16%) in LCOE across all assessed renewable technologies.

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 almost ten years. The 16 large plants in the US have been operation for between five and thirty years. Another 20 plants in other locations have been operating for two years or more.

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

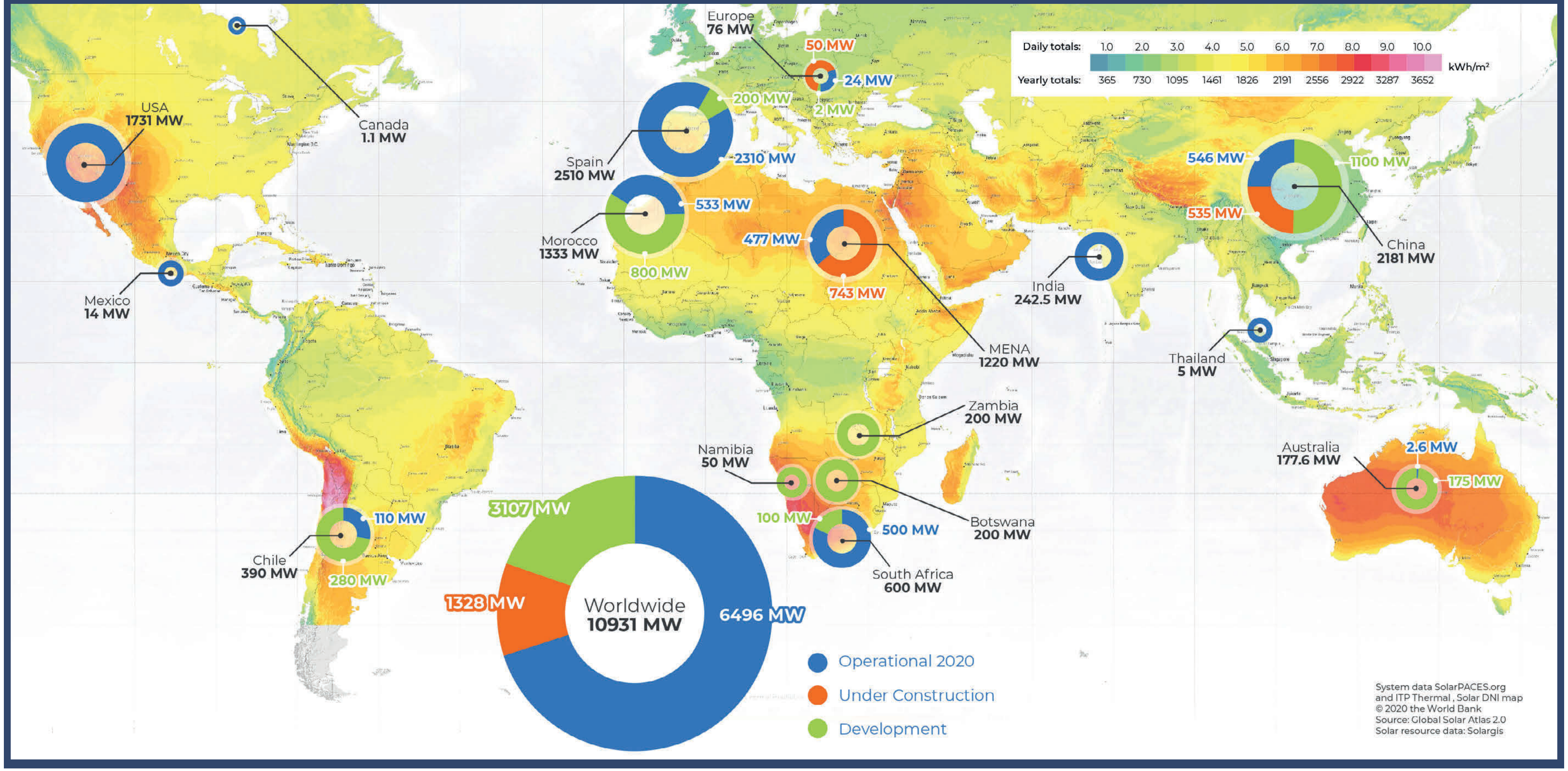
To combat climate change, we must reduce our reliance on fossil fuels. To this end, Federal and State governments have made strong commitments to reduce emissions and have provided incentives for Australian households and businesses to embrace the challenge and lower Australia's emissions.

On a per capita basis, Australia has the highest penetration of rooftop solar photovoltaics in the world and this take up is accelerating with no sign of abatement. There is, however, much more to be done as we transition our legacy fossil fuel-based energy systems to a renewables future.

While there are many pathways to reduce our reliance on fossil fuels, the adoption of low-emission technology solutions is deemed to be an integral element of Australia's transition to a low carbon future. This is reflected in the Federal Government's low-emission technology statement (LETS) and their focus on policies and programs to promote investment in low-emission technology pathways.

Australia's move away from Fossil Fuels will be a significant undertaking. Australia's prosperity has been largely built on our abundant coal resources, both as a valuable export commodity and to power our nation since the early 20th century. Large coal-fired power stations were built to serve centralised load centres, particularly along our Southern and Eastern coastlines.

SOLAR THERMAL CAPACITY AROUND THE WORLD 2021



Our highly dispersed national transmission and distribution electricity networks (the East Coast network at 40,000 km is one of the longest in the world) connects our cities and remote communities, often with long distance, low voltage single transmission lines.

Energy planners recognise that such an convoluted network is ill-suited to a future characterised by highly dispersed, decentralised renewable energy systems, optimised to take locational advantage of our resources (e.g. where the sun or wind is strongest).

As Australia's fleet of aging coal-fired power stations retire over the next 10 to 15 years, there is a sense of urgency to invest in renewable systems that can provide firm capacity and can deliver multiple-hours of reliable, low cost, energy. Specifically, renewable energy systems that can be dispatched on demand at any time of day or night.

Existing gas fired power generation assets provide an interim solution. However, while less emission intensive than coal, gas fired generation will not allow Australia to meet its emission reduction targets.

Solar Thermal Value Proposition

The Australian energy market is in rapid transition to more sustainable technology solutions. This transition will create a number integration challenges. The most significant of these challenges is the need to ensure secure and reliable supply in a market where the level of intermittent generation is rapidly increasing. Locating renewable energy assets to take maximum advantage of available resources (i.e. sun, wind, geography) will also be a key challenge.

According to the Australian Energy Market Operator's (AEMO's) Integrated System Plan (ISP), Australia's coal-fired power plants are expected to have reached the end of their technical life and be retired within 10-15 years. These plants represent a combined capacity of 130 TWh, which is equivalent to two-thirds of current total National Electricity Market (NEM) consumption. These assets also provide critical grid support services such as inertia response, voltage control and frequency control.

SOLAR THERMAL INTERNATIONALLY

| Ashalim 121MW – BrightSource

As the penetration of intermittent forms of renewable generation continues to increase, a dispatchable renewable alternative to coal fired generation is required to safeguard system security and reliability.

It is this need for renewable energy solutions that can provide firm / dispatchable capacity, at any time of day or night, which creates the greatest transitional challenge for Australia's future energy system.

Energy storage technologies, using renewable inputs, are the key to meeting this challenge. These technologies allow renewable energy to be stored and then dispatched, as required, regardless of the time of day or weather conditions

The provision of firm, fully dispatchable capacity, provides two essential functions. Firstly, short duration energy storage provides firm capacity to address system security issues. Secondly, long-duration energy storage displaces fossil fired generation at times of day where variable renewable generation is problematic (i.e. evening, morning and night-time demand) so ensuring continued system reliability.

It is the displacement of conventional generation outside of daytime hours, which is key to a low emission, high penetration renewable energy system. AEMO has identified the need for over 620GWh of renewable energy storage capacity by 2040.

Solar Thermal systems provides a technology option to support this outcome. Through the storage of thermal energy, Solar Thermal can provide firm power generation capacity and process heat, at any time of day of night. It also offers the same grid-service attributes as that of coal-fired plants.

From a systems perspective, Solar Thermal's strongest value proposition is its multi-hour energy storage. This allows Concentrated Solar Thermal to be a complementary companion with utility scale PV. Most new international solar thermal plants are being collocated next to utility scale PV installations, allowing for PV generation during daylight hours and solar thermal generation, using stored energy, during evening, night-time and morning periods.

There is also a significant market in Australia for process heat. Over $8 billion is spent annually by Australian industry on process heat. Our decarbonisation journey will need to address emissions from industry, which currently uses a third of all energy produced in Australia. Thermal energy from concentrating solar thermal systems can be stored or used directly for industrial process heat applications at temperatures from 150°C up to 1000°C or more.

Benefit to Australia of Solar Thermal

Concentrated 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. Convention power generation, using coal and gas, convert thermal energy into power. Gas is also used in industry for process heat applications. As such, well over 80% of Australia's current energy requirements use thermal energy processes. This includes most of Australia's electricity generation, 70% of Australia's industrial energy consumption, and almost all of Australia's transportation needs.

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.

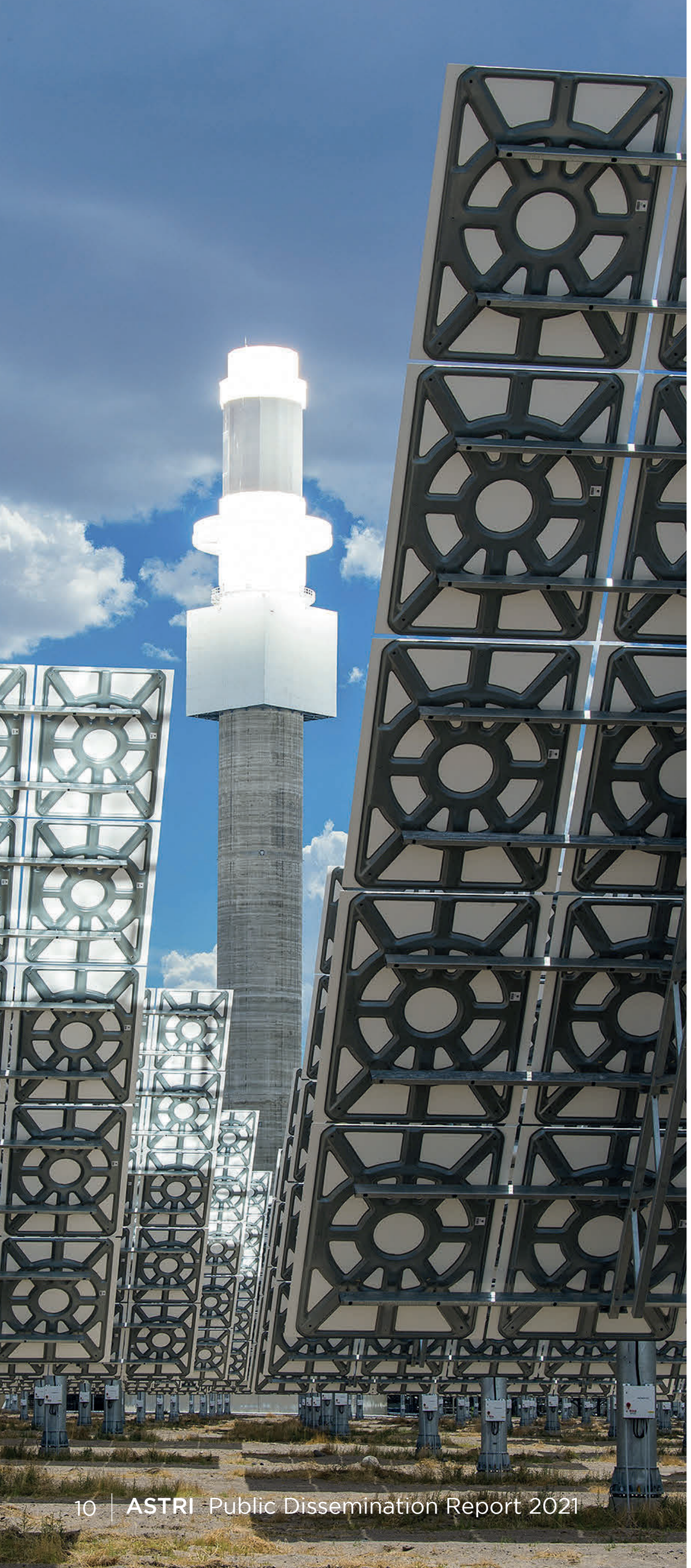
In addition to utility scale power generation, there is also an emerging market interest in smaller Solar Thermal systems (10MW to 30MW) at remote and fringe of grid locations. Such systems are viewed as a means to increase the level of renewable uptake, particularly for evening/nightime loads; to displace high-cost diesel generation; and to hedge against future fossil fuel energy price volatility.

Australia is also keen to position itself as a major global player in the production of renewable fuels, including hydrogen, ammonia, methanol). This will require significant amounts of renewable energy (electricity and heat). To maximise production, renewable energy will be required night and day. CSP can meet this need, particularily in high solar resource areas within Australia. When coupled with PV and wind generation, CSP can provide night-time power and heat, and significantly increase the capacity factor for renewable fuel production, as required in response to export demand. CSP can also be used to support high temperature solid oxide electrolysis (requirs heat and power), which produces higher hydrogen yields.

Solar Thermal can also provide a technology solution for low-emission metal/ mineral processing. Specifically, the ability of Solar Thermal to provide power and heat, at any time of day or night, makes it a good technology option to decarbonise and meet Australia's 24/7 mineral production requirements. 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 heat and power to lower the carbon liability and improve the value of Australian mineral exports (e.g. beneficiation).

The benefits of Solar Thermal 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 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.
Clean Hydrogen.	Increase the capacity factor and yield of clean hydrogen production in response to export demand.



ASTRI'S ROLE IN SUPPORTING SOLAR THERMAL UPTAKE

ASTRI has established itself 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. ASTRI has also 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.

Over the past year, ASTRI has continued to focus on de-risking solar thermal applications through the development, demonstration and integration of solar thermal technologies. ASTRI has also continued to promote and increase commercial interest in the use of solar thermal technologies to deliver cost competitive energy storage, power generation and process heat solutions.

Consistent with this approach, ASTRI's primary objective has been to facilitate and accelerate the commercial uptake of solar thermal technologies through:

- **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 a key enabler:** promoting the critical role of Thermal Energy Storage as a means to provide firm power and heat generation capacity at all times 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 (e.g. heliostats), thermal capture (e.g. receivers), thermal energy storage and, if the system is used for power generation, a power block.

ASTRI's technology development program seeks to fundamentally improve the performance of these component technologies, using technology enhancements to achieve significant cost reductions in the levelised cost of energy (LCOE) over 10 years. For power generation applications, ASTRI is targeting a 50% reduction in LCOE – from 14c/kWh (AUD) in 2019 to 7c/kWh (AUD) in 2030.

| Crescent Dunes – NREL

Capturing these performance improvements requires a range of technology enhancements, most of which are being addressed in ASTRI's technology development program, including:

- more cost effective and optically efficient heliostats;
- higher temperature, higher efficiency receivers;
- more cost-effective thermal energy storage solutions;
- more efficient, lower cost power cycles;
- advanced high temperature materials; and
- lower cost operations and maintenance technologies and strategies.

Over the next two years (2022-2023), ASTRI is developing component technologies in solar collection, thermal capture, thermal energy storage, and process heat. It is also conducting important work in advanced materials, testing cycling and durability.

| Delingha – Cosin Solar, Delingha

Focus on End-Use Application Areas

ASTRI was initially established as a researcher driven program for emerging technology development. Under this initial construct, commercial uptake was a secondary consideration. The focus was on research and development of Solar Thermal technologies to improve the performance of next generation systems. The thinking being that conventional Solar Thermal systems would be deployed in Australia, and that ASTRI should focus its efforts on performance enhancements to support the next generation of these deployed systems.

However, the expected deployment of Solar Thermal in Australia did not occur. This fact was reflected in the 2017 Mid-Term Review of the ASTRI Program, which recommended that ASTRI become more involved in commercial deployment. As a result, ASTRI has moved to undertake more collaborative activities with industry, in direct support of commercial uptake. This transition has been difficult for ASTRI's research entities, who have found it challenging to align their research activities to the commercial requirements of industry.

ASTRI's strategy seeks to define a clear set of strategic objectives and market impact areas for ASTRI, and then develop technology development and commercial activities to support these objectives in key markets.

ASTRI's current program centres around Solar Thermal for power generation within large electricity networks. However, there has been increased interest in Solar Thermal for remote area power systems (mining, fringe of grid, remote communities) and for industrial process heat applications. The use of Solar Thermal for the production of renewable fuels is also gaining increased commercial interest.

Previously, ASTRI has not focused on these other end-use applications as they do not typically fall into the 'next generation' high temperature technology pathway. However, from a commercial perspective these systems may provide a viable market solution, which can increase awareness and deployment opportunities for Solar Thermal. Accordingly, ASTRI's Strategy now includes consideration of ASTRI's role in facilitating uptake of solar thermal technologies across the following end-use markets:

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

Utility Scale Power Generation

Globally, there is 6.5 GW of Solar Thermal, in the form of Concentrated Solar Power (CSP) plants operating commercially. The first CSP plants were installed in California in 1985 – 300MW of these first CSP Plants have now been in continuous operation since 1990.

CSP requires good levels of direct normal irradiation (DNI) and thus is best suited to hot dry climates. Over 95 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. However, CSP's large scale comes at a cost. Accordingly, deployment typically requires policy measures and incentives that value daily, long-duration (8+ hours), fully dispatchable clean power generation. The majority of global deployment of CSP Systems have been in Spain, USA, South Africa, Morocco, China and the UAE.

The International Renewable Energy Agency (IRENA) "Renewable Power Generation Costs 2020" Report states that over the past 10 years the LCOE of newly commissioned CSP plants has fallen by 68%, from $340 (USD)/MWh in 2010 to $108/MWh in 2020. This was due to: a 50% reduction in the installed costs of newly commissioned CSP plants; an increase in capacity factors from 30% to 42%; and a decline in O&M costs by a third.

The three largest CSP plants, currently under construction, (DEWA – UAE 700MW; Noor Midelt – Morocco 380MW and the Likana – Chile 390MW) have stated reported tarrifs of $73 (USD),

$70 (USD) and $40 (USD) / MWh respectively. All of these project include multi-hours (10 or more hours) of storage. What this indicates is that large CSP plants, with good DNI and multiple hours of storage, can deliver cost effective dispatchable renewable energy solutions into electricity markets.

Remote Area Power Systems

Australia has a large demand for energy for remote mining operations. Australian mining operations used over 720 Petajoules 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 almost 45% used to support mineral extraction/processing. The mining sector consumes over 5 billion litres of diesel per annum for transport and electricity production. Gas is also used in mining and LNP production to generate heat and electricity.

Energy price volatility and upstream carbon pricing risks (i.e. scope 3 emissions) are forcing mining companies to examine options to reduce emissions. Those mining companies with lower fossil 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 and battery systems being installed but such systems are not currently cost- effective for longer duration energy storage (i.e. 4+ hours). This will create challenges for Australia's mining companies, which require long-duration energy storage to meet 24/7 mining and processing operations. Solar Thermal can address these challenges.

Solar thermal systems are a good 'utility scale' renewable energy option for mining, particularly in hot, dry areas. They can provide both power and heat (for mineral processing / beneficiation). Medium scale solar thermal systems are currently cost competitive against diesel for power generation. They are also competitive against PV with more than two hours of 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 important for mining entities seeking to 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 of increasing interest.

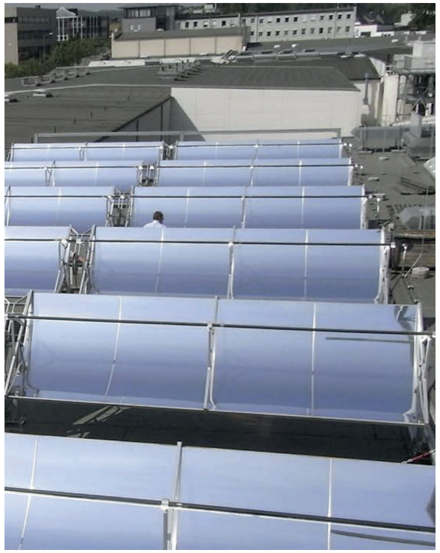
Industrial Process Heat

Industry is responsible for 42% of Australia's total final energy consumption. Of that, 51% involves the combustion of fuel for process heat. The dominant existing fuel for heat is gas (46%), with black coal (22%) the second largest. The actual heat used is less than the fuel consumed (i.e. more heat is produced than is effectively utilised), with process efficiency estimated at 80% (i.e. 20% of the 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 $10/GJ for gas, the annual cost to Australian industry for process heat supply is around $8 billion. Approximately 50%, or $4 billion/year is estimated for process heat applications in the temperature range 150°C – 500°C.

