ASTRI
AUSTRALIAN SOLAR THERMAL RESEARCH INITIATIVE

ASTRI Annual Report

Australian Solar Thermal Research Initiative

November 2014 – October 2015

This Program has been supported by the Australian Government through the Australian Renewable Energy Agency (ARENA). The Australian Government, through ARENA, is supporting Australian research and development in solar photovoltaic and solar thermal technologies to help solar power become cost competitive with other energy sources.

ARENA Program Information

INFORMATION FIELD	CONTENT
Grantee Name	Commonwealth Scientific and Industrial Research Organisation
Collaborating Organisations	Australian National University The University of Queensland The University of Adelaide University of South Australia Queensland University of Technology Flinders University
International Collaborating Organisations	National Renewable Energy Laboratory (NREL) Sandia National Laboratories Arizona State University
Subcontractors	nil to date
Program Title	Australian Solar Thermal Research Initiative (ASTRI)
Program Number	1-SRI002 (ASTRI)
Annual Report Period	1-Nov-2014 to 31-Oct-2015

ASTRI researchers, ARENA and partners in February 2015

ASTRI at a Glance

ASTRI – Australian Solar Thermal Research Initiative

ASTRI is a consortium of leading Australian research institutions collaborating with international researchers and industry to deliver cost reductions and dispatchability improvements, as well as position Australia in concentrating solar thermal (CST) power.

Grant Recipient

CSIRO

ARENA Funding

$35 million

Total Project Value

$87.3 million

Challenge

CST technologies concentrate sunlight to produce high-temperature heat for power generation, solar chemistry and other industrial processes. With Australia's solar resource, CST technologies have the potential to be an important part of the future energy mix, although innovation is required to make the technologies more cost competitive. Australia has the research expertise to partner with international researchers and industry to deliver leading-edge solar thermal concepts and profit from the growing CST sector.

Approach and Innovation

ASTRI's innovations are being achieved through a series of highly targeted research projects, in close partnership with United States research collaborators and with leading international and Australian CST companies.

ASTRI is achieving its outcomes through USA Solar Energy Collaboration (USASEC) linkages to the United States Department of Energy SunShot program, and through mobilising the international CST industry to invest in Australia.

ASTRI is coordinating a focused program with rigorously prioritised efforts, informed by an overarching CST economic energy system model. Together, the collaborating ASTRI organisations will produce a large-scale collaboration on CST across Australia, serving as a platform for new national and international linkages. It will develop a step-change in the commitment of Australian researchers to the success of CST, as well as equip highly trained graduates ready to deliver success in CST industries.

Outcomes and Benefits

ASTRI will deliver the next wave of CST research based cost reductions to enable the production of solar electricity at less than 12 cents per kWh and demonstrate the added value that CST technologies bring to the energy marketplace. In doing so, ASTRI is delivering:

- Relevant research outputs such as novel technologies, know-how and patents
- Concepts ready for commercialisation
- Knowledge sharing through media presence, publications and presentations
- A platform of ideas and options to industry on CST technologies and impacts.

Researchers will also be equipped to engage in the science and technology debates that will underpin Government policy towards CST adoption.

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Message from the Chair

ASTRI is entering its mid-term review in good shape.

In late 2015 Australia stood side by side with the rest of the developed world in a landmark commitment to reduce carbon emissions and put a stop the earth's rising surface temperature. At much the same time, the Prime Minister unveiled the National Innovation and Science Agenda, a program designed to increase collaboration between industry and researchers to find solutions to real world problems and create jobs and growth.

In early 2016, the nation's newest Chief Scientist, Dr Alan Finkel used his first address in Canberra to observe that Australia had begun its journey toward more sustainable energy practices. In the private sector, traditional heavy consumers of non-renewable fuels and energy began to talk of transition - and the transition has begun. But "begun" is all it has - we need to "accelerate that effort" in order to halt dangerous emissions, Dr Finkel observed.

On a local and global scale, the momentum toward renewable technologies is gaining pace and with it, demand for cost-effective, proven solutions that will deliver not just climate impact but growth opportunities for domestic profits, clean-technology jobs and new industry creation.

As the world considers its options, the focus sharpens on Concentrating Solar Thermal technologies – a comprehensive element of the decarbonised energy system that offers not only clean energy generation, but also storage. Dr Finkel observed, "The problem is, it doesn't matter how much wind and solar you have it's intermittent...Without storage of some kind, wind and solar will never deliver on their full potential."

As Australia considers its future in a world with a high-penetration renewable energy, the value proposition of concentrating solar thermal (CST) technologies grows: as a core stabilising technology for the grid; as a source of dispatchable electricity; as a clear solution to the wind and solar intermittency challenge.

Thanks to the continued efforts of ASTRI, Australia is in better position to capitalise on that opportunity than it was in 2012. In close collaboration with industry, and with partner institutions in USA and Europe, ASTRI has designed and continues to refine technology configurations to reduce costs and improve efficiency for CST power plant operation. This work is increasing investment appeal and decreasing technology risk.

CSIRO's latest "Australian Power Generation Technology Report" advises the current cost of solar thermal electricity is 17.5 to 35.0 c/kWh. Yet ASTRI has proposed a power plant configuration that could achieve a conservative 12.9 c/kWh in the not too distant future. In "Valuing Storage", ASTRI has forecast that solar thermal electricity could be as low as 8 c/kWh in 2025 with 15 hours of storage.

Through the applied expertise of CSIRO and ASTRI's university partners, the team is moving Australia forward on the path to seizing the local industry, global export and economic and environmental opportunities that CST technology presents. It is reassuring to be in the hands of CSIRO to use its track record in creating impact to lead and coordinate these opportunities.

A challenge is for ASTRI to broaden its mandate beyond electricity. It is an exciting time to be involved in this collaboration.

Thanks to all of the ASTRI team, on all campuses, for your continuing hard work and passion.

Kieran Jacka
Chair, ASTRI Advisory Committee

Message from the Director

Concentrating Solar Thermal (CST) started as a vision - to generate electricity from an inexhaustible source, that was available to everyone and which didn't pollute the world.

Today, CST technology stands as a global industry poised for significant growth on the back of the need to decarbonise the world energy system.

With recent rapid development of skills, capability and technology across nations such as Chile, Morocco, China, India and the USA, the International Energy Agency now predicts solar energy technologies (CST and PV) could become the largest source of electricity worldwide before 2050.

What's in it for Australia?

Australia can be at the table when global opportunities for CST market development and technology commercialisation are divided.