Concentrating Solar Thermal systems are ideally suited to industrial 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 solutions. For such systems, the inclusion of higher temperature TES systems (i.e. up to 500°C) would allow for significant displacement of gas for night-time process steam operations.

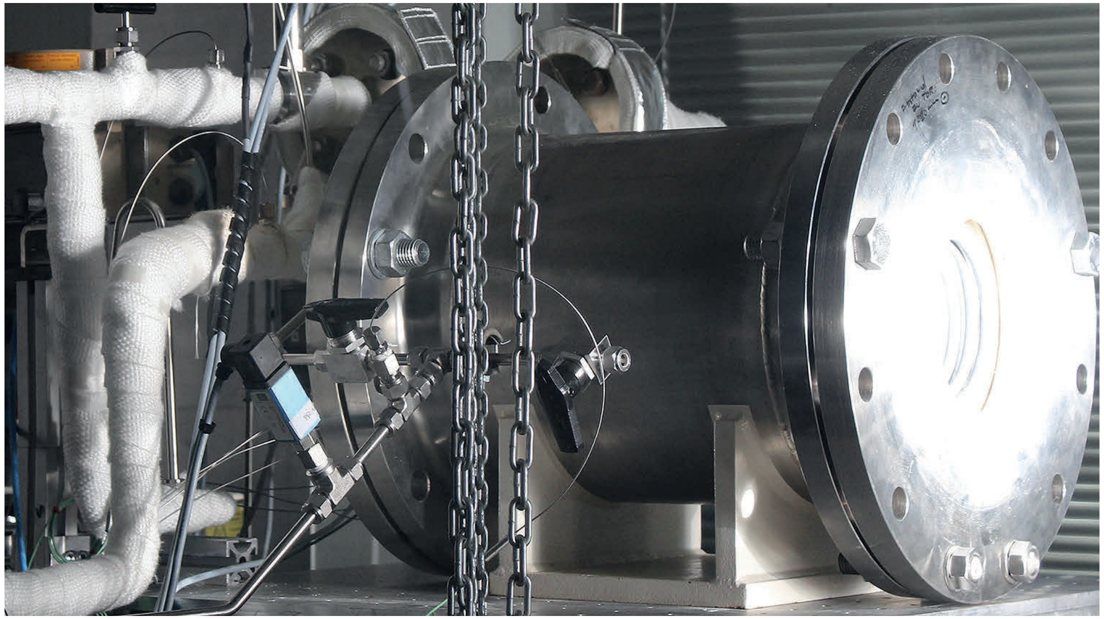
It is important to note that, while ASTRI advocates the use of Solar Thermal for process heat applications, it recognises that TES systems can be charged with renewable heat, renewable electricity or both. To this end, ASTRI views TES systems as an adjacent market opportunity that could be used to enable Solar Thermal uptake. Ultimately, a range of factors including available



| Parabolic Trough – DLR

on-site land and solar resources will determine the best renewable technology (i.e. solar thermal, PV, wind, bioenergy etc.) to charge a TES system.

Solar Thermal systems for industrial process heat applications have a range of benefits including, lower energy costs, lower emissions, lower energy price shock risks and improved energy productivity. In essence, such systems provide 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 important if Scope 3 emissions become a consideration for exports.



| Solar Steam Generator for Solid Oxide Electrolysis – DLR

| Ciemat-PSA Research Center

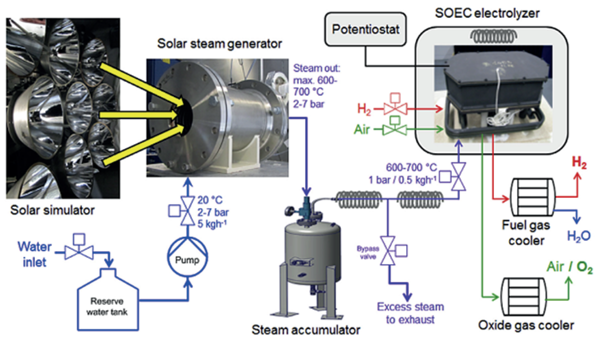
Renewable Fuel production

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 and export of renewable fuels. Renewable hydrogen is a fuel and a key input for the production of other renewable fuels (ammonia, methanol) Given its importance for Australia's energy transition, the LETS has identified low-emission hydrogen production as key investment priority area.

There are four main pathways for the production of renewable hydrogen. These include the use of renewable electricity, renewable heat (i.e. solar thermal), bioenergy or light. While all of these pathways are being explored, the current commercial clean energy focus is on low-temperature (80°C) electrolysis. However, the use of thermal energy for high temperature electrolysis has the potential to significantly increase hydrogen production yields.

While low-temperature (80°C) PV electrolysis is a proven clean hydrogen pathway, high temperature (800°C) solid oxide electrolysis (SOE), using solar thermal, can produce higher yields of clean hydrogen with less renewable energy. However, solar thermal systems have an upfront capital cost that needs to be taken into consideration. To this end, Solar Thermal for clean hydrogen production will require a trade-off between increased system cost versus increased yield.

As Australia looks towards future hydrogen export markets, consideration needs to be given as to what is the right technology mix to produce bulk hydrogen 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 – DLR

The Importance of Thermal Energy Storage

Solar Thermal's main value proposition arises from 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. For power generation, the thermal energy storage (TES) provides firm capacity, which will only increase in value as the level of variable generation increases.

TES can also be used for arbitrage, to store excess renewable electricity for use at a later time.

Multi-hour TES is fundamental to the success and uptake of Solar Thermal within Australia. This energy storage focus is consistent with the LETS, which identifies multi-hour renewable energy storage as a priority investment technology. The LETS highlights the importance of 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.

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

| Two-Tank Molten Solar Storage – Protermosolar

Thermal energy is currently the primary source for power generation and process heat applications. Most of this thermal energy is generated through the combustion of fossil fuels. 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 energy technologies. This has resulted in the increased use of renewable TES systems as a means to lower emissions, improve operational efficiencies and reduce energy costs.

The primary application for renewable 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 systems are typically based on the use of steam power generation at temperatures between 400°C to 600°C.

Recently, there has been interest in higher temperature TES as an enabler for advanced power systems (i.e. supercritical CO_2). These advanced power cycles, operating at temperatures over 650°C, enable more efficient, reliable and cost- effective power generation. They can also be used for smaller power systems (5-10MW), which would be ideally suited to remote area applications in Australia (i.e. mining and fringe of grid).

Over the past 10-years there has also 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 (i.e. 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 TES has also been identified as a potential enabler for low-cost clean hydrogen production. Solid Oxide Electrolysis (SOE) is a high temperature process that can produce larger volumes of clean hydrogen per unit cost of electricity at costs potentially significantly lower than that of current electrolysis technologies. Other clean hydrogen technologies that might benefit from TES include solar fuels and photocatalysis based systems.

| 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 6.5GW 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 is undertaking a series of techno-economic studies in key end-use markets, including mining, mineral processing. utility scale power generation, industrial process heat and renewable fuel production. This information will be used to inform market participants, policy developers and energy end-users. It will also be used to support evaluations such as AEMO's 2022 Integrated System Plan and CSIRO's GenCost.

Other advocacy activities include: the provision of advice for federal and state energy system planning activities (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.

The Australian Solar Thermal Industry Association (AUSTELA) will be a key partner in the development and implemenation of ASTRI's communication strategy

TECHNOLOGY DEVELOPMENT ACTIVITIES

ASTRI's technology development activities have been carefully 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 component technologies used in solar thermal systems include solar collection, thermal capture (i.e. receivers), thermal energy storage, and a power block, if required for power generation.

ASTRI's technology development program seeks to improve the individual performance of these component technologies, as well as their overall performance as part of an integrated solar thermal system. These performance improvements can be achieved by utilising a more efficient power generation cycle operating at higher temperature. However, higher temperature applications require significant technology enhancements. ASTRI's technology development activities are specifically targeted at these technology enhancements across the following key areas:

- Thermal Capture
- Thermal Storage
- Power Cycles
- Process Heat
- Materials
- System Modelling

Thermal capture is being addressed across three projects spanning heliostats and receivers (sodium and particle receivers). The solar thermal industry needs lighter, more optically efficient, smarter and more bankable heliostats, so ASTRI is working to support industry efforts to deliver this outcome. Receivers are an integral part of the heat capture and transfer process within solar thermal systems and ASTRI's two receiver projects focus on the design, demonstration and testing of receivers that can operate at temperatures over 700°C. This includes a sodium-based receiver and a multi-stage falling particle receiver.

Thermal Energy Storage can significantly increase the capacity factor of solar thermal systems, so ASTRI is running projects to help technically and economically de-risk high temperature thermal energy storage. Projects are in place to:

- better understand thermal storage materials
- demonstrate newly developed technologies; and
- to objectively develop, design and assess the commercial viability of emerging TES technologies.

| Circular Heliostats – NREL

| Gemasolar 20MW – 15-hour storage – Protermosolar

ASTRI's projects also look at other key elements of solar thermal systems. These include the following:

- Advanced power cycles, via the use of supercritical carbon dioxide (sCO_2) as an alternative to steam as the working fluid for power generation turbines. These sCO_2 power blocks can significantly increase power generation efficiency, are more compact and ideal for small and large power generation applications.
- Industry-backed R&D projects to benchmark the use of CST systems and solar fuels for high potential industrial process heat applications.
- A materials program that supports the other component projects by identifying suitable materials for high-temperature application and providing specific answers to many of the materials issues associated with higher temperature solar thermal technologies and material interactions.
- System modelling activities to fully understand the component cost interactions within solar thermal systems, and to understand the whole of system cost impact of solar thermal within Australia's future energy mix.

As of 1 September 2021, ASTRI had 18 projects across 7 Programs Areas. These include:

Program 1: Thermal Capture

1.1 Heliostats

1.2 Sodium Receiver

1.4 Particle Receiver

Program 2: Thermal Storage

2.1 High Temperature Thermal Storage

2.2 Heat Exchangers

2.3 Storage Technology Options

Program 3: Power Systems

3.4 Power Block Design and Optimisation

Program 4: Process Heat

4.1 HyS Cycle

4.2 Commercial Application of STEM technology 4.3 Photocatalysis

4.4 Solar Hybridised Dual-fluidised Bed Gasification

4.5 Decarbonisation of Steelmaking

4.6 Integration of CST in Bio-reforming Processes

Program 5: Materials

5.1 Advanced Materials

5.2 Operations and Maintenance

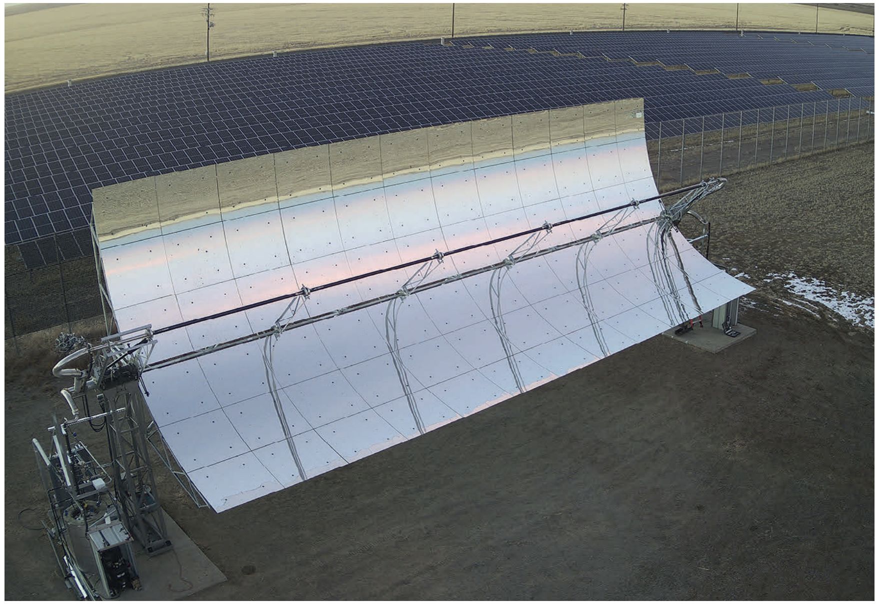
Program 6: System Modelling

6.1 Solar Thermal System Modelling

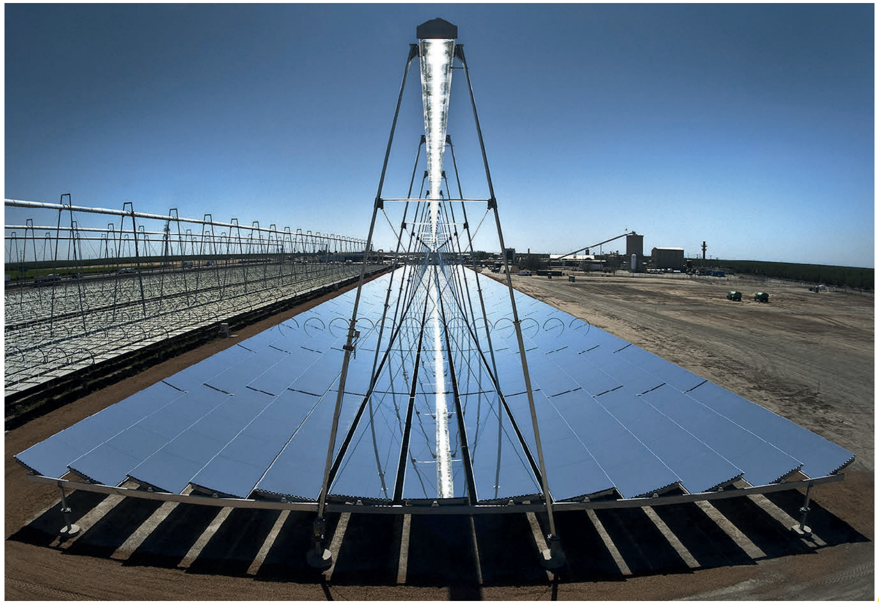
6.2 Opportunity Assessment

Program 7: System Integration

7.1 System Integration Demonstration



| SunBeam Parabolic Trough – Solar Dynamics LLC



| Linear Fresnel – US DoE

ASTRI TECHNOLOGY DEVELOPMENT ACTIVITIES 2021

| Delingha– Cosin Solar

PROGRAM 1: THERMAL CAPTURE

Project 1.1: 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 both small and large solar thermal systems.

In parallel with developing technologies for cost reduction, team members are working with industry (directly, and through SolarPACES and HelioCon activities) on measuring and ensuring 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

Over the last 12 months the project has focused on developing heliostat technologies that can reduce OPEX, CAPEX and/or improved performance of heliostat system. It has also provided technical support about heliostats to Australian projects and progressed from prototype to subsystem testing of novel heliostat technologies.

Specific achievements included:

- Testing and demonstration of a novel concept for a lightweight single-component focussing facet
- Development of an adjustable-focal-length mould for facet assembly
- Publication of open state-of-the-art characterisation data for wind loads including:
    - peak load analysis for heliostats of different aspect ratios
    - dynamic wind loads on operating & stowed heliostats in tandem configurations.
    - impact of mesh structures (wind-fences) on turbulence field approaching heliostats
    - Impact of edge-devices
- Construction of Atmospheric Boundary Layer measurement facility on a University of Adelaide rural campus. This will be developed to examine realistic atmospheric boundary layer conditions and will host wind load tests for full scale heliostats, for comparison with wind tunnel results.
- Designed and fabricated an instrumented full-scale heliostat for the outdoor wind load test comprising a differential pressure sensor array and an integrated 6-axis load cell.
- Demonstrated an energy storage system for heliostat power and field wiring cost reduction
- Undertaken extensive external engagement, particularly through Vast Solar's heliostat development 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.

Key Challenges

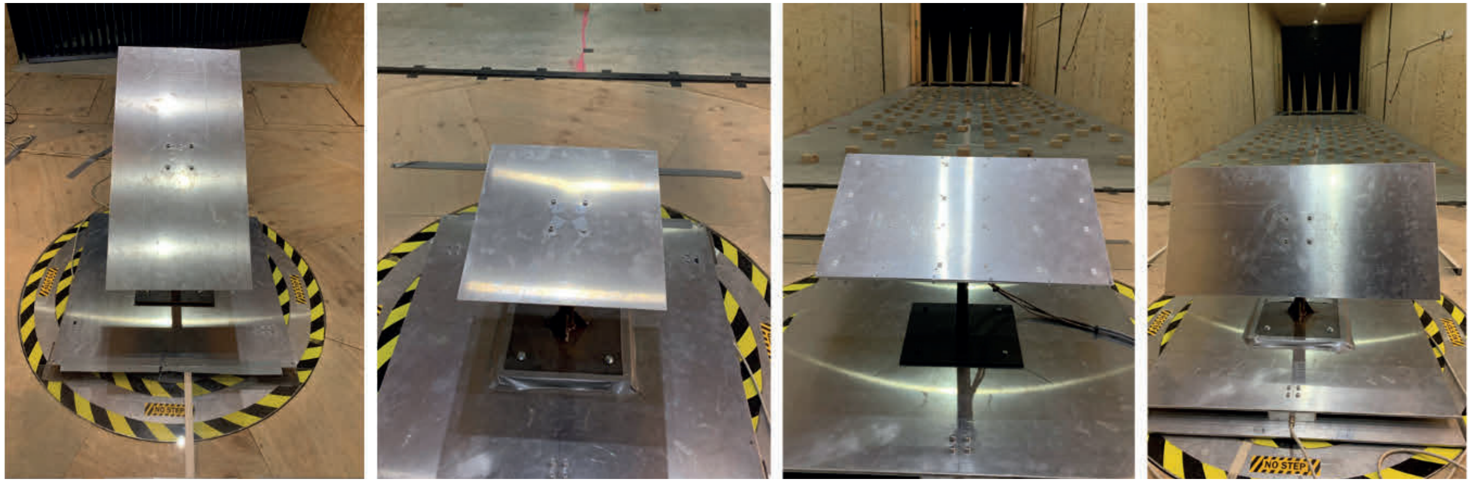
Despite the last 12 months being extremely disrupted, significant progress was made on all technology development components of the Project. While working-from-home arrangements were in place, desktop studies have progressed further than planned, while some activities that required on-site/hardware work have been carried over to 2022. Furthermore, Industry and international collaboration has been more difficult with travel restrictions in place.

Key Opportunities

If the cost and performance of small heliostats is demonstrated, proven and accepted, then any commercial tower system (large or small) will be able to use small heliostats. In fact, several large CSP systems (e.g. Ivanpah, Ashalim) already use small heliostats (between 14 to 22m^2). As receiver temperatures increase, or fields become smaller and more modular, the demand for small heliostats will continue to increase. This project is exploring opportunities for technologies developed in ASTRI to be adopted by users of large or small heliostats, decreasing cost, improving performance and therefore improving viability of CSP projects.

Disseminating information about heliostat wind-loads will have broad-reaching impact across the global CSP community, in particular if ASTRI is able to contribute to a wind-load guideline or standard. This should reduce costs and decrease risk to CSP projects.

In 2021 ASTRI joined the US Department of Energy Heliostat Consortium "HelioCon" (https:// www.energy.gov/eere/solar/heliocon). HelioCon will see the National Renewable Energy Laboratory (NREL), Sandia National Laboratories (SNL), and ASTRI work closely work with CSP developers, component suppliers, utilities, and international experts to pursue heliostat cost reductions and improvements to heliostat component performance.



University of Adelaide Wind Tunnel has been used for detailed characterisation of heliostat wind loads and wakes in controlled boundary layer conditions. This includes heliostats of different aspect ratios relevant to commercial heliostats, features for heliostat wind load and wake control, and for wind-fences for wind load reduction for edge-of-field heliostats. The lessons learned are published and disseminated across the industry through conferences and working groups.