Few countries in the world meet the conditions that make Australia one of the strongest, if not the strongest, potential contributors to technologies that will shape the future of this industry.

Enter the Australian Solar Thermal Research Initiative (ASTRI), an eight-year, $87.3 million research initiative designed to support an emerging CST industry in Australia – to deliver cost reductions and dispatchability improvements to CST technologies and to train the new cohort of high-quality and industry-aware graduates with the required CST skills to convert this opportunity into new markets and gross domestic product (GDP) growth for the nation.

Since ASTRI started in November 2012, the research program has achieved the following:

- A significant increase in participation of the Australian research community in CST. This is shown in the participation of Australian researchers in national and international conferences, in the participation of Australian research institutions in international CST research projects and programs, in the quality of the CST proposals submitted to ARENA and other funding bodies, and in the increased numbers of doctoral students and post-doctoral fellows engaged in CST research.
- A dramatic increase in the capabilities and know-how in the field of CST technologies of the Australian universities that are part of ASTRI. This is shown in the increased quality of their contributions to the research program, which reflect a continuous advance in their understanding of the problems and advantages associated to CST technologies.
- The agreement among ASTRI partners on a clear strategy to achieve the fundamental technological challenge of ASTRI – to substantially improve the cost competitiveness of CST technologies for electricity production and for the production of synthetic fuels. This strategy is based upon the concept of ASTRI CST configurations, which are solar power plant configurations with the potential to achieve the technical target of ASTRI in terms of the LCOE of the electricity produced by the power plant or in terms of the LCOE of the synthetic fuels produced.
- The exploration of new exciting disruptive CST technologies with the potential to make a big difference and to position Australia at the forefront of CST technologies worldwide. As a strategic research initiative,

ASTRI has supported research on innovative concepts to deliver relevant research outputs that produce a suite of commercialisable outcomes.

- The gradual emergence of ASTRI as the reference forum where industry, researchers, and policy makers discuss about what opportunities CST can offer to Australia and how to seize these opportunities. This is shown in the increased relevance and developing profile of public aspects of the Annual ASTRI Workshop, the participation of ASTRI representatives in government and industry events, the increased engagement with industry in Australia, and the role that ASTRI is playing in formulating an overall CST strategy for Australia. This strategy was presented at a solar research forum in December 2015 and will require changes to ASTRI to maximise the impact of the research program for Australia.

ASTRI adapting to change

As a response to the Federal Government’s new Innovation and Science Agenda calls for stronger collaboration between industry and research institutions, ASTRI has adapted in recent months from what was originally a strategic science research initiative to more of an industry development approach.

ASTRI is being challenged, alongside its existing technical and capability development, to also take responsibility for goals designed to explore and promote the value proposition of niche market applications of CST technology in the Australian context. We see this as an exciting development and leadership opportunity for ASTRI to influence the CST sector in Australia to ‘opt-into’ and advocate for its adoption across a range of sectors to drive commercialisation and industry creation.

In response to this challenge and opportunity, ASTRI should highlight the prospects for strong realisation of benefits from CST developments for the Australian public and the social benefits of a shift to decarbonise our energy networks and industrial processes as a nation.

In a world context, ASTRI is a unique research program which the Chief Scientist of the US DOE SunShot program commended “for its enthusiasm, professionalism and well-articulated research propositions”, encouraging “researchers to maintain an industrial perspective and to understand how their research in each subsystem interfaces with adjacent subsystems and fits within the context of the overall concentrating solar thermal system”

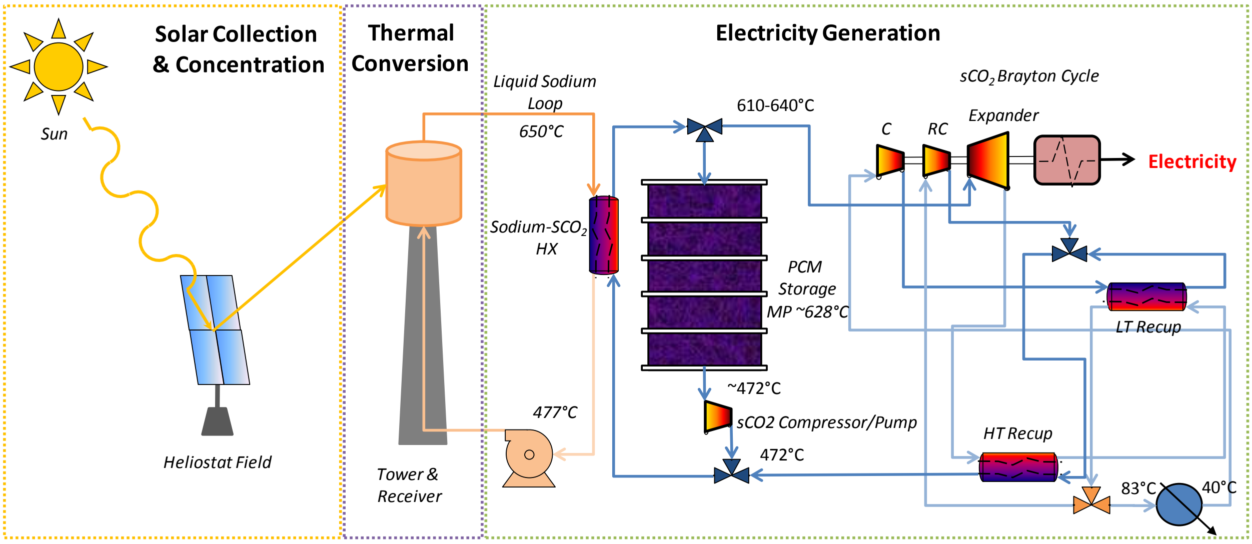
This annual report presents the highlights and achievements of being a multi-intuitional, multi-national and multi-disciplinary research program, focused on capability development through the university sector, to develop CST sub-systems and propose plant system configurations to deliver ambitious technical goals.

Manuel Blanco Ph.D., Dr.Ing
Director, Australian Solar Thermal Research Initiative (ASTRI)

Executive Summary

ASTRI has developed a concentrating solar thermal (CST) power plant configuration that could theoretically achieve a conservative levelised cost of energy (LCOE) of 12.9c/kWh, with an overall annual efficiency of 16.5%. The proposed central receiver tower power plant design is based on a 100-MWe closed-loop supercritical carbon dioxide (sCO_2) Brayton cycle power block, with single-tank phase change material (PCM) thermal storage and sodium (Na) receiver. This novel configuration reflects research outcomes to date and will be further improved.