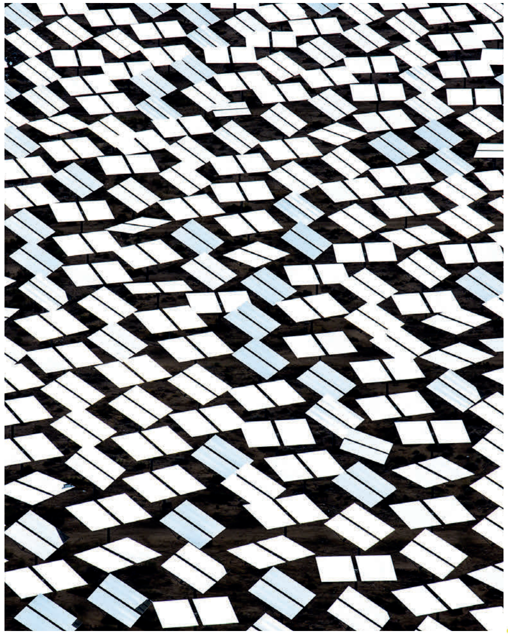
Key Learnings

Pursuing lower capital costs can come at the expense of product life, performance or increased operating or maintenance costs, so technoeconomic tools have been developed to ensure a better value heliostat system is being developed. For the first time, ASTRI Heliostats project has been able to link heliostat performance parameters all the way through to LCOE using the Solstice / SolarTherm system modelling tools developed within ASTRI.

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 commercial heliostat products).



Ivanpah 133MW – NRG Energy – Bright Source Energy

Project 1.2: Sodium Receiver Design & Testing

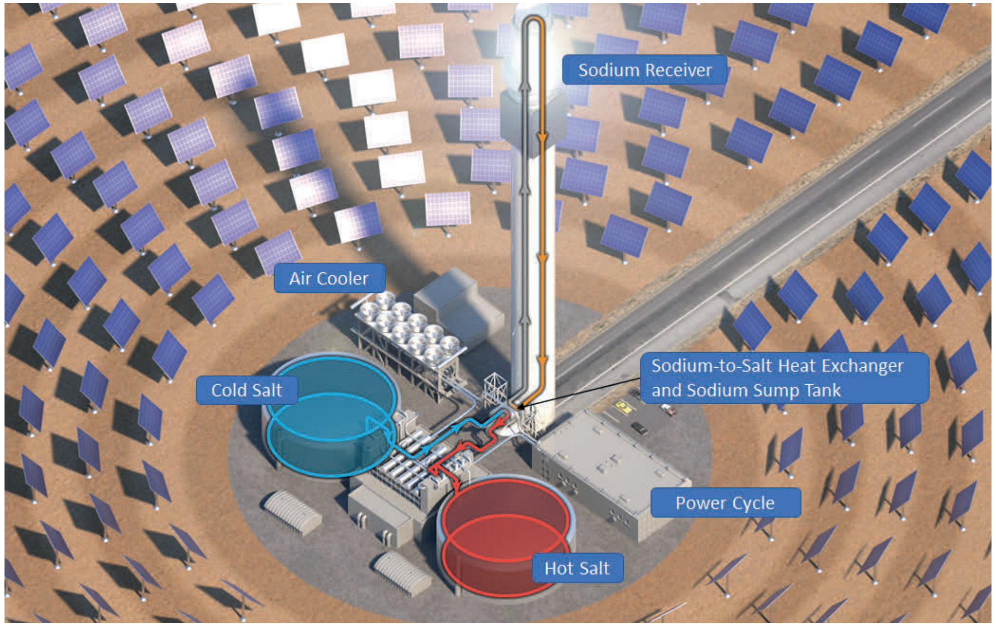
When the sun is reflected off a heliostat in a solar thermal system (CSP or CST), it is directed towards a receiver. There are many types of receivers; each is a key component of the heat transfer system.

Internationally, current tower-based solar thermal systems use liquid-based (nitrate salt) receivers. These have excellent thermal efficiency (> 90%), however nitrate salts decompose above 600°C, making them unsuitable for higher temperature applications.

ASTRI has been working with international partners (NREL, Sandia) on next-generation, high-temperature CSP solar receiver technologies, integrated into a plant designed to power advanced power cycles at around 700°C. The receiver technology is based on the use of liquid sodium as a heat transfer fluid, which allows concentrated light to be collected as heat in a highly efficient manner. Further, sodium is an enabler of plant modularity, allowing networks of solar receivers to be linked to a central power block.

Key Achievements

- New design optimisation methods employed to significantly lower LCOE including:
  - o Advanced heliostat aim point strategy and field/receiver/system co-optimisation
  - o Advanced structural integrity analysis, removing over-conservatism from design
- Led the sodium receiver work in the Gen3 CSP Liquids Pathway in the USA including:
  - o Refinement of the full-scale configuration to 2 x 50 MWe plants
  - o Commercial-scale component costing
  - o Failure Modes & Effects Analysis (FMEA)
  - o Pilot plant operational strategy
  - o 90% design submitted for the 1 MWth receiver
- Commissioning and operation of the ANU sodium laboratory up to 750°C, and commencement of testing with project partner Graphite Energy
- Completion of the design of the ASTRI Mark 1 receiver, which is now in final stages of fabrication
- Experimental testing of the impact of texturing the absorber surface, using 3D printed Inconel samples
- Durability testing of advanced absorber coatings, in partnership with John Cockerill
- Static exposure testing of Inconel 740H samples in sodium at 750°C for up to 500 hrs, and post test analysis

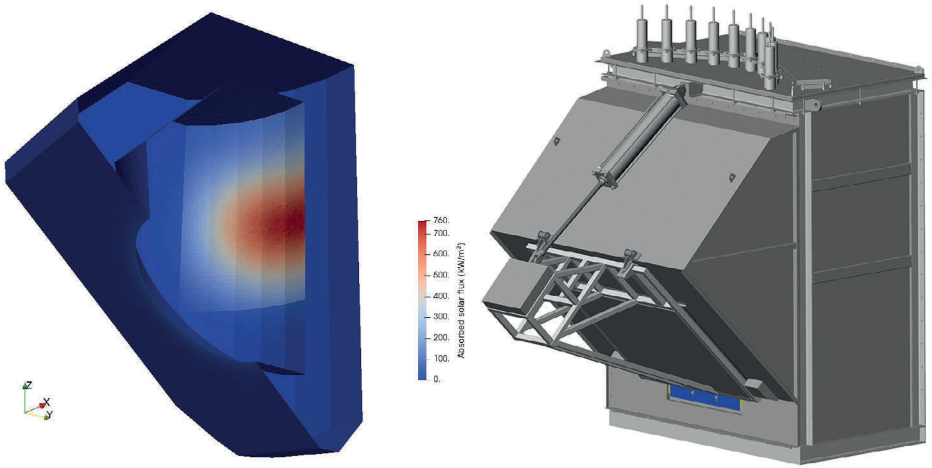


Gen3 Liquid Pathway project sodium/salt system configuration. Source: NREL

Key Challenges

While ASTRI believes that the benefits of sodium receivers outweigh the disadvantages, sodium's reactivity is an issue that has limited its global acceptance. This is why safe, successful demonstration of the operation of a sodium receiver at high temperature is essential, and the key focus within ASTRI. In 2022, the Mark 1 prototype sodium receiver will be tested on-sun at CSIRO Newcastle, at temperatures up to 650°C. Higher temperatures might also be explored once the core test program has been completed

ANU sodium laboratory, during testing of a energy storage module from partner Graphite Energy



| ASTRI Mark 1 sodium receiver, showing the predicted flux map (left) and the enclosure design (right)

| Prototype sodium receiver, during fabrication. This receiver will be tested on-sun at CSIRO Newcastle in 2022

Key Opportunities

Sodium receivers offer a cost-effective solution for current and future CSP systems and would allow operation at higher temperatures than present. Technoeconomic assessment through the Gen3 Liquid Pathway project indicated LCOE of USD $58/MWh for the configuration proposed. Further cost reduction potential has been identified with integration with alternative, but lower TRL, thermal storage technologies.

An important contribution of this project has been increasing awareness and knowledge in Australia around the use of sodium as a heat transfer fluid at high temperature, including via the development and operation of experimental test facilities. Sodium is an excellent heat transfer fluid for collecting heat at the solar receiver, but also for delivering heat at high temperature into the heart of industrial processes. This process heat application is a key opportunity for sodium-based systems in future.

Key learnings

By directly comparing a sodium and a chloride salt solar receiver in the Gen3 CSP program, we learnt that the sodium option results in a much smaller, lower cost receiver with excellent performance characteristics. However, the resulting system now has two fluid circuits, with sodium in the receiver and chloride salt in the thermal storage, and feedback from the DoE through the Gen3 CSP project was that the complexity of this configuration, with two fluids, was a concern. ASTRI has supported the development of several alternative thermal storage technologies that can be coupled to a sodium receiver at high temperature, without the need for a second fluid circuit. Another key learning was that data regarding the compatibility of sodium with containment materials, particularly high-nickel alloys, was scarce at the high temperatures targeted in the project and that there is a need for more testing in this area.

Commercialisation pathways

Sodium technology has an advantage compared to some next-generation CSP technology (e.g. gas and particle pathways) as it leverages knowledge gained over decades, and an extensive list of suppliers and developers in CSP and nuclear industries. This market presence will shorten the timeline to commercial deployment.

A potential barrier to commercial uptake are perceived safety risks associated with sodium. It is necessary to educate bank engineers and the public about sodium as a safe technology, noting that in the Gen3 Liquids salt versus sodium down-selection, the clear view of the TAC was that it would be feasible and important to do so.

Commercial interest in sodium CSP pathways appears to be building. Amongst the CSP technology developers, Vast Solar has been a champion for sodium over many years. Both John Cockerill and Nooter/Eriksen have some sodium receiver background and were active and interested participants in the Gen3 Liquids project. TerraPower's recently announced Natrium nuclear reactor will use sodium combined with molten salt storage.

Project 1.4: 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 material (i.e. particles) also becomes the storage medium.

This project will develop a multi-stage falling particle receiver designed for operation at high temperature (>800°C) and high efficiency (~90%), to be tested on-site at CSIRO Newcastle.

| Solar Research Facility Newcastle – CSIRO

Under this project ASTRI will also develop 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 project 1.7 (continuation of P1.4 Particle Receiver Project from April, 2021) aims to demonstrate on-sun operation of multi-stage falling particle receiver and integrated sub-components. The project will also provide performance analysis and simulated estimation of material degradation.

Achievements this Year

Achievements this year were drawn from a number of areas of the project.

- Particle Receiver
  - Installation/integration of 700kWt multi-stage particle receiver and sub-systems has been completed in CSIRO solar field in Newcastle.
  - Commissioning of the functionalities of individual components and the entire test system has also been successfully completed.
  - On-sun operation of the test system started with producing test data and accruing operating know-hows/experiences.
- Particle heat exchanger
  - Fabrication of 500kWt particle-water heat exchanger (cooler) embedding the newly-developed design concept (patent pending) has been completed. The cooler is currently under indoor flow test before being installed to the test system.
- Modelling:
  - Advective heat loss from a cavity particle receiver has been investigated by CFD-DPM simulation using high-performance computing. The simulation results has been used for performance estimation of multi-stage falling particle receiver.
  - Erosion of receiver material caused by particles has been analysed by DEM simulation. The simulation result could provide annual rate of material erosion.
- DOE Gen3 Collaboration (G3P3 project, Sandia National Laboratory (SNL) - led particle pathway project)
  - Final report for the collaboration activity has been provided to SNL for DOE's decision making.
  - Particle pathway has been finally chosen by DOE as Gen3 CSP technology for demonstration.
- Final report for P1.4
  - Final reports for P1.4 (from CSIRO, UniA and ANU) has been submitted, reviewed and approved by ASTRI management.
- Continuation project (P1.7)
  - Continuation project which is mainly focusing on on-sun test of particle receiver system has been approved to be undertaken by CSIRO.

Key Challenges

Since the particle receiver system is the first of its kind to the research team, a number of unexpected engineering and operating issues (such as particle flow issue caused by water leak or humidity) were encountered and had to be resolved while installing and commissioning the test system.

Though the receiver performance study has progressed significantly, accurate estimation of various heat losses is still challenging, as there are extremely limited experiences and studies available in the particle technology area. ASTRI expects on-sun operation will provide a number of the answers we require.

Material durability issue (especially related to erosion and attrition) also needs to be closely investigated and clarified. Current project (P1.7) carried theoretical analysis leveraging US research groups' experimental study on material degradation. Contract variation for further study/inspection on material degradation in conjunction with additional on-sun test has been negotiated with ASTRI.

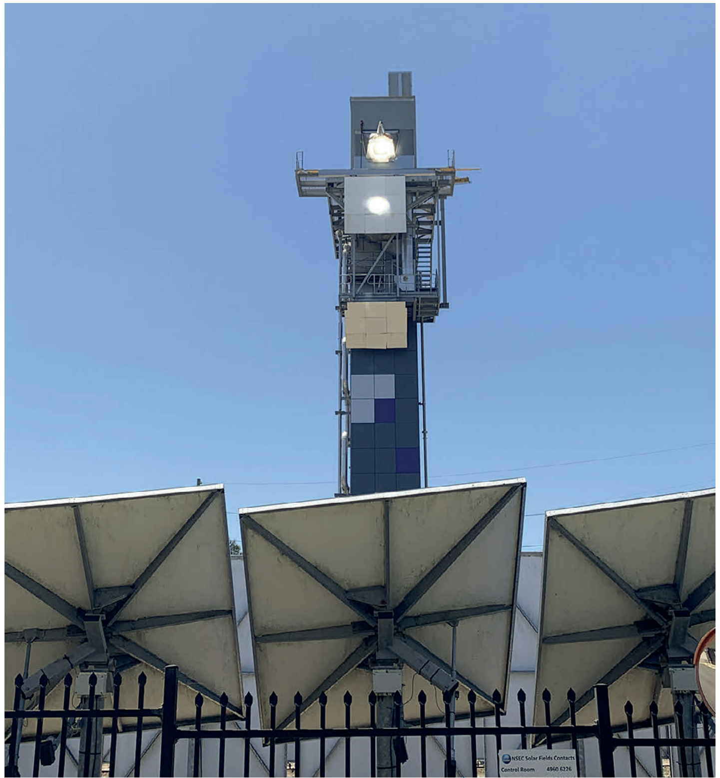
Opportunities

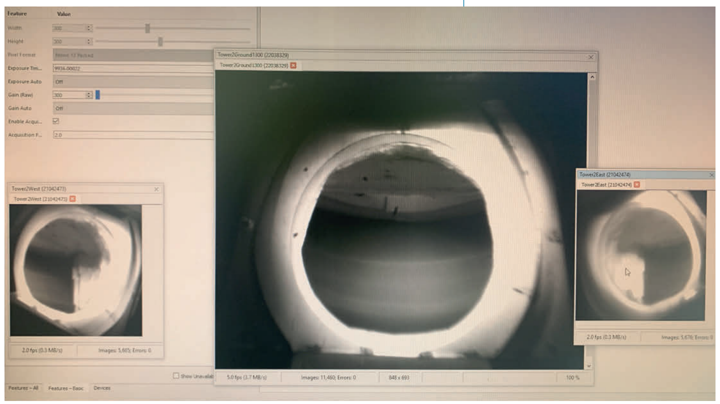
A series of discussions (with a potential industry partner) on the commercialisation of particle receiver technology have actively progressed.

Opportunity of a continuous collaboration with SNL for Gen3 G3P3 demonstration project is open and awaiting SNL's decision.

Research team has been exploring the use of particle receivers for high temperature clean hydrogen production (e.g. via high temperature electrolysis), for other applications including additive heat for high temperature industrial process heat applications and for providing cost-effective "thermal battery" technology, where excess electricity from periods of peak PV and wind is used for charging.

Research fund for a collaboration project with KIER (Korean Institute of Energy Research) on a solar thermal particle system to assist (heat and power) high-temperature electrolysis has recently been awarded by the NST-CSIRO collaboration program.





Particle receiver test system under on-sun operation (top left), screen capture of receiver monitoring system while on-sun operation (bottom left) and 500kWt particle-water heat exchanger (cooler) fabricated and ready for indoor flow test.

PROGRAM 2: THERMAL STORAGE

Induction Heating

Project 2.1: High Temperature Thermal Storage

Thermal Energy Storage (TES) is an important component of solar thermal systems, particularly high temperature CSP and CST systems. Although these solar thermal systems don't require TES to operate, without it these systems would find it impossible to compete with the cost and capacity of other forms of energy generation like PV and wind.

The project aims to technically and economically de-risk practical solutions for high temperature thermal energy storage. It does this by better understanding storage materials, designing and developing appropriate storage systems for these materials, improving numerical models and demonstrating the developed technologies. Several potential high temperature TES solutions are being explored and benchmarked internationally.

Achievements this Year

There were many key achievements across assessments, design, construction and international collaboration.

- Completing experimental characterisation of key candidate storage materials (melting point, latent heat, heat capacity, thermal stability, density and thermal expansion) and alloy degradation when containing candidate storage materials.
- Developing methodologies to design and assess the exergy and energy performance of thermal storage systems.
- Carrying out thermo-mechanical analysis on small-scale and large-scale designs of PCM based TES.
- Finalising thermo-mechanical analysis of lab scale storage system (for testing PCM storage with liquid sodium).
- Designing and constructing PCM thermal enhancement experimental test rig and testing several thermal enhancement methods.
- Completing exergy, energy and economic assessment of different promising storage systems including two-tank molten salt and liquid sodium, graphite, cascade PCM and hybrid graphite-PCM.
- Collaboration with national and international commercial companies to develop high temperature storage technologies (including CCT Energy Storage, MGA Thermal, Furnace Engineering and Buhler Group).

Key Challenges

As the temperature of solar thermal systems increase, so too can the potential cost of TES solutions. This is why ASTRI focuses its efforts on TES solutions that use low cost materials, have higher energy densities, reduce TES volume requirement, are contained and operate in inexpensive and efficient storage systems; and achieve improved cost performance outcomes.

Another challenge included access to a facility to demonstrate sodium-driven storage system(s) at >700°C for model validation.

Scalable demonstration and operational data increases external investor certainty and can translate to improved understanding of the capabilities of high temperature thermal energy storage. The team has processes in place to overcome these risks.

Opportunities

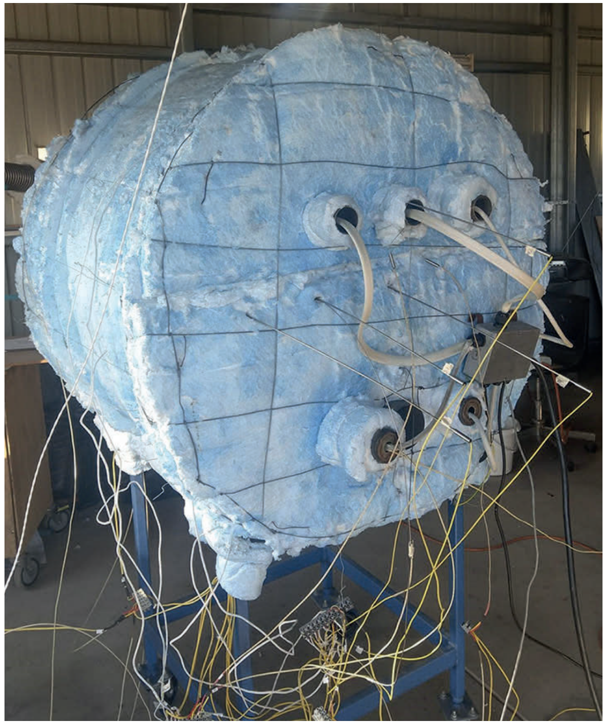
There has been recent interest in developing TES technologies that are able to use solar thermal heat and electrical input to increase storage density – particularly at a lower material and capital cost (a hybrid CSP system is one example). There is also growing interest in TES for non-solar thermal applications including delivering process heat, providing combined heat and power, or as a thermal battery (with a sCO_2 or steam turbine) utilising electricity from variable renewable sources.

At present, approximately 70% of the 95 CSP systems operating worldwide include TES. When considering new and under construction CSP systems, almost all include TES. In the future we will see higher temperature TES systems with lower cost materials, high energy density, high material durability (low degradation), more flexible charging and discharging storage systems, lower operational and maintenance costs and lower volume/infrastructure requirements.

In addition to the growing CSP market, there will likely be significant growth in TES being utilised within existing

A completed PCM-TES vessel for testing with a liquid sodium heat transfer fluid at greater than 700°C

A commercial scale, high temperature TES prototype for gas displacement



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

infrastructure to replace coal and gas boilers for power generation and process heat.

Key Learnings

- The higher the temperature the more critical material compatibility issues. The related cost impact can be exponentially higher as a range of new materials and processes may be required, all having higher initial costs. Operating at lower temperatures can potentially deliver a quicker commercially viable solution.
- PCM TES can effectively deliver sufficient storage at effective techno-economic performance levels, on the basis that material compatibility issues are resolvable.
- Thermo-mechanical design represents the major technical challenge to overcome for PCM TES. PCM stability and high thermo- hydraulic performance were found to be achievable.
- Comparison of storage technologies are challenging as ultimately several uncertainties are generated when operating at the limits of existing materials, which can offset thermodynamic efficiency gains.
- It is necessary to apply a methodology of dynamic simulation of multiple charging-discharging cycles and size the TES system based on the performance when equilibrium conditions are reached. A system-level assessment is critical to determine the boundary conditions to achieve the economic viability of CSP technology with a TES system.

Commercialisation pathways

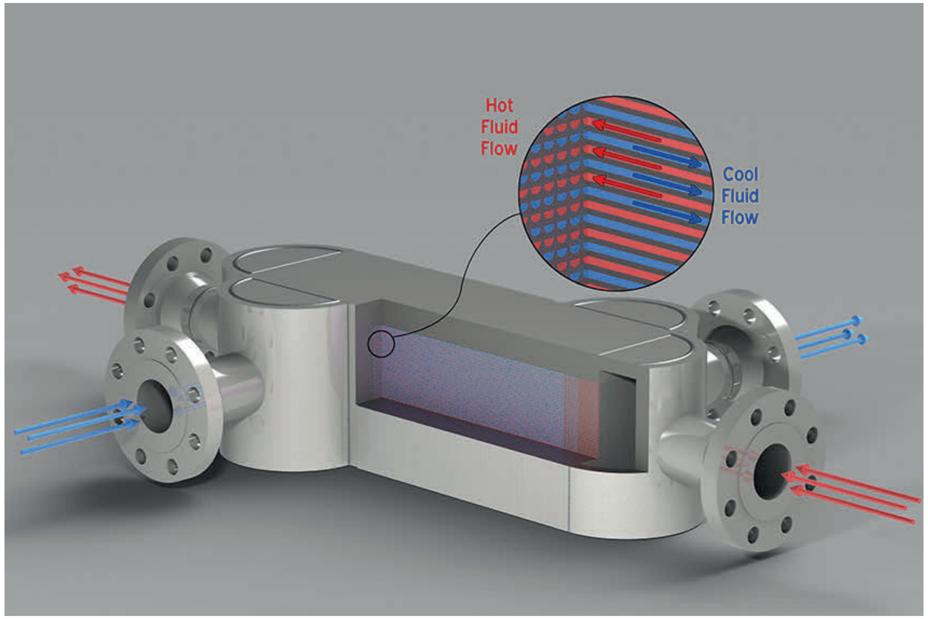
Potential opportunities exist with direct electric charging of TES for decarbonisation of process heat and district heating, where space efficiency is important. Discussions with potential commercial partners nationally and overseas are underway. The facilities developed at UniSA are planned to be used for pilot plant testing with these potential partners.

Project 2.2: Sodium to sCO_2 Heat Exchanger Development

The heat exchanger in a high temperature concentrating solar thermal system is critical, as it allows separation between the heat transfer fluid (HTF) and the working fluid for the power generation unit.

As next generation solar thermal systems with higher temperature HTFs and high-pressure working fluids begin to be used simultaneously, new designs of heat exchangers will be required to reliably, safely, efficiently and cost-effectively operate under these challenging conditions. These heat exchangers may also be required to operate using different fluids.

By working with leading heat exchanger companies, ASTRI will be able to design and optimise an appropriate heat exchanger without needing to fabricate it ourselves. In particular, the project will assess the technical merits of utilising a relatively new configuration of heat exchanger – the Printed Circuit Heat Exchanger (PCHE), to determine if manufacturing compact heat exchangers in Australia will be a cheaper option in the near future.



| Schematic diagram of a Printed Circuit Heat Exchanger (PCHE). Image: Vacuum Process Engineering

Achievements this Year

This year was the final year of the project, with much of the work focussed on wrapping up key milestones. Achievements include:

- Conducting detailed discussions with Argonne National Laboratory on sodium and sCO_2 interaction under ASTRI conditions for HAZOP minimisation.
- Completed CFD modelling of a PCHE under ASTRI conditions. This included:
  - Verifying the accuracy of the model using up-to-date experimental data
  - Conducted a parametric analysis to determine the design configuration with highest thermo-hydraulic performance
  - Reported on the outcome of the optimisation of the PCHE for conditions relevant to ASTRI
- Completed the development of an accelerated testing regime for lab-scale PCHE units to assess thermo-mechanical performance under transient conditions relevant to ASTRI
- Holding productive discussions with the University of Wisconsin (Madison) regarding ASTRI's PCHE testing and opportunities for collaborating on research.
- Undertook a rigorous work, health and safety risk assessment to conduct an experiment to test the effects of high temperature Na interacting with CO_2;
  - Developed a new experimental setup to address potential safety considerations raised by key stakeholders

Challenges

The challenges for this project are both technical and market based.

Technical challenges include the requirement to withstand the significant cycling from idle to full thermal/pressure load (so the power block is fully dispatchable and can maximise revenue), and the large difference in pressure (and associated high temperature gradients), across the heat exchanger from sodium to sCO_2.

The fact that these technical challenges are on the cutting edge of research (and even beyond it in some instances) makes it critical to ensure that a suitable compact heat exchanger can be made to ASTRI requirements.

To continue this push, ASTRI will increase its engagement with major international research institutions and technology developers and explore the use of higher temperature sodium/sCO_2 heat exchangers for other applications.

Commercially, there is currently a lack of understanding about the performance of PCHEs at ASTRI requirements, so the project team has been working to clearly explain the focus of the project to industry. Some PCHE manufacturers have been unwilling to engage to date; solutions to this challenge are being pursued by the ASTRI Project Team.

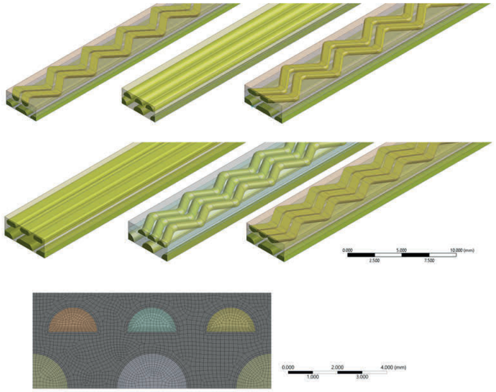
Opportunities

PCHEs operating at higher temperature and/or pressure offer numerous opportunities including – but not limited to – enabling more efficient power systems, lower operational costs than their alternatives, and their potential for other applications, including heat for renewable solar fuels (such as hydrogen) or for high temperature industrial process heat applications.

Cutting edge and future manufacturing methods will eventually push down the price of compact heat exchangers operating under the ASTRI requirements, meaning that current investigations into heat exchangers will assist in reducing the LCOE in future.

Commercialisation pathways

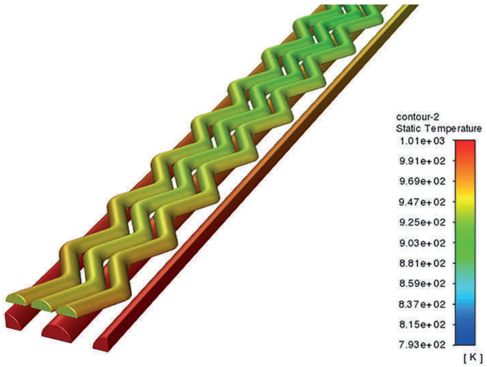
The project's commercialisation strategy will see ASTRI become a service provider to the PCHE (Printed Circuit Heat Exchanger) industry, enabling a PCHE to be developed for ASTRI's needs.



An example of computational models of 6 different channel configurations for sodium/sCO_2.

Top two rows: Geometry of the computational PCHE modules.

Bottom: A mesh cross section showing circular sodium channels with semicircular sCO_2. channels.



An example of a temperature contour computed through modelling of a PCHE channel under conditions relevant to ASTRI. In this case, circular channels are used for the sodium, and semicircular channels are used for the sCO_2.

Noor Ouarzazate – MASEN

Project 2.3: Storage Technology Options

Project 2.4: TES Integration and Evaluation

Thermal Energy Storage (TES) can significantly increase the capacity of high temperature solar thermal systems. This project has aims to develop, design and assess TES technologies so that high temperature solar thermal systems become commercially attractive.

After completing a successful scoping study on various TES solutions, including a review of the many high-temperature TES options (sensible, latent heat, thermo-chemical) that could potentially meet ASTRI's cost and performance criteria, ASTRI examined how the TES solution impacted the entire system in terms of cost and risk.

Now, the project is focused on objectively demonstrating TES in a real world environment, so industry can see its benefits to TES systems overall.

Achievements this Year

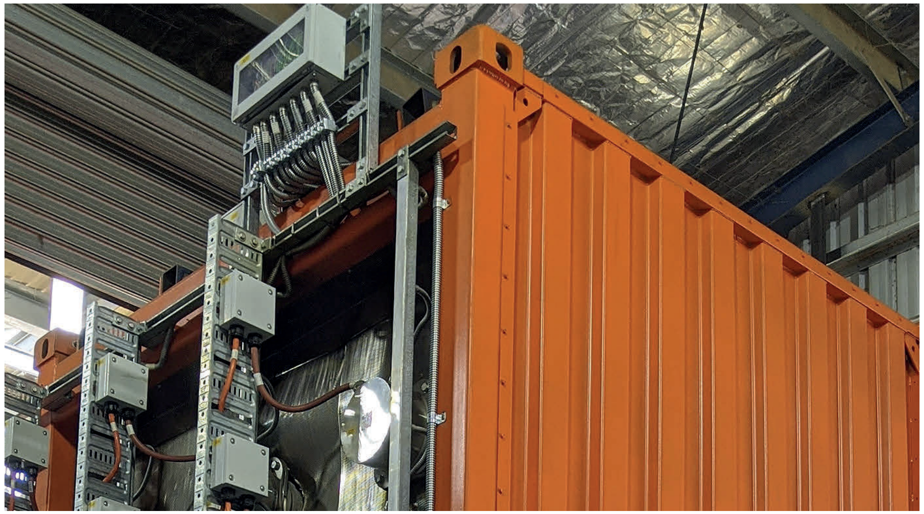
In 2021, a selection of the project's achievements include:

- Completing short-term compatibility testing of MgO samples (as the preferred filler material in a packed-bed storage) in liquid sodium at high temperature.
- Completing extended thermal testing (>1000 hours) of candidate Miscibility Gap Alloys (MGA) composite materials.
- Designing and manufacturing a sensible packed-bed storage Figure 9a) and a latent-heat MGA storage (Figure 9b) for testing on the small-scale sodium flow loop in ANU.
- Demonstrating calcination reaction and calcination-carbonation cycles of a packed-bed solar thermochemical reactor using the high-flux solar simulator in ANU.
- Developing methodologies to estimate the potential cost of TES solutions for ASTRI's liquid sodium solar thermal systems.
- Developing process flow and interface specifications for TES integration and demonstration at pilot-scale on the CSIRO sodium loop.
- Undertaking preliminary review of prospective end-users of energy from TES systems in Australia.
- Continued engagement with domestic TES developers (MGA Thermal, Graphite Energy).

Key Challenges

While 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 the following challenges:

- The TES materials need to be durable and stable at high temperatures over an extended life.



| Graphite Thermal Energy Storage (TES) Unit – Graphite Energy

| Modular Energy Storage Blocks – MGA Thermal

- The TES systems need to be relatively low cost, which is the key differentiator between thermal and battery storage.
- The TES systems need to be easy to scale up and simple to operate.
- There is a lack of real life demonstration of high temperature TES systems.

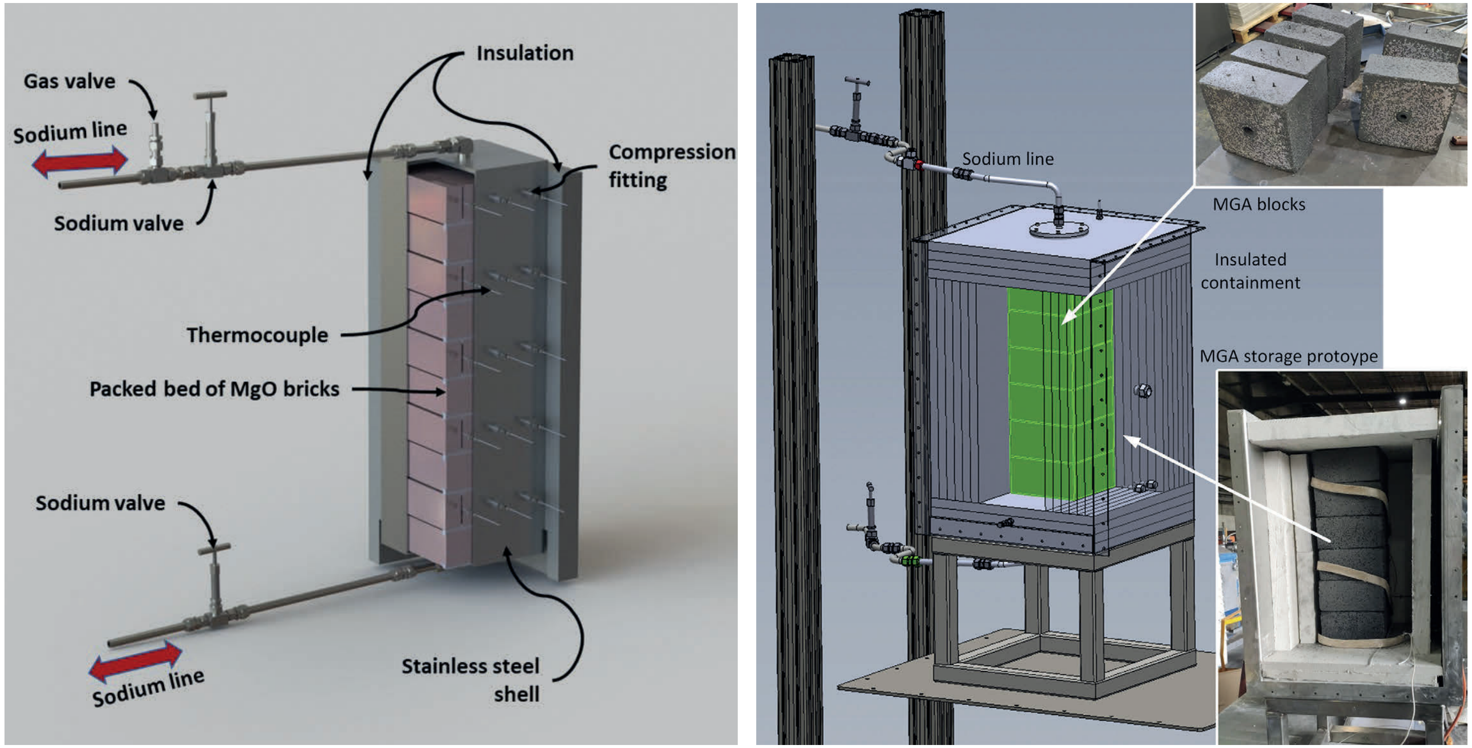
Opportunities

Energy storage (of heat or electricity) has become a major focus of decarbonising industry and there are strong adjacent markets for energy storage. Each provides many market opportunities for thermal energy storage outside of solar thermal systems.

Electric-charged TES from renewable energy sources like PV and wind are an emerging market opportunity for longer duration energy storage – for example, they could be used to provide dispatchable renewable electricity generation, 24/7 heat for industrial processes and improve the capacity of future hydrogen generation.

Key learnings

- A stable experimental setup avoiding past issues (i.e. sodium loss, gasket damage) has been established, which allows a safe operation for long exposure sodium compatibility testing of filler materials. Techniques for post-exposure analyses have also been learned and developed.



| **(Left)** Section view of the packed-bed storage prototype **(Right)** MGA storage prototype

- Cascaded latent heat TES systems using thermally conductive MGA composites potentially offer an effective solution for balancing between cost, energy density, response time and optimal energy utilisation at a suitable temperature range.
- Despite operational limitations of the existing solar thermochemical reactor prototype, the project has provided some valuable insights into the challenges involved in designing and operating high-temperature thermochemical reactors for energy storage via calcium looping.

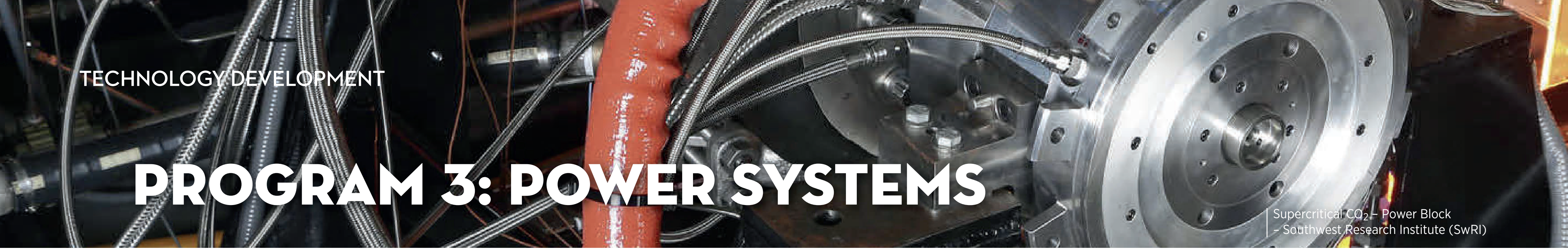
Commercialisation pathways

The commercialisation strategy is to understand prospective end-users of energy from TES systems and create awareness and interest in the use of TES to store renewable energy.

Successful demonstration is vital, and thus the project plan includes a pathway from lab-scale prototype testing and then integration at CSIRO at pilot scale.

The project team also aims to have collaboration/commercialisation arrangements established with industry.

PROGRAM 3: POWER SYSTEMS



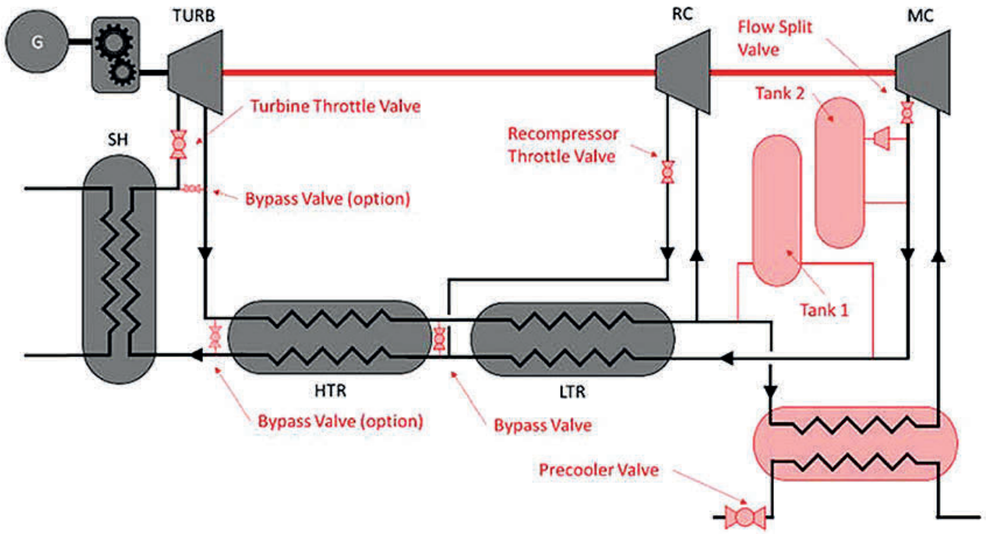
Supercritical CO_2 – Power Block – Southwest Research Institute (SwRI)

Project 3.4: Advanced power cycles

This project is concerned with advanced power cycles, and in particular cycles that use supercritical CO_2 as the working fluid. Prior to 2021 ASTRI, through the University of Queensland, had been developing radial expander technology for use with a CSP front end. This particular project has been more concerned with modelling of those cycles, particularly at conditions away from steady state design point.