Central receiver tower system with sodium receiver, phase change material for thermal storage and supercritical CO_2 power block



Technical Highlights and Achievements

HELIOSTAT FIELD COST DOWN PROJECT (P11)

The heliostat and the mirror facet development research shows the drop-in and sandwich panel heliostat concepts have excellent promise for meeting the ASTRI cost target. The development of the mini-facet heliostat is being discontinued due to general doubt over its ability to meet cost targets. Optical modelling shows tilt-roll heliostats achieve higher annual efficiency and higher mirror density in most cases.

Wind turbulence in the atmospheric surface layer needs to be considered for structural design at the maximum height of the heliostat structure. If the size of gusts is larger than the chord length of the heliostat mirror, then the wind loads can lead to structural failure from overstressing when the peak wind stresses exceeds the material capacity of the structure.

RECEIVER PERFORMANCE PROJECT (P12)

A preliminary scale-up study for the tubular sodium receiver indicated that a receiver efficiency of 88% is achievable with an expectation that the 91% performance target will be achievable once non-uniform flux and possibly cavity geometry is incorporated into the design.

Both particle receiver concepts are advancing well and appear to have a good prospect of meeting project performance targets, although more work is required to produce efficiency estimates for the vortex receiver in particular.

HIGH-TEMPERATURE THERMAL STORAGE PROJECT (P21)

The main findings have involved the selection of materials for investigation and the planning of the investigation based on reviews and leveraging relevant work in other ASTRI projects. The estimated unit cost of selected storage technologies ranges from $9/kWh$_t$ to $40/kWh$_t$.

The technical and economic characterisation requirements for candidate materials for different storage systems have been identified. This has assisted in the identification of several potential thermochemical cycle systems that are compatible with the temperatures proposed in the receiver project and the sCO_2 power cycle project. The preliminary costing of materials for thermochemical cycles and an understanding of the costs associated with other particle storage media have assisted with selection of initial concept design of novel storage systems and plans for their investigation.

RELIABLE, LOW-COST, PHASE-CHANGE MATERIAL THERMAL STORAGE SYSTEMS PROJECT (P22)

Five candidate phase-change material (PCMs) have been identified, with storage temperatures ranging from 540 °C up to 710 °C. A new encapsulation system comprising a geopolymer made from fly ash and black slag is being developed. This is ideal for corrosive PCMs such as those based on chloride salts as well as providing high rates of heat transmission. The tube-in-tank flow configuration which maximises latent energy extraction is the two-dimensional counterflow arrangement

SUPERCRITICAL CO_2 POWER BLOCK PROJECT (P31A)

Completion of the techno-economic analysis identified that using a temperature of approximately 610 °C offers the best development target for achieving low cost electricity. Development of a radial turbine through a staged scale-up of size and conditions is proceeding to this design temperature.

Development of the hybrid cooling tower has been proceeding with spray dispersion modelling conducted and pilot plant commissioning underway.

ALTERNATIVE POWER BLOCK PROJECT (P32)

Development of sub/trans-critical Rankine and Brayton Cycles has reviewed regeneration and reheat and intercooling, showing that a Rankine cycle with reheat/intercooling provides a favourable efficiency. Since Rankine cycles appear to be well suited to utilising a wide operating temperature range with little change in efficiency, a cycle design can potentially be tailored to improve the economics of the combined solar heating and storage system. Analysis of regenerative Brayton cycles with a range of alternative working fluids suggested that sCO_2 was the most viable working fluid for efficient operation, with alternative working fluids having significantly lower efficiency.

COST-EFFECTIVE OPERATIONS AND MAINTENANCE PROJECT (P41)

The key mirror cleaning parameters affecting mirror cleaning have been identified. In doing so, it is now evident the test facility to validate the models and measure the cleaning efficiencies of various techniques requires improvement to change the mirror positions and angles to optimise the nozzle orientation for the effective cleaning. Procedures for the synthesis of dual-scale roughness for hydrophobic films to reduce moisture that promotes soiling have been developed and demonstrated.

A failure modes and effects analysis (FMEA) has been implemented for the five major subsystems of CST power plant: (1) collector system, (2) receiver system, (3) thermal storage subsystem, (4) steam generation subsystem and (5) electrical generation subsystem. The completed receiver system analysis highlighted a loss of absorptivity due to coating degradation is one of the major failure modes.

Dust produced at several Australian sites has been characterised, allowing development of physical models for the degradation processes, starting with the mirror soiling model. This includes correlation analysis of dust concentration vs. environmental conditions for the development of a mirror fouling model using existing data.

SOLAR FUELS PROJECT (P42)

Our research into broadening the value to CST technologies has established cost targets for solar fuel plants. The ASTRI levelised cost of fuel (LCOF) targets ranges are:

- A target of $0.90/L for lignite coal feedstock and $1.0/L for solar reforming of natural gas,
- A target of $1.20/L for conventional renewable feedstock with a life-cycle emission of CO_2 that is at least 10% lower than conventional diesel, and
- A target of $2.50/L for future renewable feedstock with a life-cycle emission of CO_2 that is at least 50% lower than conventional diesel.

The qualitative solar fuels evaluation matrix devised in a scoping study has been revised to a quantitative matrix for comparing solar fuels from all available CST technologies and feedstocks. A published performance assessment of Fischer-Tropsch (FT) liquid fuels production using solar hybridised dual fluidised bed gasification of lignite showed the annual solar share depends of the char conversion and quality of the solar resource. For a solar multiple of 3 and bed material storage capacity of 16 h, assuming a char conversion of 100%, the annually averaged utilisation factor of the heliostat field was 40.8% and annual solar share was 21.8%.

Progress against Program Outcomes

PEOPLE

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

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

Human heliostats – Convergence is harder than it looks

LARGE-SCALE COLLABORATION

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

Collaboration in ASTRI research projects

	Nodes and Project Collaboration		CSIRO	ANU	UQ	UoA	UniSA	QUT	Flinders	SNL	NREL	ASU	Other
P01	**Overarching Economic Model**	1	Lead	x	x	x	x				x		
	Node 1: Reduce capital expenditure (CapEX)			Lead					CoLead				
P11	Heliostat Field Cost Down	2	x	Lead		x	x		x	x	x		
P12	Receiver Performance	3	x	Lead	x	x			x	x			
	Node 2: Increase capacity factor		Lead				CoLead						
P21	High-temperature storage technology	4	Lead	x		x	x			x	x		
P22	Reliable low-cost PCM thermal storage	5	x				Lead	x			x		x
	Node 3: Improve efficiency		CoLead		Lead								
P31	Supercritical CO2 power block	6	x		Lead			x		x	x		x
P31	Alternative power blocks	7	Lead		x			x					x
	Node 4: Add Product Value					Lead		CoLead					
P41	Cost Effective Operations and Maintenance	8	x	x	x			Lead	x				x
P42	Solar Fuels	9	x	x		Lead	x		x			x	xx
P02	**Education Program**	10	x	x	x	Lead	x	x	x			x	x

ASTRI continues its commitment to collaboration across the six universities and CSIRO, spanning three states and the Australian Capital Territory. This collaboration has been made possible by the wide use of teleconferencing and videoconferencing tools, as well as visits between institutions where it is deemed more appropriate. Our well-run and targeted research projects facilitate this interaction, with planned monthly meetings between multiple institutions. Project Leaders ensure that other ASTRI researchers are kept updated through monthly updates on the ASTRI wiki and monthly meetings. These have proved fruitful, with many ideas being developed.

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

ENGAGEMENT AND LINKAGES

A core engagement for ASTRI resulted from its establishment as a Strategic Research Initiative (SRI) under the United States-Australia Solar Energy Collaboration (USASEC) in 2012. From this, Dr Ranga Pitchumani continued being the US DOE member of the ASTRI Advisory Committee until he returned to his university post. Dr Joe Stekli will take up this important role and continue encouraging collaboration and engagement with the National Renewable Energy Laboratory (NREL), Sandia National Laboratory (SNL) as well as Arizona State University (ASU).

The Director of ASTRI, Dr Manuel Blanco, has spent significant effort to network with other leaders in CST and to search for potential partnerships. In 2015 Dr Blanco was awarded a prestigious Chair of Excellence at Universidad Carlos III de Madrid (Spain). The award funds allowed Dr Blanco to be based at the university and establish collaboration with the department of Thermal and Fluids Engineering on the development of open source modelling tools that ASTRI is leading to increase the accuracy of prediction and decrease the risk of new technology concepts. ASTRI has looked to Europe for collaboration, with potential linkages through SolarPACES and STAGE-STE. This placement also allowed Dr Blanco to make contact with a range of companies in Spain and Europe on behalf of ASTRI, as well travel and have discussions about further interactions with China, India and South Africa, who are all emerging players in CST.

Direct engagement with industry and government has resulted in a range of contributions to ASTRI projects. ASTRI has valuable in-kind support from RATCH-Australia for the mirror cleaning part of the operation and maintenance (O&M) project. Funds from the Queensland Government have helped in the development of research infrastructure for the hybrid cooling tower to be used in the supercritical carbon dioxide (sCO_2) project. The total value of support from these funding partners has been $527,000. Currently, ASTRI is seeking more direct and technical involvement with particular projects, as well as more general support. Costing review is also a valuable contribution that industry can make to the ASTRI research program.

ASTRI display at the Australian Parliament House in August 2015

KNOWLEDGE SHARING

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

With support from ARENA, the ASTRI Annual Workshop in February 2015 was a major success with a Public Symposium on Cost Reduction Status of Concentrating Solar Thermal (CST) Technologies, bringing together researchers, industry, government, as well as international experts. The ASTRI Economic Workshop initiated a dialogue between the researchers, CST industry, and government; ultimately providing endorsement for ASTRI's economic modelling that underpins the demonstration of technical progress. The internal workshop highlighted the direction and achievements of 2014, which were endorsed by the international experts and resulted in a media release from ARENA.

ASTRI has significantly increased the focus on communications with the appointment of a dedicated Communications Advisor. A broad range of ASTRI stakeholders including Federal Government, industry, media and partners have been engaged and briefed on program progress and milestones. This was achieved via a range of channels including events, media relations, briefings, and speaking engagements.

Key highlights were the ARENA 'Tomorrow's Energy Solutions Showcase' at Parliament House which provided the opportunity to brief and engage more than 160 Parliamentarians, Senators and advisors on CST and the opportunity for Australia, as well as the opportunity created by ASTRI for Louise Vickery from ARENA to present at the annual SolarPACES conference in Cape Town, South Africa.

Two media announcements communicated the value of global collaboration in advancing CST technology developments in Australia as well as the value proposition of CST power plants with storage for Australia's renewable energy future. The two announcements were:

- 'Print your own 3D solar field' – covering publication and dissemination of ASTRI's 3D printable 25MW solar field and CST power plant model (desktop); and
- 'ASTRI Director appointed chair of international solar thermal collaboration' – covering Dr Manuel Blanco's re-election as Chairman of the International Energy Agency Executive Committee for SolarPACES.

Close collaboration with ARENA saw cross promotion of these announcements via traditional and social media platforms.

Cross promotion of 'Print your own 3D solar field', October 2015

https://twitter.com/arena_aus/status/656612558552494081

http://www.astri.org.au/uncategorized/print-your-own-solar-field/

About Concentrating Solar Thermal Technologies

Concentrating solar thermal (CST) technologies can produce high-temperature solar thermal energy that can be used to drive industrial processes, including electricity production, and to drive chemical reactions. The most proven CST technologies generate electricity using sunlight.

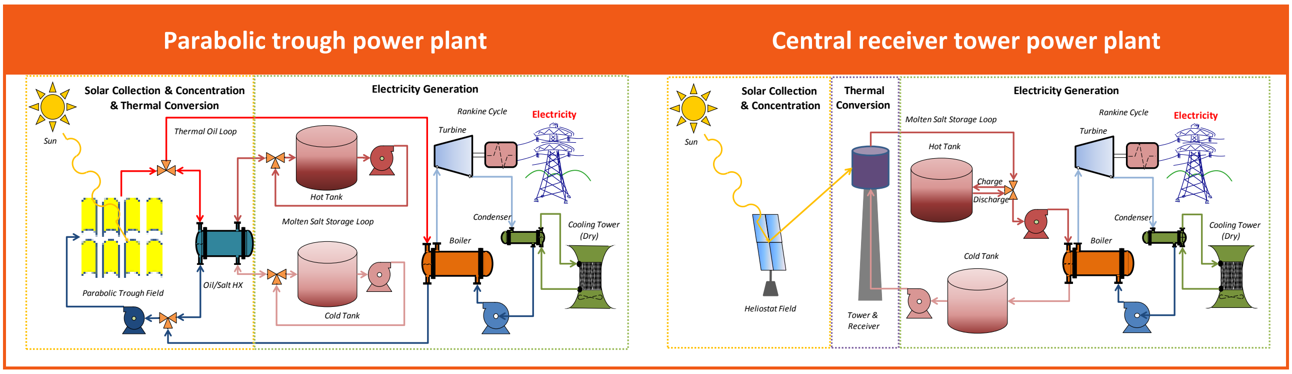
In all CST technologies, reflectors are used to collect the solar radiation and concentrate it on a receiver with a much smaller area. A higher concentration ratio of reflector-to-receiver area produces higher flux at the receiver, allowing higher temperatures to be achieved in a heat transfer fluid. The thermal energy in the heat transfer fluid can then either be stored, or converted into process heat, or converted into mechanical energy and ultimately into electricity through a power cycle.