The project examined:

- Part-load and off-design simulation of the ASTRI Power Block integrated into the P6 ASTRI system models
- ASTRI Power Block transient-response models using ASPEN Plus Dynamics first and then Open Modelica
- Operational control strategies for the ASTRI Power Block



Achievements

A 10 MWe s-CO_2 RCBC was simulated using an open-source Modelica library called Supercritical CO_2 Power block Emulator (SCOPE), which is designed and developed to numerically investigate the part-load performance and dynamic behaviour of the s-CO_2 RCBC. For part-load simulation, 256 combinations of different HTF inlet temperatures, turbine inlet mass flow rates, split ratio and ambient temperatures were simulated to generate the off-design performance map.

The generated performance map, which can be queried as a look-up table to provide key power block performance parameters such as efficiency and power output, is essential to enable the power block annual simulation efficiently and accurately under different external environmental situations.

The transient behaviour of sCO_2 power blocks: a commercial package was simulated using Aspen Plus Dynamics, and a general-purpose simulation language OpenModelica. Two common cases, i.e. flow-driven and pressure driven scenarios were simulated to investigate the power block response in terms of turbomachinery shaft speed, power consumption and power generation. Both tools show that the dispatch control of a supercritical CO_2 power block is not as easy as varying one or two parameters. Merely modulating the turbine inlet flow rate or turbine inlet pressure cannot produce the net power output change to meet the load requirement of the power grid. Appropriate control strategies should be developed first and then studied using either of the two tools presented in this section (but preferably SCOPE because of its flexibility) as the transient simulation tool to generate operating procedures for dispatchable s-CO_2 RCBC power blocks of the future.

The Control System for the ASTRIPB sCO_2 Power Block is intended to provide coordinated control, via a limited set of actuators, to ensure desirable operation characteristics of the Power Block in operation. Two scenarios were considered:

- the “infinite bus” case, representing a scenario in which the Power Block is connected to a large grid, and
- the “isolated load” case, where the Power Block output represents a large fraction of the local generation.

Key Challenges

Due to the fact that sCO_2 power block technology is still emerging, there was little in the way of practical or experimental evidence to support the validity of the modelling results. Nonetheless the modelling is based on well-understood classical turbomachinery design fundamentals.

Opportunities

This project provided the platform for continued work in order to better understand how sCO_2 turbine technology would perform, and be controlled, in a real-world situation. Ongoing work should include:

- Implementation of proposed control scheme in OpenModelica transient simulation.
- Comparison of similarly sized sCO_2 RCBC, Steam Rankine Cycle (SRC, boiler-following), and Supercritical Steam Cycle (SCC, modified sliding pressure) in terms of contributing inertia, Primary Frequency Response (PFR), and Secondary Frequency Response.
- Investigation of system dynamics and control schemes where using direct air cooling with sCO_2 RCBC, instead of water cooling.

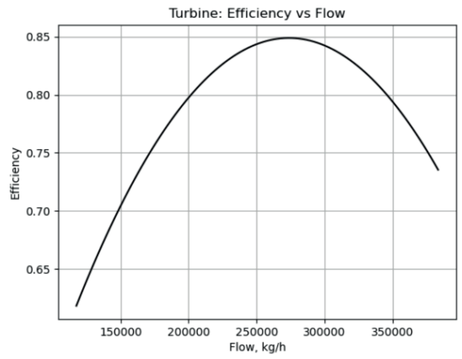
Key Learnings

It is a complex process to control a power block in an optimised manner when it is part of a grid, whether large or small. The first assumption is that the turbine is being fed by thermal energy storage with suitable discharge rates, thus taking the feed source variable out of the equation. However the turbine still needs to respond to external signals and demands from the grid system or grid operator. The operator of the power block has a small number of options to control output, such as flow rate or pressure, and most likely requires a combination of these.

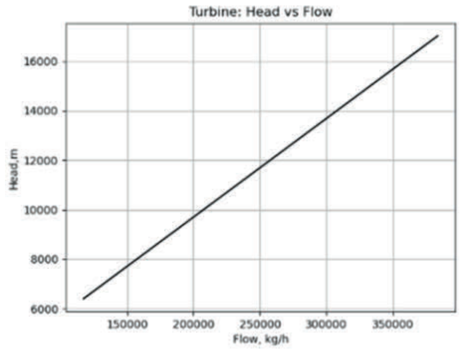
The dispatch control of a sCO_2 power block will require independent control of turbine inlet temperature, compressor inlet temperature, and the flow split ratio. The reference values for these controlled variables may be modulated to respond to changing load and ambient conditions.

Commercialisation Pathways

The models were developed on an open-source platform and thus the models per se are not anticipated to result in sale of commercial licenses. However the data generated, and subsequent analysis is expected to be of value to those using or anticipating to use sCO_2 power blocks.



| Transient behaviour: Efficiency vs Flow



| Transient behaviour: Head pressure vs Flow

| Jemalong – Vast Solar.

PROGRAM 4: PROCESS HEAT

| Industrial Process Heat

Project 4.1: Integration of Solar Thermal Hydrogen and Oxygen Production via the HyS Cycle into Copper Production

This project aims to assess the potential for the integrating the hybrid sulphur cycle HyS and copper processing to co-product hydrogen and oxygen in order to lower costs for remote high temperature industrial processes.

Additionally, it undertakes preliminary investigations of the potential of a "Generation II" solar thermal reactor within the HyS process. The solar bubble receiver has been demonstrated at TRL-3 at the UoA (potentially replacing the DLR's current reactor), offering addition cost-lowering potential through its ability to lower reaction temperatures and increase heat transfer.

The project has been undertaken in collaboration with DLR, Greenway Energy and BHP to provide strong leverage and ensure industrial relevance.

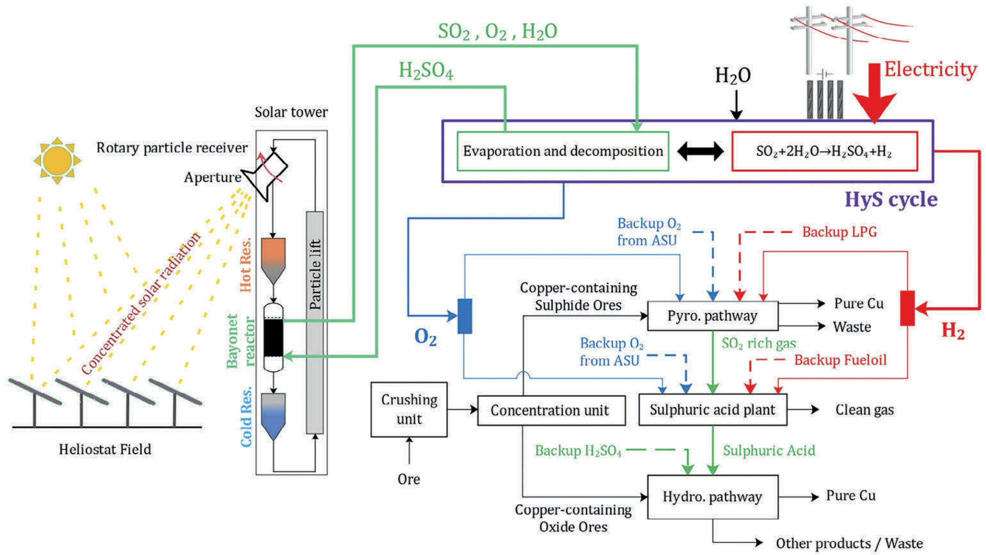
Achievements this Year

The project has delivered on all of its milestones, despite the limitations imposed by Covid-19. Overall, the results from the program are very encouraging, and have come partly due to close collaboration, coordinated research activities and shared modelling and fortnightly meetings with DLR and GreenWay Energy, in addition to three meetings per year with BHP (for the Technoeconomic analysis - TEA work).

The project's strategy was also enhanced by funding (from DLR) of a post-doctoral researcher to this project. This has allowed additional input on simulation of the HyS cycle. The team has also refined the bubbling reactor aspect of the program to minimise the impact of Covid-19 and maximise alignment with other ASTRI programs. The solar bubble reactor technology will now be configured so it can be coupled with either ASTRI's or DLR's particle receiver and storage systems.

Other key achievements include:

- Demonstration of ASTRI's unique capability to identify and model high-value opportunities where CST has potential to make economic sense in complex industrial processes.
- Demonstration of novel IP with strong potential for solar processes, through our significant advances in the development of the novel reactor technology for CST using bubbling reactants within molten catalysts.
- Confirmation that the HyS cycle is economically attractive compared to fossil-fuel based alternatives. We estimate that the production cost with the (TRL-5 based) carbon neutral HyS cycle will be competitive with current fossil-fuel-based copper production in Olympic Dam without a carbon-price. Furthermore, the approach becomes increasingly attractive where any excess H_2 is 'sold' (or valued) for an assumed price of AUD 4/kg.
- Confirmation that the (TRL-5 based) HyS cycle is economically competitive with electrolysis/battery (both polymer electrolyte membrane electrolyser (PEM)/battery or alkaline electrolyser (AES)/battery). This is largely because it requires



Schematic representation of the proposed process configuration for the integration of the hybrid sulphur cycle HyS cycle with the copper production plant less than 25% of the electricity of expensive conventional electrolysis, while the rest of required energy is supplied from solar thermal which is cheaper to store. This HyS cycle is also slightly cheaper than AES combined with pumped hydro, although we consider that pumped hydro is unlikely to be available at economic scale in close proximity of the Olympic Dam.

- Determining that further cost savings will be possible if the next generation bubble receiver is successful: we estimate this would bring a further 10% benefit.

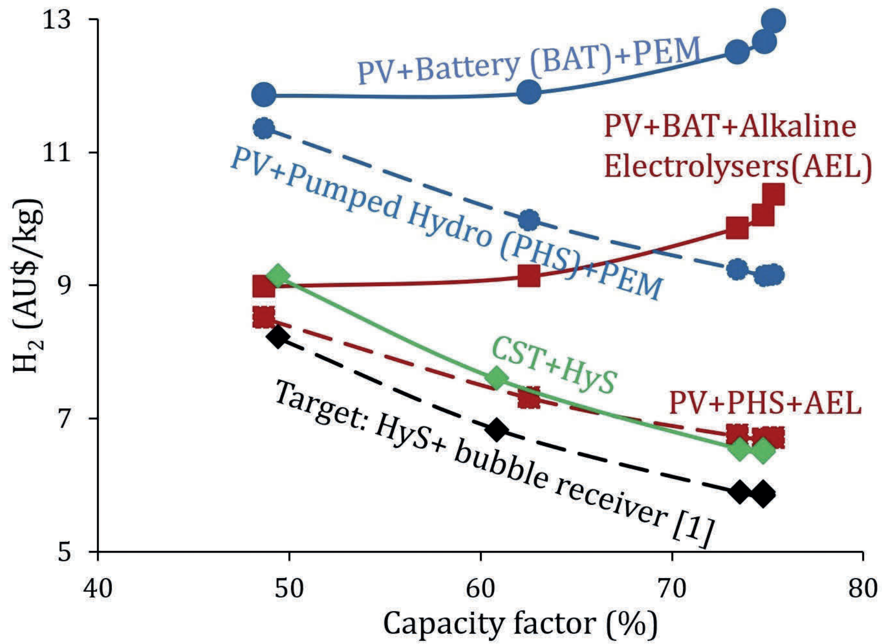
Key Challenges

The key challenges of the project are as follows:

- **High temperature CST particle technology:** The project depends on the development of a reliable high temperature solar thermal technology with storage and heat exchanger. However, these risks are being mitigated both by the ASTRI and G3-P3 programs and by the parallel DLR centrifugal receiver development program.
- **Molten metal reactor technology:** The key challenges to the development of a reliable molten-metal reactor technology are containment of molten metal and thermal management (heating and cooling the reactants and preventing solidification). We are mitigating the risk of containment by selecting a reactor with a relatively low reaction temperature of ~650°C, which allows the use of well-established metals for containment. We are also developing a novel patented technology that will allow thermal management to avoid solidification challenges by using circulation of gases for the heat transfer.
- **Integration into an industrial process:** The use of CST to supply H_2 and O_2 bypasses the significant risks that would otherwise be generated in seeking to directly couple heat into an industrial process.
- **Upscaling risks:** The risks of upscaling the molten reactor technology include the lack of data and the need for ongoing funding. These risks are being mitigated by seeking funding from multiple sources.

Opportunities

The ASTRI program has demonstrated that the HyS cycle has strong potential for remote high temperature industrial processes. The technical capabilities, collaborations and know-how developed through this project offer potential for ASTRI to contribute significantly to decarbonising this sector in Australia, including by expanding our assessment to other mineral processes. This will pave way to further leverage these projects from HILT CRC.



Comparison of the estimated production cost of H_2 (AU$/kg) tailored to Olympic Dam copper

Both DLR and Greenway Energy will continue to partner in the next stage of this project. We are also seeking cash/in-kind contribution from BLP, Oz Mineral and TEK7, as technology providers. The DLR funded post-doc (tasked with further developing the HyS cycle's integration to copper processing) offers the potential to further decrease the costs. Additionally, DLR and UoA are also seeking external funding to further support this program.

Decarbonising Steelmaking

Project 4.2: Identifying Pathways to Commercial Application of Beam-Down Particle Technology in Mining and Off-Grid Applications

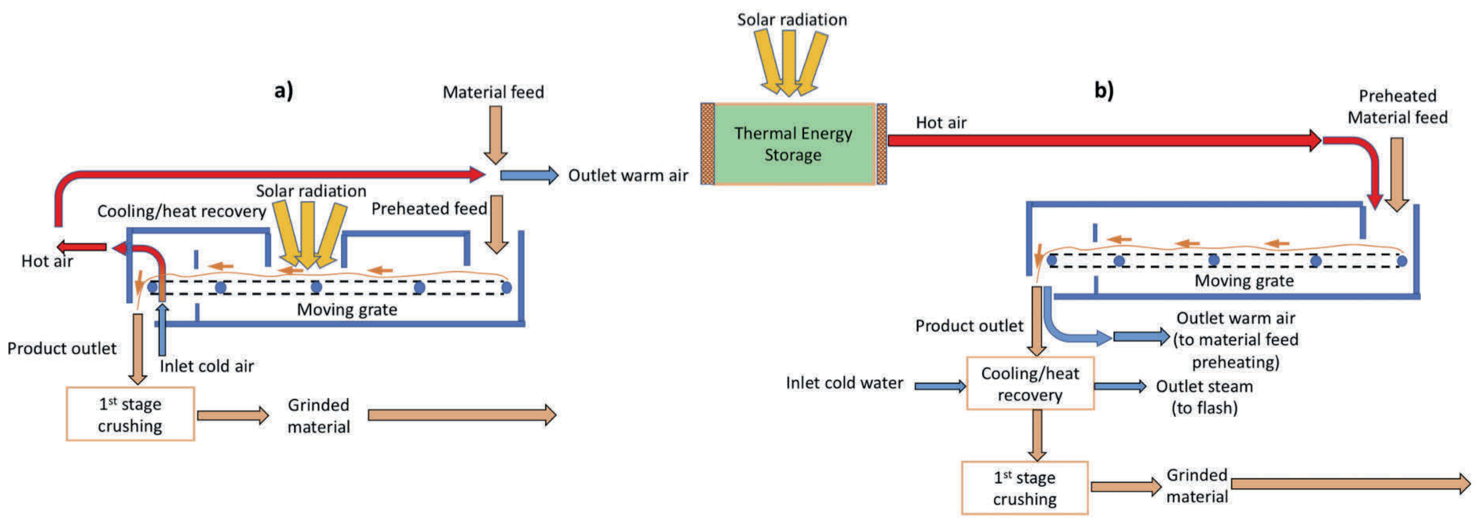
The primary aim of this project is to investigate the value proposition of beam-down particle technologies for both mining/mineral and off grid applications. In particular, the project assesses a novel process of thermal pre-treatment of particulate material under development at the University of Adelaide. This process aims to reduce grinding energy in comminution circuits that use concentrated solar thermal (CST) radiation as their heating source.

The project was undertaken in collaboration with Magaldi Power (main partner) and BHP (as external partner). Both partnerships provided strong leverage and ensure industry relevance.

Achievements this Year

The project has delivered on all of its milestones, despite the limitations imposed by Covid-19. Achievements have included the following:

- **Value proposition confirmed and preferred route identified:** The team has proven that the novel thermal ore pre-treatment by concentrated radiation leads to a reduction of the required crushing energy of up to 40% without altering the mineral properties of the valuable minerals. Nevertheless, only the directly irradiated route was found to be efficient in providing this reduction, requiring fast heating rates. The use of slow heating rates (convective heating) was found to be inefficient in reducing the crushing energy for short exposure times (order of seconds) or energetically inefficient for longer times (10-20 min). This implies that solar thermal energy would need to be applied directly, rather than via thermal storage. The major benefit of the proposed treatment was found to be for hard ores rather than soft ones.
- **Energetically attractive and synergistic with other energy sources (potential for hybridisation):** We have proven that, for the directly irradiated route, short exposure times are sufficient to provide up to 40% crushing energy reduction. This is a step-change of at least one order of magnitude in terms of energy required for the heat treatment in comparison with existing pre-heating methods (generally requiring heating time of 1-2 hours), which makes the process energetically attractive. That is, the net energy required for heating is lower than the energy saved in the crushing unit, of up to 40% (after accounting for heat recovery). Similar performance can be achieved utilising other radiative energy sources (e.g natural gas) featuring similar heating rates and fluxes to that of the simulated CSR. This indicates a strong potential for direct hybridisation.
- **Optical analysis:** the team developed a unique optical beam down system able to irradiate a specific portion of a conveyor to meet the specification of the thermal pre-treatment process. In particular, the team demonstrated that a very high pick flux is achievable on the almost entire surface of the receiver. Additionally, with a sufficiently large rim angle, a nominal capacity of 40MWth on the receiver is achievable.



Schematic representation of the proposed a) directly-irradiated and b) indirectly-irradiated beam-down moving grate configurations using for thermal pre-treatment of bulk material to reduce the energy required for the crushing process

Key Challenges

The key challenges identified at the completion of all activities are as follows:

- **Compatibility between scale of beam-down and thermal energy requirement for a large scale mine:** For processes involving minerals such as nickel-iron ores, high volumes are generally treated on a daily basis (500 up to 5000 ton/hr). However, the maximum capacity of a single beam-down tower to date is around 5-10MWth. This means a very large number of beam-down solar belts and associated optical components would be needed to perform the heat pre-treatment. Also, in addition to this challenge, the need to use high flux irradiation in a continuous process (rather than stored thermal energy) would limit the solar contribution to 25%, which constitutes a further barrier to the use of solar thermal for this application.
- **Increased complexity of plant and CAPEX in comparison with non-solar routes:** The technoeconomic analysis of non-solar routes (via combustion) to provide the heat indicates that this thermal pre-treatment solution is more cost-effective and earlier to implement from both a logistic and operation point of view than the solar one, with a very low CAPEX in comparison with CST.

Untreated Ore 1

Treated samples at different temperatures

Influence of the directly irradiated CSR (from solar simulator) on the macro-features of a nickel-based ore (termed Ore 1) for different temperatures.

Opportunities

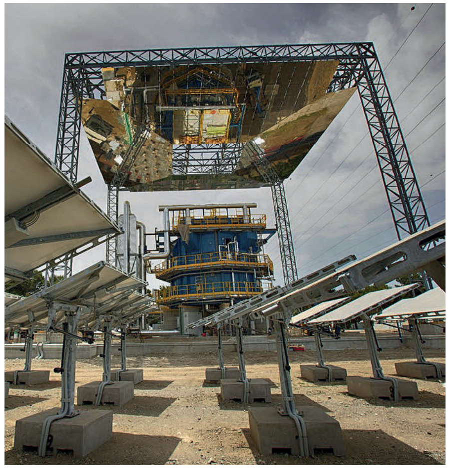
Overall, the ASTRI program has demonstrated the value proposition of a novel thermal comminution process for mining/mineral applications and the technical capabilities, collaborations and know-how developed over this project offer potential for ASTRI to contribute significantly to decarbonising this sector in Australia.