The most significant advantage of CST technologies over other renewable energy technologies is their ability to store thermal energy and convert it into process heat or into electricity when needed; dispatchable power generation.

The most common energy storage medium is molten salt, and the most conventional power cycle is the superheated steam Rankine cycle. The Rankine cycle is also used in fossil fuel and nuclear power plants, but CST technologies have the potential to achieve more efficient power cycles at higher temperatures. The most proven CST power plants use parabolic troughs, although the rapidly emerging alternative is a central receiver tower, sometimes referred to as a power tower.

Parabolic troughs are linear focusing technologies, with a concentration ratio of 50–80. The trough reflects the sun's rays onto a linear receiver fixed at the focus on the parabola, and tracks the sun in one direction – normally from east to west. The receiver usually consists of an absorber metal pipe insulated inside an evacuated glass tube. A synthetic oil is generally used as the heat transfer fluid, which can be heated to temperatures of around 400 °C.

Central receiver towers are point-focusing technologies with a concentration ratio of about 200–1000. A field of many mirrors, called heliostats, reflects the sun's rays onto a central receiver located on a distant tower, possibly a 1km away. Each heliostat has two-axis-tracking to direct the sun's rays towards the central receiver, which is normally an array of absorber tubes, referred to as an external receiver. The heat transfer fluid in the absorber tubes could be molten salt, which can be heated to temperatures of around 560 °C, or steam. Other heat transfer fluids are under consideration, as well as cavity receivers, which partially insulate the absorber tubes to reduce heat losses.



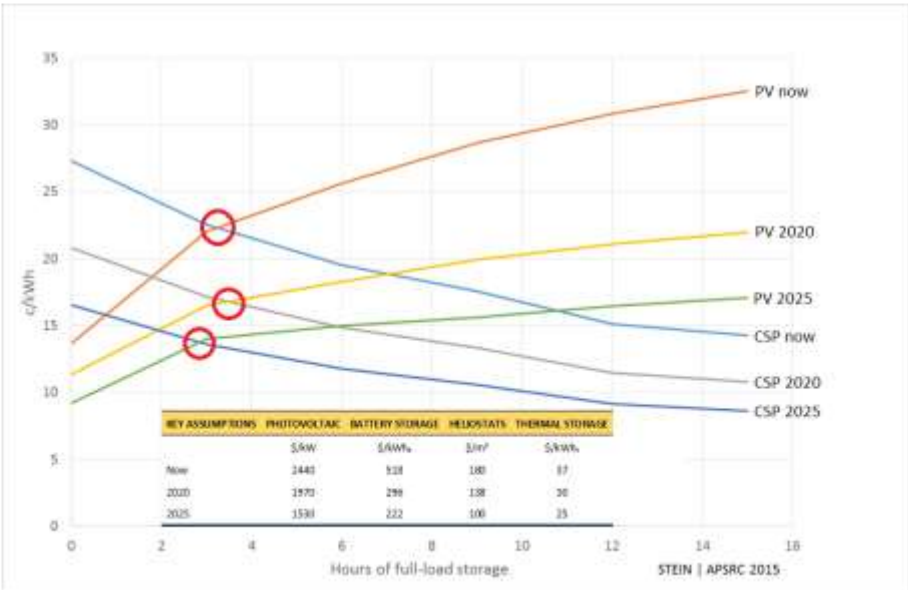
Valuing Storage

At a time of higher emphasis being placed on storage systems as a whole and electrical storage in particular to facilitate further utilisation of renewables, the role of thermal storage which provides a more economical storage option becomes even more significant. The potential for integrating the much lower cost thermal storage needs highlighting in the current dialogue on large electrical storage installation.

The energy industry is presently strongly promoting the benefits of battery storage to both support grid stability as non-dispatchable renewables (PV and wind) are deployed, and to also allow arbitrage benefits resulting from variable electricity prices across the day and year. At the present time, domestic level battery storage is available from retailers for approximately \$1700/kWh$_e$ (eg Tesla Powerwall). It is anticipated that this cost will fall dramatically, although even a ten-fold decrease would still leave it more expensive than existing 2-tank molten salt storage (approx. \$115/kWh$_e$) and much more than future thermal storage where installed costs could be approximately \$60/kWh$_e$ resulting from both global and national research.

It is important however to consider a complete system including both the generation and storage of renewable electricity. The graph of "LCOE break-even point of CSP with thermal storage against PV and battery storage" summarises this analysis, showing a few possible scenarios. It clearly shows the economic benefits of thermal storage integrated with CSP over PV + battery systems when more than a few hours of storage is required. Note that this analysis is not dependent upon whether the battery storage is large scale grid-connected or "behind-the-meter". Note also that this is an LCOE analysis and as such does not consider the additional value that storage can realise from time-of-use price signals. Such an analysis would further enhance the lower cost storage options.

Increased levels of storage improve the value proposition for CSP

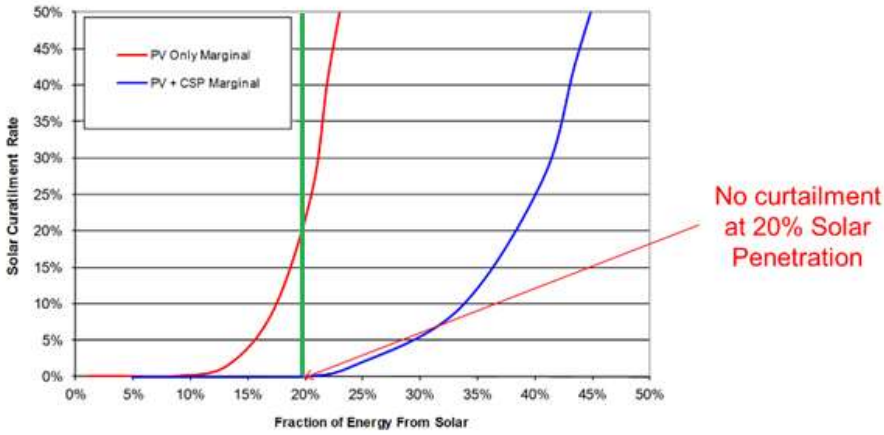


LCOE break-even point of CSP with thermal storage against PV and battery storage

The other key value that low cost thermal storage provides, is in underpinning the increased penetration of variable renewables such as PV and wind. This issue is becoming increasingly apparent in regions such as South Australia and the ACT where high levels of renewables are mandated but will not be achievable without low cost storage. As PVs in particular reach higher penetrations, the larger generators are expected to ramp down as PVs come on in the morning and then ramp up as the sun goes down. This is increasingly uneconomic for those units, and can create the conditions of an unstable grid. Work by NREL has quantified this effect in the Californian market. The graph of “Curtailment of solar assuming an equal mix (on an energy basis) of PV and CSP” illustrates, for one particular scenario, how dispatchable CSP can increase the penetration of PV.

It is important to note that much of this benefit comes from the additional flexibility that newer more modern and modular turbines integrated in CSP systems do afford over the existing fossil-fired steam turbines.

Beneficial impact of low cost CSP storage on the increased penetration of PV’s



Curtailment of solar assuming an equal mix (on an energy basis) of PV and CSP

Denholm, P. and Mehos, M. (2011) “Enabling Greater Penetration of Solar Power via the Use of CSP with Thermal Energy Storage” Technical Report NREL/TP-6A20-52978

ASTRI Research Structure and Governance

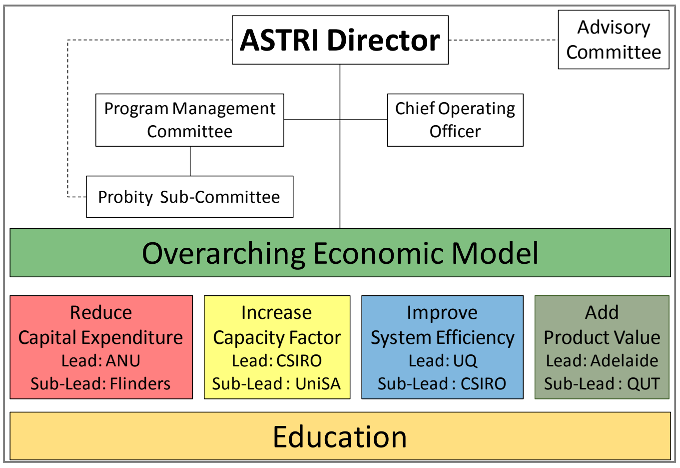
The governance framework within ASTRI has a node structure based on technology challenges to ensure the partners commit to the broader strategic objectives. The intent is to work towards collaborative outcomes greater than each partner can realise independently.

ASTRI has been implemented through:

- A Funding Agreement between the Australian Renewable Energy Agency (ARENA) and CSIRO as the ASTRI lead party
- A Collaborative Research Agreement between CSIRO and the Australian partner Universities to pass through required terms and provide a framework for the conduct and management of the Program.

The Australian partner institutes that make up ASTRI are CSIRO and the following six universities: Australian National University (ANU), University of Queensland (UQ), University of Adelaide (UA), University of South Australia (UniSA), Queensland University of Technology (QUT) and Flinders University (UF).

ASTRI Governance Reporting Structure



The three key governing bodies within ASTRI are the Advisory Committee, Program Management Committee and Probity Sub-Committee.

- *Advisory Committee:* provides advice on the strategic direction of ASTRI through review and contributions to the development of annual strategic plans. The members of the Advisory Committee have been chosen to include representatives with research management, finance and commercial skills and experience.
- *Program Management Committee:* provides advice and assistance to the ASTRI Director on the research program and ongoing management of ASTRI. The Program Management Committee comprises the Principal Investigators, who represent their university and the node in which their university is a leader or co-Leader.

- *Probity Sub-Committee*: reviews decisions in ASTRI about CSIRO, since the Director is a CSIRO employee. The membership is from the Program Management Committee to provide support on decisions relating to resources and conflicts of interests and probity.

This last year has seen a number of changes in people within this governance structure.

- The Advisory Committee Chairman and Industry Advisor, Mr Kieran Jacka, left Acciona and remains chairman of the committee as an independent industry advisor
- The other inaugural Advisory Committee Industry Advisor, Mr Anthony Wiseman, left AREVA and resigned from the committee
- The Advisory Committee welcomed Mr James Fisher from Vast Solar as an Industry Advisor
- The Advisory Committee welcomed Mr James Harding from Abengoa Solar as an Industry Advisor
- The CSIRO representative on the Advisory Committee, Dr Jim Smitham, retired and was replaced by Dr David Harris, CSIRO Energy Research Program Director for Low Emissions Technology
- The US DOE representative on the Advisory Committee, Dr Ranga Pitchumani, returned to his academic posting and is to be replaced by Mr Joe Stekli
- The Principal Investigator from the Queensland University of Technology, Prof John Barry, retired and was replaced by Prof Ted Steinberg
- Of the other Key Personnel in ASTRI, Prof Bassam Dally from the University of Adelaide, has handed over to Prof Maziar Arjomandi.

Advisory Committee Members

Chairman and Industry Advisor
Mr Kieran Jacka
Independent Industry Advisor

Industry Advisor
Mr James Fisher
Vast Solar

Industry Advisor
Mr James Harding
Abengoa Solar

ARENA Representative
Ms Louise Vickery
Projects
General Manager

CSIRO Representative
Dr David Harris
CSIRO Energy Flagship
Research Director

Program Management Committee Representative
Prof Paul Meredith
University of Queensland
Principal Investigator

US DOE Representative
Dr Ranga Pitchumani *
SunShot
Chief Scientist

* To be replaced by
Mr Joe Stekli

Program Management Committee

Chairman
Dr Manuel Blanco
CSIRO
ASTRI Director

Mr Wes Stein
CSIRO
Principal Investigator
Node 2 Leader

Prof Wojciech Lipinski
Australian National University
Principal Investigator
Member of Probity Sub-committee

Prof Paul Meredith
The University of Queensland
Principal Investigator
Advisory Committee Representative

Prof Gus Nathan
The University of Adelaide
Principal Investigator
Node 4 Leader

Prof Wasim Saman
University of South Australia
Principal Investigator
Node 2 Co-Leader
Member of Probity Sub-committee