Despite the scale constraints for the use of direct irradiation with high throughput mines, such as those employed in copper and iron-ore, there may be potential for low volume, high value ores.

While directly irradiated solar is unlikely to be key in mining processes needing to treat high volumes of radiant heat on a daily basis, there is an opportunity to assess integrating thermal storage to provide electricity on-demand. This could be more cost-effective and/or efficient than current electricity production methods.

Small-scale, high-value mining processes offer potential to use solar to provide radiant heating. These low volume operations like gold ore processing may still have potential if the value proposition of 50% crushing energy can be confirmed. CST also offers potential as a combined thermal comminution/CO_2 mineral carbonation process in these environments.

Magaldi Power will continue to partner in the next stage of this project, which will aim to assess the impact of solar thermal pre-treatment on mine waste/tailings as a mean to potentially enhance the properties of these materials towards CO_2 capture via mineral carbonation. A major Australian industry partner has also expressed its interests in further assessing the role of the solar route for the combined thermal comminution/CO_2 mineral carbonation process.



Beam Down: Solar Thermo Electric Magaldi (STEM) Plant – Magaldi

Project 4.3: Photocatalytic Hydrogen Production from Water

Photocatalysis is an emerging technology that has the potential to generate storable chemical fuels directly from solar energy. The best-known example is water-splitting to produce H_2 and O_2 from water. This project involves developing a thermo-photocatalytic reactor that can operate under intense illumination and concomitant high temperature, to maximise photocatalytic water-splitting to produce hydrogen and oxygen from water.

Although the intrinsic (quantum) efficiency of the best current photocatalyst is extremely high, approaching 100%, the commercial implementation of photocatalytic water-splitting is currently retarded because the metal-oxide semiconductor can only use the high energy (UV) component of the solar spectrum, which limits the overall solar to hydrogen (STH) efficiency. This low utilisation of the solar spectrum can be overcome by using the visible and IR components of the solar spectrum to heat the reactor to increase the kinetics of the reaction.

Achievements this Year

The project team has demonstrated that the principles of thermo-photocatalysis are sound and have met the agreed milestones in our project plan. Major achievements over the past 12 months have been:

- Demonstrated increased H_2 and O_2 production with increasing UV intensity, up to 150 suns.
- Demonstrated increased H_2 and O_2 production with increasing reactor temperature, up to 120 °C, with concomitant increase in pressure.
- Undertaken longevity testing and characterisation of the photocatalyst under these conditions.
- Resolved issues relating to delamination of the photocatalyst from the substrate.
- Completed an assessment of suitable construction materials for the reactor.
- Completed tests with a facsimilie reactor using a concentrated solar simulator to provide expected relationship between concentration level and temperature.
- Submitted a patent describing the use of a thermo-photocatalytic reactor for water-splitting under concentrated solar conditions.
- Secured continued funding from an industry partner to continue funding the development of the technology for 2.5 years with an option for a further 2 years to demonstrate on-sun.

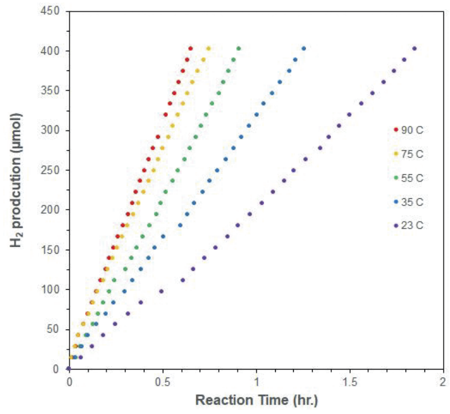
Key Challenges

An observation noted when operating at pressures above 2 bar is the accumulation of gas bubbles between the glass window and the surface of the photocatalyst sheet. This accumulation indicates that although we have shown a linear increase in H_2 (and O_2) production with increasing temperature and light intensity, that the removal and collection of produced gases becomes retarded. A number of reactor modifications were made, such as changing the water depth, to mitigate this but none were fully successful. Consequently, a revised reactor design to allow improved egress of the gaseous products has been constructed and will be used for the next stage of testing using a concentrate solar simulator.

The project to date has involved a reactor that is independently heated (in an oven) and irradiated (with a UV LED array). The next step is to combine the light and heat source from a concentrated solar simulator. We expect that there will be a co-dependence between the light intensity and the temperature of the reactor and so there is likely to be a trade-off to find the optimum conditions.

Opportunities

Photocatalytic water splitting has inherent features that gives it a huge advantage compared to other renewable energy technologies. Its sheer simplicity means low capital expenditure is required, and operational costs are small. For this reason, techno-economic assessments of photocatalytic water-splitting have shown that hydrogen produced by this approach will be competitive even against fossil fuel-sourced products. This prospect looks even more promising as the project continues progressing its technology along the TRL scale.



Production rate for H_2 and O_2 production increases linearly with increased UV intensity, from 10 to 100 suns at 90˚C.

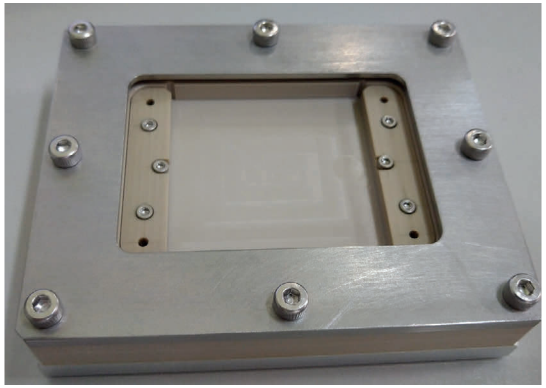
Zero Emission Clean Hydrogen – IEA

Key Learnings

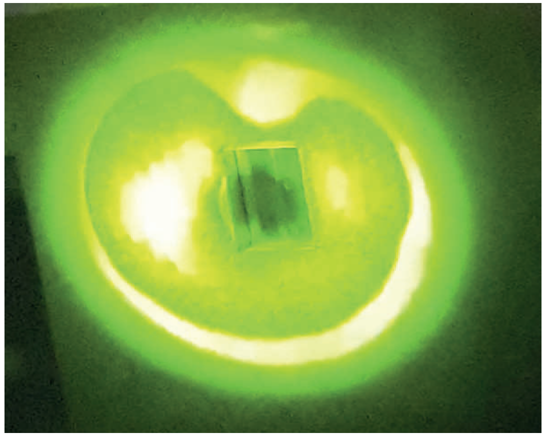
The testing in this project has involved operation under separate UV illumination (from a UV LED) and heating (in a heating oven). Thus we have demonstrated that photocatalytic water-spitting responds favourably to conditions corresponding to concentrated solar radiation i.e. increased solar flux and temperature. This opens up the possibility of operating it under a suitably designed concentrating field. We know that the temperature of the system cannot exceed 300°C because of the materials used. We also know that beyond a flux equivalent to 150 suns the H_2 and O_2 production no longer respond linearly. This places a limit on the type of concentrating solar field that would be compatible with photocatalysis.

Commercialisation Pathways

A patent describing the use of a thermo-photocatalytic reactor for water-splitting was submitted in April this year. We have been talking to various companies to financially support the continued testing of thermo-photocatalysis. This engagement has led to a recent agreement with Sparc Technologies Limited to support the project for 2.5 years to undergo this testing under combined light and heat from a concentrated solar simulator, and a further 2 years to build and test a proto-type demonstration unit.



New thermo-photocatalytic reactor for improved gas egress.



Facsimile Reactor Under Concentrated Solar Light

Ivanpah – NRG Energy; Bright Source Energy

Project 4.4: Solar Hybridised Dual Fluidised Bed Gasification with Particle Technology

This project aims to de-risk the Australia sugar and/or horticultural industry through a new "green diesel" product – a solar hybrid dual fluidised bed (SDFB) gasifier using particle technology. This would reduce the industry's carbon foot of and its exposure to the cost of diesel.

Dual fluidised bed (DFB) gasification technology has the flexibility to achieve a steady-state output of high-quality syngas. This is highly desirable as it would help simplify integration of an additional liquid fuel synthesis process for the supply of diesel and/or gasoline for the sugar cane transport fleet.

Ultimately, the project strategy aims to help provide access for this industry to a 100% renewable and continuous generation of heat, electricity and liquid fuel. The starting point of the project is to develop a techno-economic model to evaluate viability of hybridised solar thermal processing of bagasse.

Achievements this Year

We have completed the annual performance and technoeconomic assessment of the SDFB configuration to convert bagasse to 'green diesel' for a sugar mill a Harwood, NSW as well as three other locations in QLD and WA.

We have also assessed cotton gin waste, an alternative feedstock, to liquid fuel located at Emerald, QLD. We have demonstrated that the minimum selling price of 'green' diesel from solar hybridised dual fluidised bed (SDFB) gasification of bagasse can be comparable with the fossil-based diesel on the market based on the optimistic scenario. In addition, a valuable product, activated carbon, is generated from the SDFB route.

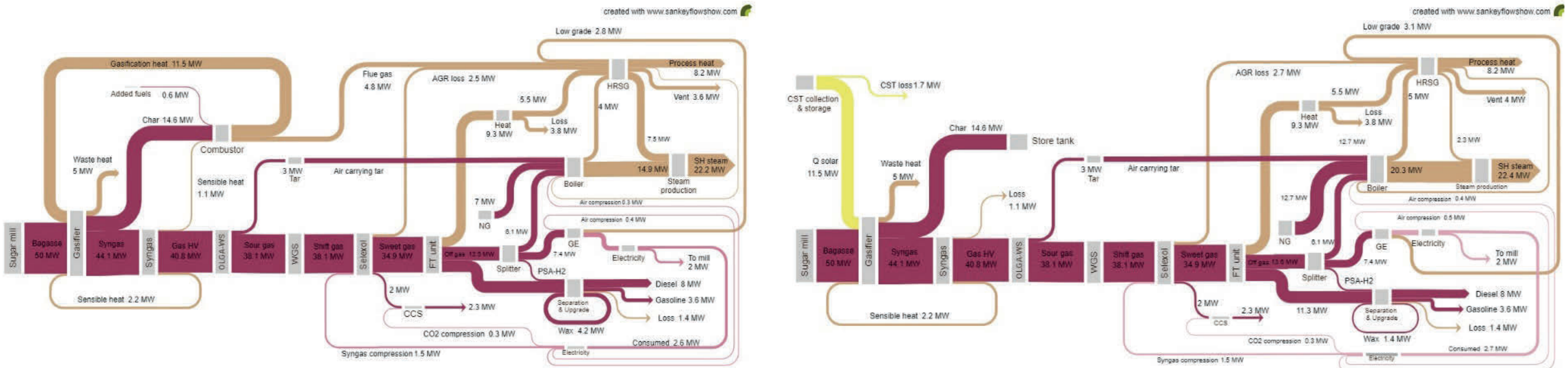
Key Challenges

There are three key challenges for this project. These are:

- the availability of a commercial particle receiver to provide particle temperature at 950°C;
- the integration of particle storage system with the dual fluidised bed gasification system;and
- the need to overcome the potential particle agglomeration issue with the solar hybrid dual fluidised bed gasification system. This is due to the interaction of fuel ash (bagasse) and solids (as fluidised bed material or heat transfer carrier) operated under concentrated solar thermal, reducing and oxidising environments.

Opportunities

The SDFB gasification technology can increase production of high value product for the input feed-stock relative to convention DFB technology, which is commercially-available.



Sankey diagram of hourly energy flows in Scenarios a) 2a and b) 3a (daytime) during crush season (material, heat, and power streams in purple, gold and pink, respectively.

This technology has the flexibility to achieve a steady-state output of syngas, which is highly desirable to simplify the additional integration of a chemical synthesis/H_2 separation process, which is also commercially available.

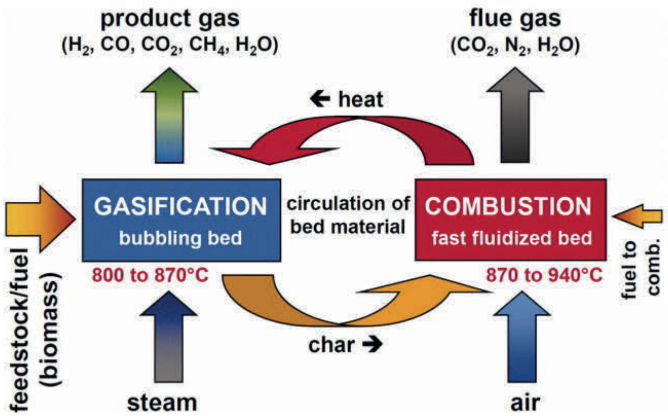
Key Learnings

- the minimum selling price of 'green' diesel from solar hybridised dual fluidised bed (SDFB) gasification of bagasse can be comparable with the fossil-based diesel on the market based on the optimistic scenario.
- high value of activated carbon can be generated only from the SDFB configuration.
- the dominant factors on the minimum selling price of diesel is selling price of activated carbon> discount rate > total direct cost of plant.
- the sensitivity of minimum selling price of diesel to location (solar resource) is approximately 10%.
- process or energy optimisation has to be tailored for each industrial application.

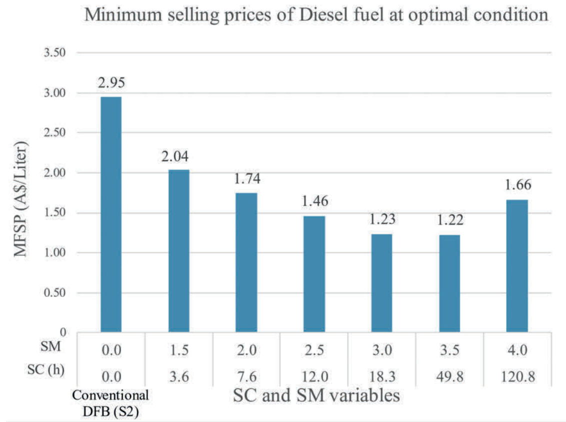
Commercialisation pathways

To de-risk solar fuels production and increase knowledge of the actual cost of production:

- Full system analysis of the cost of production all the way from the biomass feedstock to the fuel/char/ electricity; and
- New experimentally validated data addressing critical challenges for integrating CST into solar hybridised dual fluidised bed gasifier (SDFB) to TRL 6-7
  - o Particle behaviour (agglomeration/ attrition) under CST, reducing and oxidising environments; and
  - o Hydrodynamics – the solid circulation between the particle receiver and the SDFB gasification technology.



Dual Fluidised Bed Gasifier Process



Effect of solar multiple (SM) and optimum storage capacity (SC) on minimum selling price (MSP) of diesel for conventional dual fluidised bed gasifier and hybrid solar dual fluidised bed gasifier at Harwood, NSW, with 30% reduction on the direct costs.

Crescent Dunes – NREL

Project 4.6: Solar Reforming of Carbonaceous Feedstocks

Efficient management of ever-increasing amounts of municipal, industrial, and agricultural wastes is beneficial to minimising environmental impacts and this has been recognised in many countries. The large land areas available in Australian rural and regional areas has resulted in slower uptake of new technologies but converting waste into useful products and energy has been identified by Australian government as a priority area for investment and growth. Replacing natural gas with biogas in liquid fuel production processes could result in a carbon neutral system, but both the scale of biowaste resources and the requirement for energy input can restrict the scale of application. By integrating solar thermal energy inputs with the process (in combination with high temperature storage), it's possible both to optimise the conversion of biowastes to biogas and provide an entirely renewable pathway to commercial-scale liquid fuel production.

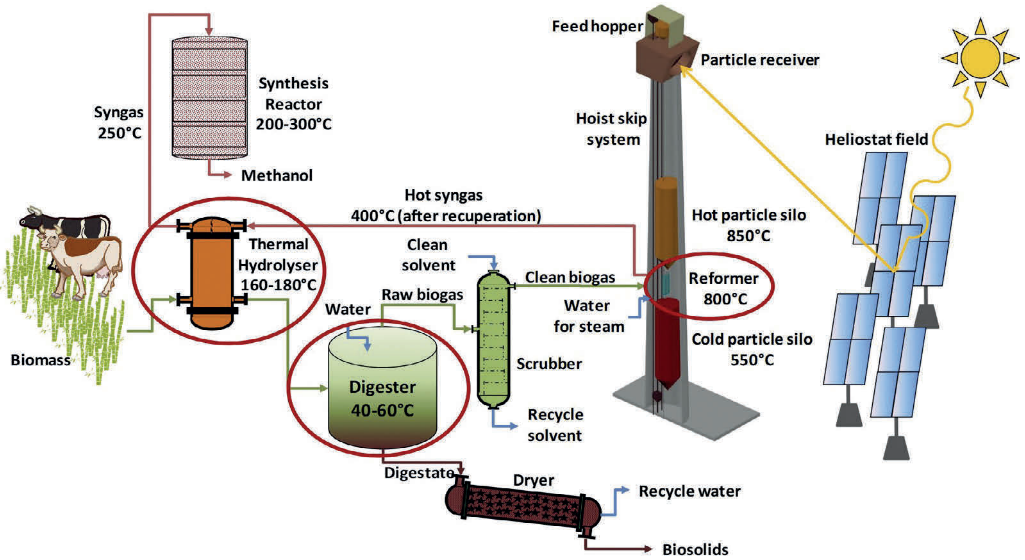
Availability of resources is very specific to locations, so several sites for case studies were selected for a detailed assessment including optimised plant design, performance modelling and financial assessment with the following characteristics:

- Newman (WA) – A very high solar availability site in the Pilbara region where water from an abandoned mine is available for cropping of sweet sorghum;
- Townsville (Qld) – A high solar availability tropical site utilising bagasse from the neighbouring Burdekin region, the largest sugar cane processing region in Australia; and
- Oakey (Qld) – A moderate solar availability site in southern Queensland that is dominated by animal processing operations, with the biomass feed being animal wastes.

At each of these sites the performance of both solar and biowaste conversion needs to be modelled with a coordinated process plant optimisation to ensure that the availability of solar thermal energy input is matched with the available biowaste resource. The simplified process design in highlights the locations in the plant where solar heat is used to supply high temperature reforming operations, then lower grade waste heat is used to enhance the operation of the biological processing systems.

Achievements this Year

The project developed integrated models that were used in combination with assessments of the solar and biowaste resources at the three case study sites to size and then cost the various plant components. Performance predictions for sites were then used to determine the likely economics of producing methanol from the hybrid solar-biomass plants. Two values for the levelised cost of methanol were determined for each case, one as a pure renewable product and the other utilising natural gas to maintain the plant at design output during periods of low resource availability.



Integrated solar-biowaste system for producing renewable liquid products showing areas for use of solar heat

Determining optimal combination of solar and biowaste resources is complex, but in general the availability of sufficient high energy content biowaste (e.g. animal wastes) appears to have more significance than solar resource. The cropped biomass using wastewater at a high solar availability site is likely to incur additional costs in crop management that were not considered but may offer better economy of scale by allowing larger plants to be constructed. Poor energy content biowaste, such as crop residues, are not preferred for the process due to the low production rates of biogas and are likely to be more suitable for other biomass utilisation technologies

Key Challenges

Combining two renewable energy sources into a single process plant provides unusual challenges in identifying sites where the resources are compatible in type and scale.

- High biomass concentrations are not common in high solar availability regions, as water supply is often limited.
- Seasonal variability for both resources can be considerable and makes continuous stable plant operation difficult to achieve with single biomass feedstocks.
- Any additional harvesting, transport and preparation costs are likely to make the process uncompetitive.
- It is difficult to guarantee that a pure renewable product can be consistently produced and having access to a backup supply of natural gas improves the process performance

Key Opportunities

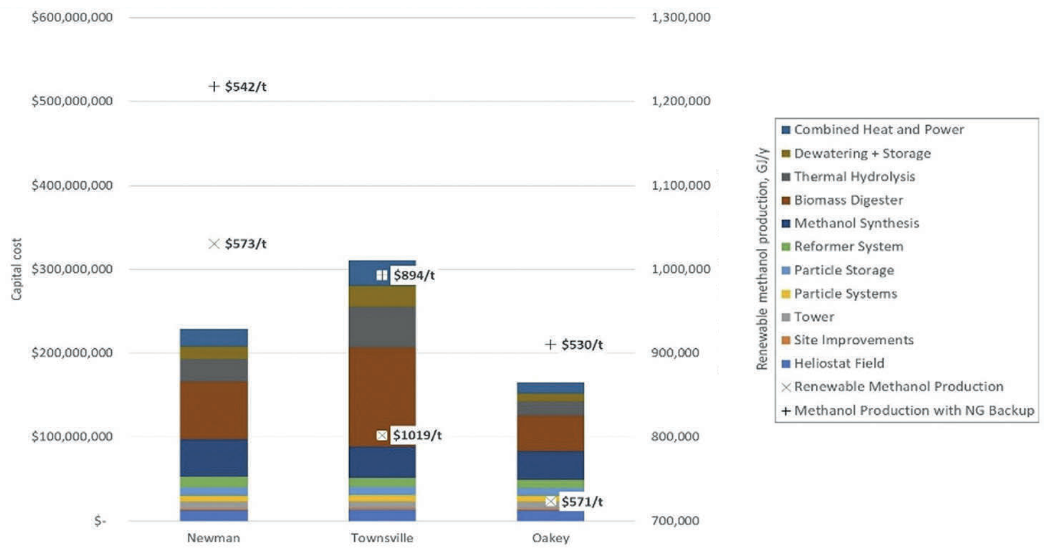
The project has identified the key factors that influence the cost and performance of the hybrid plant design and this can be used as an initial filter for estimating if a site has commercially attractive characteristics. The estimated cost of produced methanol is sufficiently close to commercial prices that a full design assessment may then be warranted for sites of interest.

Key Learnings

Using multiple renewable inputs into an integrated process can result in complex interactions that produce non-simple performance, so specific studies on individual sites are required to determine the likely success of the process.

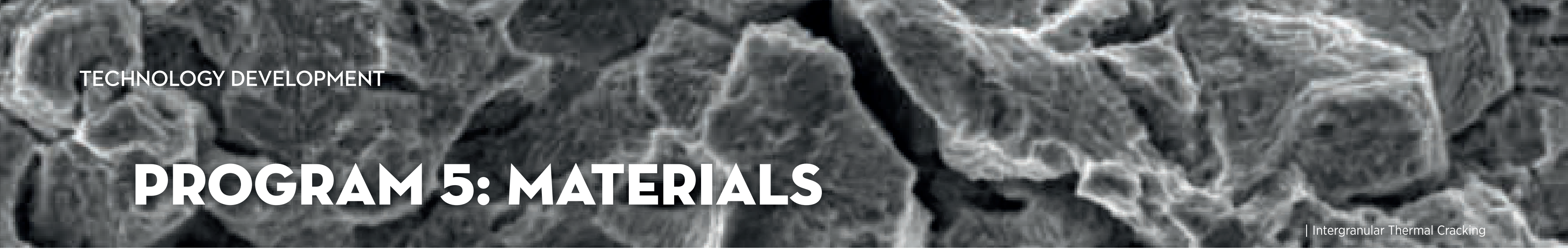
Commercialisation pathways

Requires interest from a commercial operator with large biowaste supply in an area with adequate solar resource. Confidence will be improved through further demonstration.



Summary of plant costs and methanol production cost with and without backup natural gas feed

Crescent Dunes Heliostat Cleaning – NREL



PROGRAM 5: MATERIALS

| Intergranular Thermal Cracking

Project 5.3: Advanced Materials

The 30-year design life of a solar thermal systems (CSP and CST) requires full understanding of material compatibility and associated characterisation of material degradation to make 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.

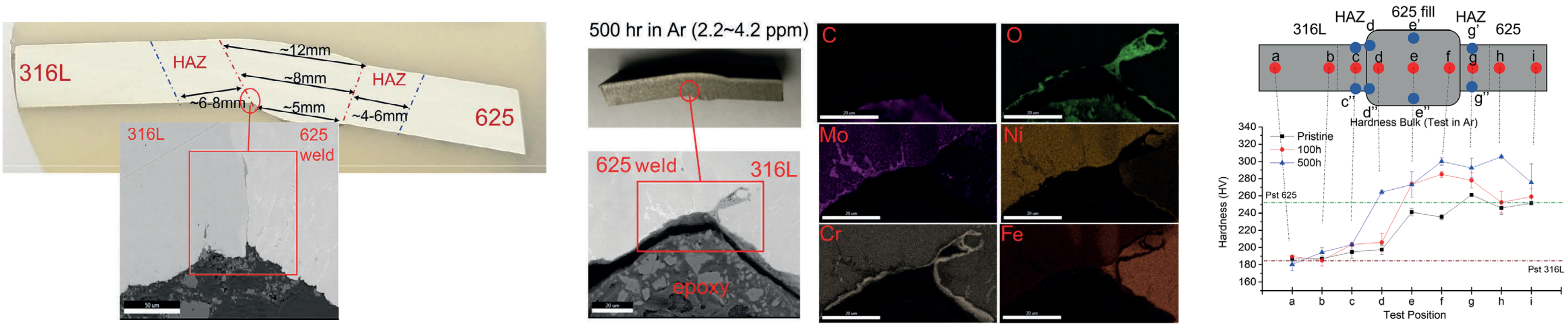
The materials program is providing specific answers to many material issues and closely associated research gaps for ASTRI's solar thermal technologies. Examples include providing engineering material degradation test data to identify corrosion, cycle fatigue, and other material issues for specific alloy/thermal energy storage media, alloy/sCO_2 and alloy/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 material 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:

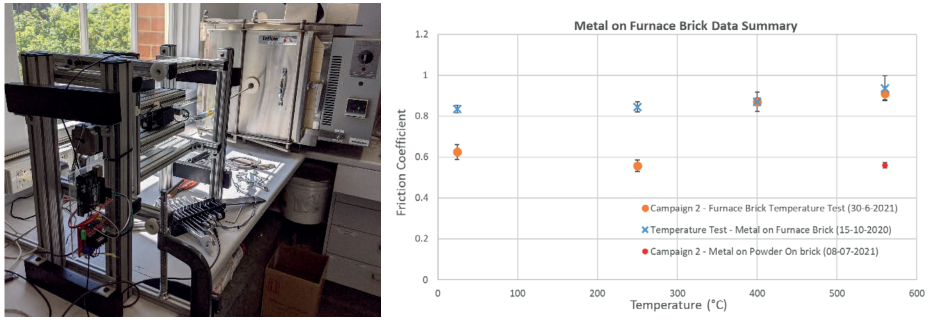
- international collaboration to tap into existing knowledge;
- design of components to include sample specimens/tubes for destructive exposure testing;
- static testing of samples under laboratory conditions;
- a dedicated sodium exposure test program; and
- degradation of priority alloys after exposure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

Achievements this Year

- Completed characterisation of failure mode of an existing receiver and assisted in translating learnings into the current ASTRI receiver program.
- Developed the ability to study Liquid Metal Embrittlement potential of liquid sodium on different alloys.
- Developed and implemented new test protocols and capabilities including:
    - o static sodium test capability.
    - o methods for small punch test to evaluate liquid metal embrittlement (LME).
    - o high temperature transient creep and mechanical strength test capability which is unique in Australia and will allow the evaluation of novel alloys under ASTRI conditions. Initial data for select alloys being obtained.



Inconel 625 and 316L weld exposed at 750 °C for 500 hr; **(left)** polished cross-section showing distortion and a primary crack; **(middle)** analysis of 625 fill-316L weld boundary, and **(right)** hardness profile from 316L to 625 across the weld section.



(Left) Experimental apparatus to determine friction coefficient between thermal energy storage tank material bottom and substrate tank foundation, and **(Right)** example of friction coefficient data for metal plate friction on furnace brick.

- Utilised previously drafted experimental protocols to determine corrosion rates of a number of priority alloys.
- Developed program to characterise welds used in CSP (sodium, salt, carbon) & impact of corrosive environments.
- Built significant engagement with VAST Solar and Graphite Energy to identify and provide initial experimental results to de-risk their CSP work:
  - o Developed ability to characterise (CSP) thermal energy storage tank frictional interactions with substrates to prevent large (catastrophic) tank failures.
  - o Developed approach to study LME for CSP applications and provided input for VAST related to LME risk utilising sodium in CSP plant.
  - o Developed and implemented research program to characterise carburisation potential of alloys used in CSP thermal storage for Graphite Energy.
- Conducted a workshop with Particle Receiver project group to provide input and advice on abrasion and wear of components and particle attrition.
- Worked with ANU to resolve fabrication welding issues related to new ASTRI sodium receiver.
- Worked with VAST and CSIRO on materials issues and design of the new sodium test loop and exposure system.

Key Challenges

- The need to rapidly develop new test protocols to fill data/knowledge gaps. Pressure to rapidly assist design decisions for ASTRI industry partners, knowing that the outcomes of research and the recommendations made have significant impact across the CSP industry both domestically and internationally.
- Rapid development of new testing capabilities in Na and consideration of a new mechanical strength testing program.
- Changes in ASTRI design conditions, candidate alloys, defined priorities (for support of industry partners) and PCMs/thermal storage solutions in other projects, which have resulted in new test requirements.
- Identifying appropriate alloys and joining methods and validating choices for specific CSP applications in support of ASTRI and international collaborations (heat exchangers, welds/joins in sodium or sCO_2 systems, etc.).

Key Opportunities

- The ASTRI Materials group has established an international reputation in the properties of alloys at extreme temperatures and under harsh environments. This achievement continues to position ASTRI as an expert advisor on CST and CST system materials for domestic and international companies and organisations such as Vast, NREL, DOE, Graphite Energy and John Cockerill.
- 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.

Key Learnings

- Capability to expose alloys to liquid sodium at controlled oxygen levels and characterise degradation.
- Capability to mechanical test alloys for creep & fatigue at CSP relevant thermal conditions (isothermal & static).
- Capability to characterise welds after exposure (thermal and heat transfer fluids).
- Ability characterise carburisation of alloys in CSP relevant conditions.
- Ability characterise CSP thermal storage tank and substrate interactions.

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 and/or cost perspective.

Project 5.4: Operation and Maintenance

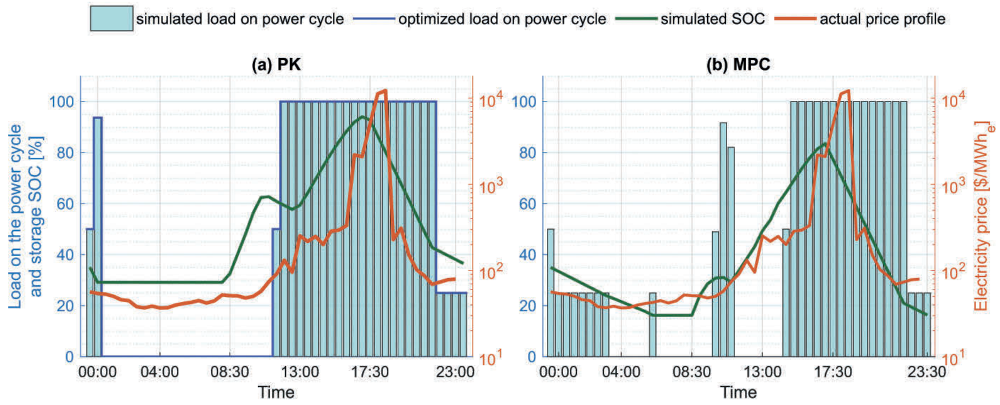
The cost of Operation and Maintenance (O&M) for solar thermal, which includes the cleaning of heliostats, optimising staffing levels, and managing the failure risks of key equipment, are not well documented and not well understood which is a critical factor in the de-risking of investment in CSP/CST. 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.

Achievements this Year

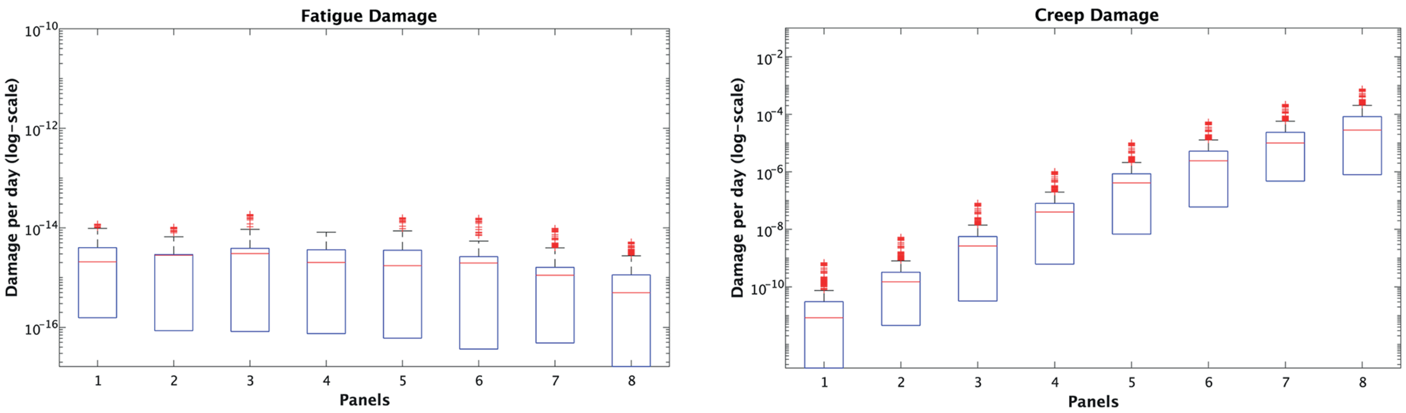
The project team has made progress in several areas, strengthening international collaborations with both industry and research institutions. The soiling model has been refined and applied to actual CSP sites and the tuned models has been used to optimise cleaning resources and schedules for new plants. The receiver thermal model has been exploited to develop degradation models and assess the impact of basic maintenance policies. Finally, a dispatching optimisation tool for CSP plants has been developed to dynamically update the dispatch plan in real-time based on up-to-date forecasts of direct normal irradiance (DNI) and electricity spot prices. This tool has been used to assess the economic performance under uncertain DNI and electricity prices. The detailed achievements in 2021 were:

- Worked closely with Vast Solar:
  - o Continued soiling characterisation of their Mount Isa site. Reflectance losses predictions are now available via the soiling model;
  - o Cleaning resources and timings for the solar fields were optimised using in the tuned soiling model, site weather data, and plant design data provided by Vast;
  - o Analysis of atmospheric extinction to assist in estimation of expected generation for the Vast tower design;
  - o The assessment of mirror reflectance loss due to corrosion.
- Collaboration with Mars Petcare to assess soiling for reflectance loss predictions for a CSP plant.



| Dispatching optimisation outcomes for perfect knowledge (left) and Model-Predictive Control (right).

This included:
  - o Installation of a mirror test rig and dust sampler on site for measurement;
  - o Analysis of particulate matter to approximate the local dust size distribution.
- Expanded the collaboration with ACWA power for soiling predictions and cleaning scheduling optimisation:
  - o Preliminary soiling assessment exploiting publicly available data, incorporating ACWA power design values;
  - o Cleaning schedule optimisation performed assuming unknown parameters whose impact has been evaluated through a sensitivity analysis.
- Improved the reflectance loss model for the previously developed soiling model to more accurately account for the blocking and shading of dust particles at different angles of incidence.
- Created a model for creep/fatigue assessment in collaboration with Politecnico di Milano to provide life estimations for a cylindrical receiver. This work was accepted for oral presentation at SolarPACES 2021.
- Developed a billboard receiver thermal model with multi-parallel flows that is currently being exploited to predict life estimations of billboard receivers.
- Developed model predictive control for optimal dispatching under stochastic weather and electricity



Daily damage due to fatigue and creep in a central receiver.

price environment, which has been adapted to the peculiar characteristics of the Australian electricity market. This activity resulted in the submission of a journal paper to Energy Conversion and Management.

- Developed a laboratory method for simulating the soiling of surfaces/ mirrors using "dirt" as the source of dust.
- Developed a method of measuring adhesion of particles to surfaces which has shown that there is a strong dependence of both particle size and the scale of surface roughness.

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.

Although a collaboration with two Australian and one international industry partners has been successfully established in the past few months, this is currently limited to design phase considerations for heliostats cleaning, and still misses the actual operating data that are required for validation of other equipment models (e.g. receiver and storage).

The inclusion in the HelioCon project may alleviate this issue, at least for heliostats. Additionally, equipment degradation modelling for new technologies is currently difficult to validate, as there is no available reliability data for some key subsystems (e.g. receivers).

Key Opportunities

Numerous commercial opportunities are arising from this project, and there is potential to establish ASTRI as an expert advisor 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, moisture levels etc. Such a unit could provide greater confidence on the economics of investment and O&M costs in particular.

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

Key Learnings

- While highly location dependent, soiling rates in Australia are likely to be significantly lower than those observed in the Middle East.
- For the designs analysed, receiver degradation appears to be creep driven.
- Uncertainty in DNI (or electricity prices) forecasts can be mitigated by updating the dispatch policy frequently. However, predicting profits by assuming perfect forecasts will over-predict profits significantly (about 20% in our study in Woomera, South Australia).

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.

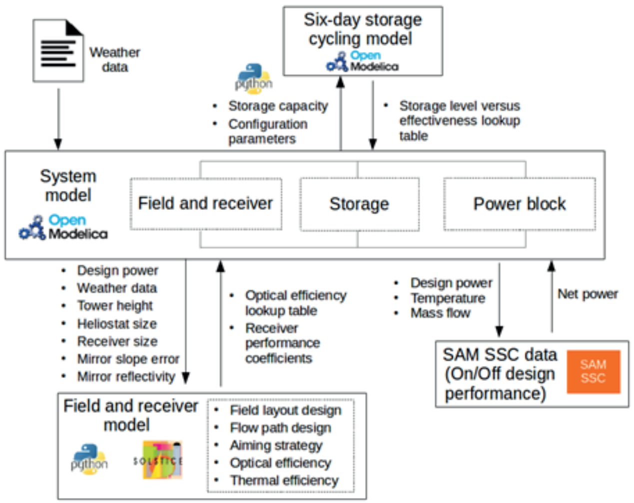
PROGRAM 6: SYSTEM MODELLING

| Systems Integration

Project 6.1: System Modelling

This project is concerned with developing tools to undertake performance and cost analysis of CSP at the system level. It builds on and utilises the more detailed modelling conducted at the component level in other ASTRI projects. The project objectives are:

- Provide high-quality annual performance simulation tools to ASTRI and the broader CSP community
- Develop ASTRI configurations, deliver LCOE reductions
- Develop and disseminate 'baseline' models for validation and track ASTRI progress
- Analysis of system-level impacts of thermomechanical degradation
- Optimise and refine systems for lowest LCOE
- Undertake sensitivity analysis of the various configurations
- Contribute to the US DoE Gen3 liquids and solids pathways
- Develop a standardised approach to modelling CSP process heat systems



Achievements this year

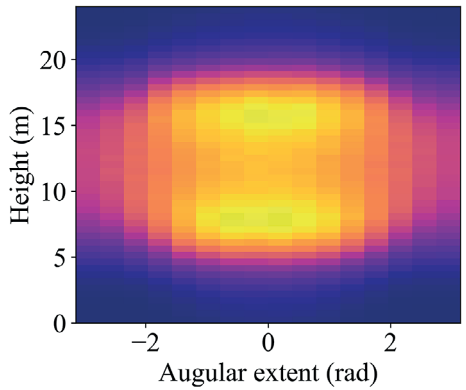
The model and software have been developed on an open-source platform. It has been used to optimise configurations for both the liquids pathway and the solids pathway for the US DoE Gen3 program, as well as an ASTRI configuration based on a Na receiver with detailed aiming strategy and sCO2 power block, resulting in an LCOE of 56.55 USD/MWhe. The model incorporates a detailed heliostat aiming strategy feature that allows the receiver to be designed to be smaller and have lower cost. This balances receiver tube creep-fatigue with annual output.