Prof Ted Steinberg
Queensland University of Technology
Principal Investigator
Node 4 Co-Leader

Prof David Lewis
Flinders University
Principal Investigator
Node 1 Co-Leader

Other Key Personnel

Dr John Pye
Australian National University
Node 1 Leader

Prof Hal Gurgenci
The University of Queensland
Node 3 Leader

Prof Dr Maziar Arjomandi
The University of Adelaide
Education Leader

Dr Andrew Beath
CSIRO
Overarching Economic Model Leader
Node 3 Co-Leader

Ms Sarah Miller
CSIRO
Chief Operating Officer

ASTRI Project Leaders

Dr Andrew Beath
CSIRO
P01 Project Leader
Overarching Economic Model

Dr Maziar Arjomandi
The University of Adelaide
P02 Project Leader
Education

Dr Joe Coventry
Australian National University
P11 Project Leader
Heliostat Field Cost Down

Dr Joe Coventry
Australian National University
P12 Project Leader
Receiver Performance

Dr Jim Hinkley
CSIRO
P21 Project Leader
High temperature storage

Prof Wasim Saman
University of South Australia
P22 Project Leader
Reliable low-cost phase change material thermal storage systems for CST

Dr Kamel Hooman
The University of Queensland
P31 Project Leader
Supercritical CO2 Systems - Power block

Dr Emilie Sauret
Queensland University of Technology
P32 Project Leader
Alternative power blocks

Prof Ted Steinberg
Queensland University of Technology
P41 Project Leader
Operations and Maintenance

Prof Gus Nathan
The University of Adelaide
P42 Project Leader
Solar Fuels

Progress towards Program Outcomes

ASTRI was initiated as a Strategic Research Initiative (SRI) under the United States-Australia Solar Energy Collaboration (USASEC). ASTRI, for the first time in Australia, draws together leading researchers from universities plus CSIRO to create a dedicated CST research community committed to collaboration. Our progress towards the major outcomes are as follows:

Large-scale collaboration on CST across Australia serving as platform for new international linkages

ASTRI has created a **large-scale collaboration** across three states of Australia and the ACT, with a focus on significant well-run and targeted research projects rather than many small projects. The initial period of ASTRI was devoted to cementing the partners and improving the knowledge base about CST to grow a mature targeted research community, noting most of the ASTRI members had not worked together before. The focus on significant projects has also encouraged two projects to have a postdoctoral fellow and a senior research fellow assist with project management, thereby increasing the experience of these researchers within ASTRI and their preparedness for leadership within an Australian CST industry and the research community. Project Leaders applauded their project reviews as being beneficial and arising uniquely from such a large-scale collaboration.

Australia has considerable potential for CST, based on its solar resource and ability to deliver large scale, world class infrastructure. However, Australia cannot reduce the cost of CST technology alone. It must connect with international development led by industry and supported by governments that target accelerated cost reduction pathways through collaboration and the development and commercialisation of new technologies. ASTRI is the platform both for Australian engagement with international developments, primarily the USA Solar Energy Collaboration (USASEC), and for forging the pathways for the growth of CST in Australia. At SolarPACES in 2015, there was an agreement that one of the most valuable US collaboration activities will be review of the ASTRI CST configurations.

Step-change in the commitment of Australian researchers to the success of CST

The commitment of Australian researchers to the success of CST has previously been cyclical and dependent upon funding opportunities. When ASTRI was proposed, only CSIRO and the Australian National University (ANU) had any significant research CST activity, with the other universities having played active roles in research propositions on “proven” technologies under the Solar Flagships Program. Four of the ASTRI research partners had CST projects with funding from the Australian Solar Institute, now ARENA.

Prior to ASTRI, CSIRO had 20 full-time staff in the Solar Group focussing on CST research, with a further 13 full-time-equivalent staff contributing specific skills from across CSIRO to predominantly co-investment applied research projects. The majority of these CSIRO staff are still dependent upon the cyclical funding opportunities, with ASTRI involving those members with the best CST knowledge, research management skills and academic standing to supervise doctoral students. For CSIRO, ASTRI is a strategic research program to lay a foundation for developing next generation CST improvement concepts and cost reductions.

Prior to ASTRI, ANU was seeking to build on its pioneering role in the development concentrating solar thermal technologies and strengthen its research presence in concentrating solar thermal engineering. Through the commitment of ASTRI, ANU made 2 senior academic appointments, with Prof Al Weimer appointed and adjunct Chair in Solar Thermal Engineering and Dr Wojciech Lipinski appointed as an Associate Professor in Solar Thermal Engineering.

The University of Queensland combines its expertise from UQ Solar (photovoltaic) and Mechanical Engineering to lead the ASTRI supercritical CO2 power block development through radial turbine development and hybrid cooling. The main contribution from The University of Adelaide to ASTRI is in the development of low cost solar fuels, with interests in receiver development and heliostat aerodynamics. The University of South Australia has strong background in phase change materials for energy storage at ambient temperatures and are moving to high temperature systems for CST. In 2015, Associate Professor Frank Bruno and team won the ANSTO Eureka Prize for Innovative Use of Technology Winner for "Melting salt to store solar power". The Queensland University of Technology and Flinders University both bring material science capabilities to ASTRI, together providing expertise in corrosion, nano-coatings and catalysis.

2015 ANSTO Eureka Prize Winner, Associate Professor Frank Bruno

Within ASTRI, a challenge is to deliver both academic qualities in the research as well as contribute to the cost reduction in CST. It is expected that the academic quality will be delivered through post-graduate research topics, with their academic supervisors being "the glue" with responsibility to ensure relevance of the outcomes to the ASTRI Node targets and ultimately the ASTRI LCOE reductions.

Several indicators that ASTRI is adding value in the **step-change in the commitment** of Australian researchers to the success of CST are:

- By taking a systems approach whereby each ASTRI research project needs to contribute to the reduction of the LCOE of the overall system concept either by reducing the cost of a component or subsystem, improving its efficiency without substantially increasing its cost, or both. In 2015, this led to identifying 16 topics for ASTRI Round 3 expressions of interest
- The influence of ASTRI on the quality of solar thermal submissions in the ARENA R&D rounds, with researchers cross referencing projects and highlighting how the new submissions fitted with ASTRI projects and existing ARENA projects
- A solar fuels project with cost targets. This is believed to set a world bench mark, and it addresses an issue that has also been identified at the international level by the IEA SolarPACES, the Implementing Agreement of the International Energy Agency (IEA) for Solar Process and Chemical Energy Systems. A SolarPACES Executive Committee meeting in 2014 discussed the convenience of establishing some type of cost target for solar chemistry technologies, in order to facilitate assessing progress in the

development of those technologies. ASTRI has already established levelised cost of fuel (LCOF) targets, with being:

- A target of \$0.90/L for lignite coal feedstock and \$1.0/L for solar reforming of natural gas,
- A target of \$1.20/L for conventional renewable feedstock with a life-cycle emission of CO_2 that is at least 10% lower than conventional diesel, and
- A target of \$2.50/L for future renewable feedstock with a life-cycle emission of CO_2 that is at least 50% lower than conventional diesel.