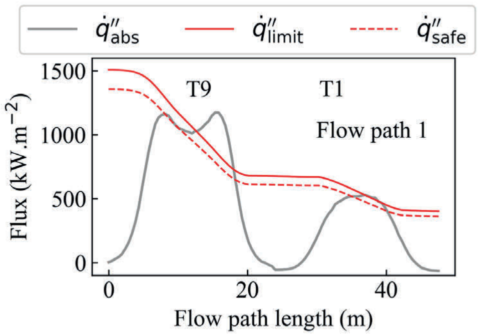
The model also analysed and optimised particle receiver and storage configurations, as well as undertake modelling of University of Adelaide's hybrid sulphur industrial process heat technology which resulted in a levelised cost of heat of 10.3 USD/GJ.

Key Challenges

The model incorporates surrogate modelling for each of the components and processes in an integrated CSP system. The project needed to wait for these to become available which then delayed the outputs of the system-level model.

Crescent Dunes – NREL





Key Opportunities

Modelling is important in order to understand the costs and performance of components and processes when integrated in larger scale systems. It is also important for understanding key sensitivities and trade-offs between cost and performance that then feed back into the component development program.

Key Learnings

A key feature of the modelling project has been in the development and understanding of applying lower order surrogate models for components and processes that allow "fit-for- purpose" analysis without extensive computer time.

Commercialisation Pathways

Having developed this model on an open-source platform it was not the intention to commercialise the model per se. However the model itself can be used by experienced ASTRI scientists and engineers to undertake modelling for others. This has already been the case for the US DoE Gen3 program, and is emerging as paid work for HelioGen, a US CSP start-up company. It is anticipated that other similar opportunities could emerge, especially as the model is broadened to incorporate a broader range of CSP technologies.

Solana – Abengoa

Project 6.2: Opportunity Assessment

In previous assessments in ASTRI, the emphasis has been on identifying opportunities for CST technologies in supplying electricity for network distribution, focusing on sites and plant designs that were projected to be commercially viable in the near-term.

However, some conventional CST and new ASTRI technologies are also appropriate for applications in industrial heat supply, and these may provide opportunities for smaller scale demonstration and commercial scale applications that provide early market entry.

Identification of potential applications and locations commenced with a broad review of industrial energy usage by location, scale and process type, then proceeded to more detailed assessments of specific potential applications in different industry types.

Achievements this Year

Highlights from the project output include the following:

- Broad review of Australian industrial energy opportunities by type and scale
- Assessment of specific industrial applications requiring different scale and temperatures
- Completion of three case study analyses at varying locations and from different industries to identify optimum CST plant designs and financial performance when matched to the site energy needs

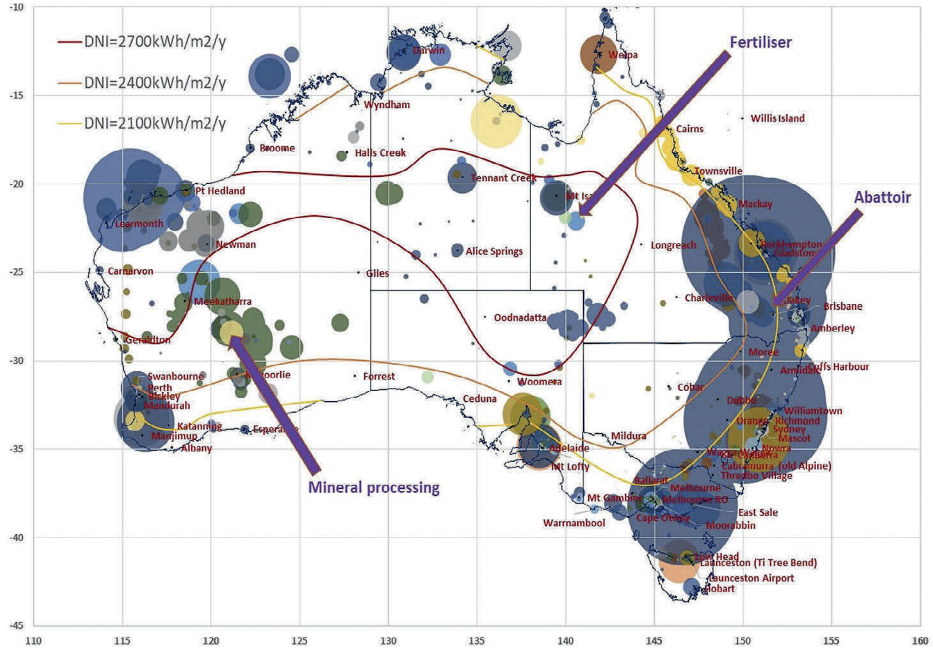
The sites selected for the three case studies are indicated and are representative of other similar industrial plants in the minerals, chemicals and food processing sectors that constitute a significant fraction of Australia's fuel usage beyond electricity generation. The scale of energy use at the sites varied from requiring solar plants ranging from 37.5MWt to 150MWt with required temperatures including low temperature (~200°C) for the abattoir, moderate temperature (~300°C) for the mineral processing and high temperature (~850° C) for the fertiliser sites.

ASTRI Particle technology was considered for all cases, but in comparison with conventional industrial parabolic trough CST systems for the lower temperature applications. In all cases, an optimised CST system was found to be competitive with natural gas at prices appropriate for the scale and location of the industrial application. Particle technology has benefits over conventional CST technologies for larger scale, higher temperature and more southerly location applications.

As a general assessment, a simplified particle system of 50MWt solar scale with a 15MWt steam generator was assessed at a wide range of sites. This neglects the more complex optimisation and matching to industrial site needs, but provide a quick indication of the potential for solar application.

Key Challenges

- Uptake of CSP in Australia has been slow, in part due to the known issues with conventional CST technologies but also due to the perception as high cost and competition from lower cost but less flexible technologies in the electricity market;
- Newer CST technologies can address some of these issues, but for electricity require large scale implementation to be economically attractive; and
- Industrial applications offer other opportunities for CSP on the basis of competitive costing against fuel provision, but require detailed system optimisation to match the specific site needs.



Industrial site emissions in Australia with specific sites assessed for CST performance

Key Opportunities

Improved competitiveness of CSP for electricity applications is expected with the new ASTRI technologies under development, specifically where system size can be reduced while maintaining efficiency to allow use in off-grid, small grid and individual industrial site applications.

The flexibility in operating temperature promised by the particle receiver and storage system under development in ASTRI provides an opportunity to consider implementation in industrial heat applications across a broad range of industries.

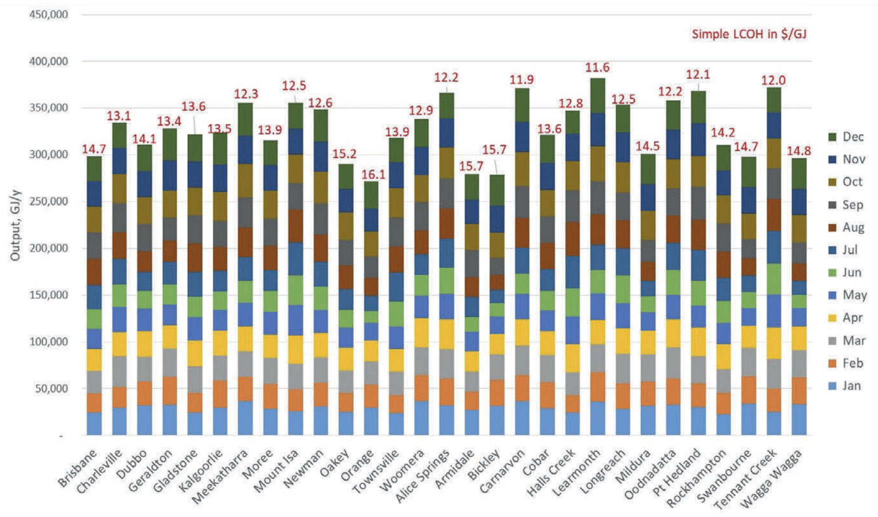
Longer term, the anticipated improvements in assessment of both electricity and industrial heat applications through model developments will allow for more rigorous design details on new plant items and additional data from pilot plant operations.

Key Learnings

Industrial energy usage in Australia covers a wide range of processes, locations and scales that makes general assessments of commercial options for CST implementation challenging.

Commercialisation pathways

Assessment tools developed in the project are available to provide support to industry in evaluating the technical, operational and commercial potential of prospective applications.



Indicative LCOH at individual sites for a 50MWt particle tower with 12 hours storage and 15MWt output

Solar Research Facility Newcastle – CSIRO

PROGRAM 7: SYSTEM INTEGRATION

| Vast Solar Jemalong - Vast Solar

Project 7.1: Integration Testing

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 Newcastle. This facility will utilise ASTRI technologies based around high temperature sodium 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 5 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.

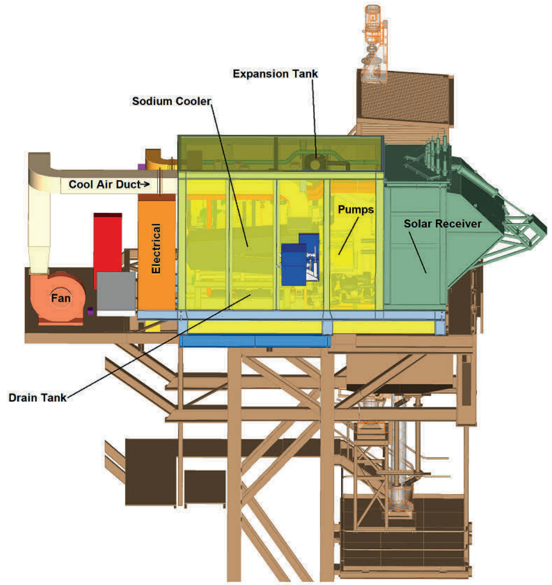
It is expected that this project can be used to integrate other key components of CSP into the sodium loop, such as alternative receiver designs, heat exchangers, thermal storage, and energy transfer to power cycles like the supercritical CO_2 Brayton cycle.

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

Achievements this Year

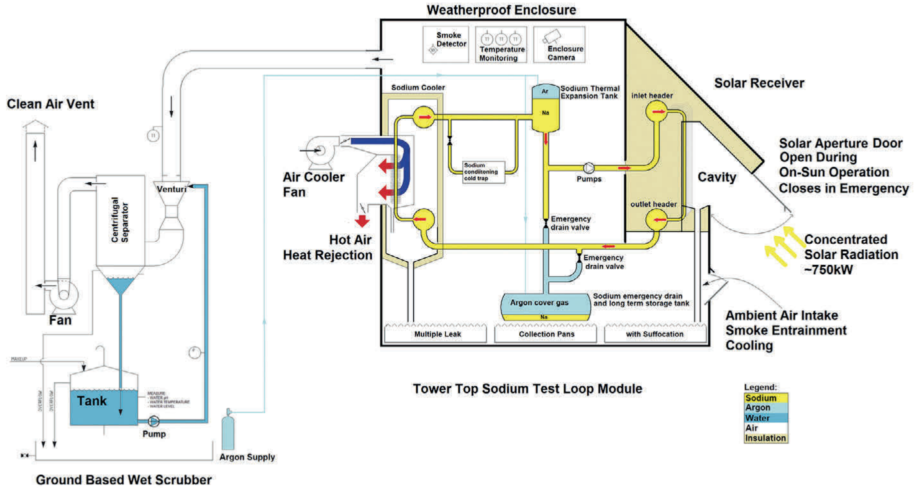
Over the past 12 months the project focussed on executing packages of work for successful completion of the process design, and plant design for the sodium test loop and safety management systems. The project was successful in engaging Vast Solar Pty Ltd to convert the preliminary design by CSIRO into a fully designed and engineered system. Specific achievements include:

- Awarded a contract to Vast Solar Pty Ltd for taking the preliminary design by CSIRO into a complete engineering design package, as Stage 1 of the work. Stage 2, mentioned later, is for the construction.
- Incorporated the design of ASTRI MK I sodium cavity receiver from ASTRI's Sodium Receiver Project (P1.2)
- Completed a HAZOP process on the process design.
- Took delivery of long lead equipment (electromagnetic pumps, flowmeters, the cold trap, and pressure transmitters) from Creative Engineers Inc (USA).
- Finalised the P&ID drawings complete for IFT Sodium Test Loop and for the safety management systems for the prevention and control of sodium leaks and fire prevention.
- Completed the construction of the sodium to air cooling heat exchanger and took delivery Dec 2021.
- Received completed engineering design package and cost estimate for deliverying the sodium test loop module, fume scrubber system, including sodium filling, testing and commissioning at Vast Solar's Jemalong Solar site.
- Project budget and delivery schedule adjusted to accommodate the higher cost realised as a result of completion the engineering, and de-risking the system.
- Awarded an extension to the existing design contract for stage 2 of the works, 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.



| Final Engineering Design of the Sodium Test Loop Module.

Completed Tube Bundle for the Sodium to Air Cooler Heat Exchanger



Sodium Safety System Schematic

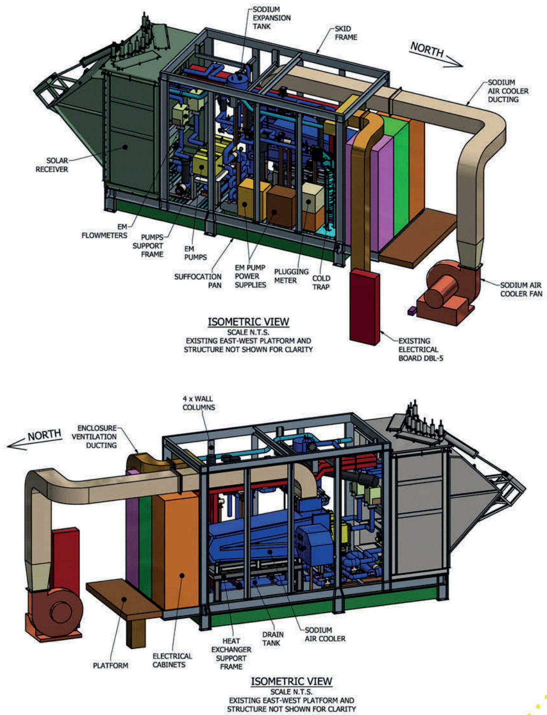
Key Challenges/Learnings

- The resultant design produced a system that is not only a high temperature circulating sodium loop as a test bed for a range of technologies applied to a CST application, but also a system designed to detect a sodium leak using temperature, smoke, and inventory control, and then shutting down the sodium flow, returning the sodium to a central storage vessel, thus preventing further sodium leak and intentionally letting the small amount of leaked sodium combust, all while having a scrubber operating to extract and neutralise the sodium oxide smoke. With safety being of the highest priority the system is designed to be intrinsically safe.
- This placed a larger requirement on the fire management and safety system and that the system is designed with the likelihood that a leak will occur, resulting in a fire, with automatic detection, management and system shutdown to extinguish the fire and be intrinsically safe.
- Developing this system has been a challenge because two independent systems have been designed and will be tested together, which are linked to function in parallel with each other. The Sodium loop can operate if the safety management system says so. The fire management system operates independently on the sodium test loop.
- The need to have two systems has increased the cost and the challenge is to manage that cost with expectations.
- Dangerous material handling up to 250 kg of Sodium is under safety review by CSIRO management.

Key Opportunities/ Commercialisation Pathways

ASTRI believes that liquid sodium as a heat transfer fluid in CSP application 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 a complete engineering-level design concept that will progress to full-scale testing and integration within Australian and global solar thermal systems. ASTRI will start commissioning power systems in July 2022.

Opportunities exist to collaborate with Vast Solar on this project and on other solar thermal opportunities involving sodium. There is one pipeline opportunity to test an alternative solar receiver design on the sodium test loop.



Overall Skid General Arrangement

ASTRI MOVING FORWARD

The ARENA annual review of the ASTRI Program identified the need to rationalise ASTRI's work program around a more targeted set of higher TRL and commercially orientated activities.

A Review was undertaken by the ASTRI Technical Advisory Committee TAC to assess and prioritise ASTRI's projects based on technical and commercial merit criteria. This review resulted in significant rationalisation of ASTRI's technology development activities from 18 Projects to the following 7 projects:

- Project 1.1 Heliostats
- Project 1.7 Particle Receiver – Demonstration
- Project 2.5 Thermal Energy Storage (TES) Commercial Demonstration
- Project 4.2 Commercial Application of STEM Technologies
- Project 5.3 Advanced Materials
- Project 5.4 O+M Technologies
- Project 7.1 High Temperature Sodium Test Loop

These 7 projects will now form the basis of ASTRI's 2022 Work Plan.

ASTRI's focus is to progress these activities through to pre-commercial demonstration and operational deployment. This focus applies specifically to ASTRI's Particle Receiver, Sodium Test Loop and Thermal Energy Storage Projects. ASTRI is seeking to progress these technologies to a point where they are ready for co-investment with industry on a more substantive operationally focused demonstration. This could also include a range of end-use applications, such as remote area power systems, industrial process heat and/or the production of clean hydrogen.

ASTRI does not view these component technologies as having separate deployment pathways. The aim is to offer different solar thermal technology solutions for different end-use applications. The collector field and power block would ultimately be the same, but industry would be given the choice of a particle or sodium-based system, with different storage options (salt, sensible graphite, or particles). This work is intended to be progressed through a range of mechanisms including direct engagement with industry, through the HILT CRC or through new and emerging state-based programs.

P1.1 Heliostats

This work will focus on heliostat design and cost optimisation activities. The activities will feed directly into the $25 Million US DoE Funded HelioCon project, being managed by NREL. ASTRI is part of the Project Consortia. Other activities under the project include:

- a techno-economic analysis of heliostat Whole of Life cost impacts,
- Heliostat wind load testing & analysis – indoor wind tunnel & outdoor test facility
- Validation of supercapacitor-based actuation

| Crescent Dunes – NREL

- Interaction with Vast Solar and SolarPACES Task III
- Assessment of heliostat operational strategies and guidelines

P1.7 Particle Receiver – Demonstration

This work will initially focus on completion of the on-sun testing of the Particle Receiver at CSIRO Newcastle. The work will then focus on a commercial demonstration activity with an Australian mining/mineral processing entity. Other activities under the project include:

- Continued testing of particle receiver, storage and heat exchanger
- Modelling of the CSIRO receiver (thermal aspects considering CFD & hydrodynamics) using experimental data
- Improved understanding of long-term particle properties

P2.5 Thermal Energy Storage (TES) Commercial Demonstration

This work will focus on commercial demonstration of an Australian manufacturer TES system. Activities under the project include

- Preparatory work for TES demonstration
- Techno-economic analysis of TES markets
- End-use applications of TES systems (power/heat)

P4.2 Commercial Application of STEM Technologies

The work will focus on use of Beam Down Solar Thermal systems to improve the economics of tailing management on mining/mineral processing sights. Activities under the project include:

- Explore commercialisation opportunities
- Investigate mining sector demonstration
- Techno-economic analysis of Beam-Down technologies for mining

P5.3 Advanced Materials

This work will focus on supporting high temperature material interactions. The work activities include:

- Sodium/alloy interaction lab investigations and analysis; impact on material selection and optimum operating temperature for future receivers
- Liquid metal embrittlement – understand mechanisms & impact on alloy selection
- Investigate thermo-mechanical properties of selected alloys
- Provide input to analysis of particle receiver materials as required
- Support O&M component and material lifetime assessments with data as required
- Understand weld properties of alloys subjected to thermal and oxidation stresses

P5.4 O+M Technologies

This work will focus on supporting industry in reducing the operation and maintenance costs of Solar Thermal systems and component technologies. The work activities include:

- Optimisation of staffing and labour allocation
- Heliostat field cleaning and development of novel coatings
- Development of condition-based monitoring solutions
- Reliability and O&M scheduling of critical components
- Storage/dispatching management
- Quantification of CSP component and operational costs (to de-risk CSP).

P7.1 High Temperature Sodium Test Loop

This work will focus on the fabrication, testing and commissioning of a high temperature sodium loop at CSIRO Newcastle. The work activities include:

- Fabricate sodium loop and scrubber
- Shakedown testing at Jemalong

P3.5 Power Block – Demonstration (Unfunded)

This work will focus on engagement with a sCO_2 OEM, to facilitate an in-country demonstration of an operational sCO_2 power cycle. Target size is 2-5MW

P4.3 Photocatalyst (Unfunded)

This work will focus on supporting the Photocatalysis project through work on the Solar Thermal Collector needed to deliver the required heat and light for the photocatalytic process. The work activities include:

- examination of solar thermal collector system
- design of solar thermal collector system

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