Highly trained graduates ready to deliver success in CST industries

Prior to ASTRI, there was no dedicated undergraduate concentrating solar thermal technologies degree anywhere in the world. ASTRI is developing education course modules to inform **highly-trained graduates** of CST and to deliver success in CST industries. As a multi-disciplinary topic, the modules can be flexibly targeted at under-graduates in a range of science and engineering courses, as well as contribute to coursework programs and short courses for post-graduate students. Attempts to ensure the concentrating solar thermal course modules are complimentary with exiting courses in photovoltaics have been limited by IP concerns.

In 2014 a CST training course was run within ASTRI. This course targeted researchers new to CST or ASTRI. The attendance to the course exceeded initial expectations. Those attending the CST course rated it highly, and also valued the opportunity to network with other researchers with expertise in a large variety of different disciplines. In 2015, the ASTRI Annual workshop included simple CST activities that required a breadth of CST knowledge that could be best achieved by teamwork.

ASTRI had major growth spurts with the each round of project approvals and continues to grow with quality staff, postdoctoral fellows and students. The post-graduate completion rate is expected to trend above the milestone requirements, with two Masters students having completed their project.

Relevant research outputs: novel technologies, concepts, know-how, publications and patents

The structure of ASTRI as a large-scale collaboration with technical nodes also ensures the research topics are synergistic and projects will deliver **relevant research outputs** and a suite of **commercialisable outcomes**. This focus on significant projects also creates a critical mass in each topic that facilitates **international linkages**, with interest from the USA and many other countries around the world.

Researchers equipped to engage in the science and technology debates that may underpin Government policy towards CST adoption

The ASTRI Overarching Economic Model is intended to inform ASTRI researchers and provide a unifying factual basis upon which researchers equipped to engage in the science and technology debates. While passionate about their own research, researchers are often ill-equipped to provide informed comment outside their areas of specialty. A key aspect of this is to understand how their specific areas of research will impact on LCOE, overall system performance and added-value that CST technologies bring to the energy marketplace. A further early career “Young Suns” day is planned for the 4th ASTRI Annual workshop to purse this further for the current cohort of student and postdoctoral fellows.

Performance against the ASTRI Objectives

ASTRI was initiated as a Strategic Research Initiative (SRI) under the United States-Australia Solar Energy Collaboration (USASEC) and the ASTRI objectives were formulated in terms of the SRI objectives. Our performance against these objectives is as follows:

Research Quality

Objective: to undertake highly innovative and internationally competitive research with a strategic focus on CST technologies that will lead to breakthroughs in the cost of solar energy.

KPI: Number of refereed journal publications

Since ASTRI commenced in December 2012, twenty-nine refereed journal papers have been published. Eleven other articles have been drafted and are in various stages of the review process.

The published journal articles have mainly come from the first-round projects, with several on the topic of hybrid cooling and related to phase-change materials (PCMs). Papers related to solar fuels, receivers and heliostats topics are starting to emerge and future papers will come from a wider variety of projects and activities.

The full list of refereed journal papers published by ASTRI are listed under Publications and Presentations.

KPI: Percentage of joint refereed journal publications

The published papers have not yet shown a true reflection of the collaboration, with only four of the published papers being authored by more than one ASTRI partner institutions. There are a further five publications involving US partners or non-ASTRI partners. While this demonstrates ASTRI is achieving the intended highly innovative and internationally competitive research, there is still a need to ensure that there is meaningful collaboration between institutions on research which result in future joint journal articles.

United States Collaboration

Objective: to participate in significant collaborations with leading United States researchers and institutions.

KPI: Visits to/from United States Collaborators

There six visits this year involving US partners involved

- The US-DOE Chief Scientist, Dr Ranga Pitchumani, attending the ASTRI Annual Workshop in February and interacting with many of the researchers as well as Advisory Committee
- US researchers attending meetings of different ASTRI project teams
- ASTRI researchers having discussions with potential collaborators while in the US, and
- The Director having discussions with ARENA and US collaborators about US involvement in ASTRI

This demonstrates that interactions are occurring on many level which is required for a program of this size. While potential collaboration topics have been identified from these exchanges, funding opportunities to support United States researchers remain a hurdle.

An important outcome of discussions between the Director, ARENA and US collaborators about US involvement in ASTRI is the agreement that US collaborators will review the ASTRI CST configurations. This review will allow timely peer review of the technology concepts, as well as cost comparisons from the US perspective. Interacting on this high-level of detail will also provide an entry point for more targeted collaboration.

ASTRI Public Symposium in February 2015

Dr Ranga Pitchumani, US DOE

Dr Luis Crespo, ESTELA

KPI: Number of new projects started with United States institutions

ASTRI projects have nominated United States participation and the ASTRI Solar Fuels project, P42, has formalised collaboration on two activities through visiting scientist agreements. The ASTRI partners have published several papers involving US contributors that represent new projects on phase change material and hybrid cooling towers with US institutions. In order to ensure that ASTRI optimises its gains from these collaborations, ASTRI Project Leaders report monthly on research exchanges with US research partners.

In addition to these projects, the partners ASTRI have had visiting students or scientists and other research engagement with CAS (China), CIEMAT (Spain), ETH Zurich (Switzerland), KIT (Germany), Loughborough Uni (UK), UMH (Spain), Uni Padua (Italy), Uni Texas (Austin), Universidad Carlos III de Madrid (Spain), Universitat de Barcelona (Spain), University of Lleida (Spain), University of Montpelier (France), VKI (Belgium).

Human Capacity

Objective: to build human capacity in solar research and development by supporting researchers of high international standing as well as the most promising emerging and mid-career researchers.

KPI: Number of new staff/postdocs/PhDs recruited

Since 2014, ASTRI has grown from a collaboration involving 97 researchers, postdocs and students, to include another 48 people. The number of students has grown from 21 to 43 post-graduate students, including 6 Masters students. There has been 144 researchers involved in ASTRI, with 2 Masters who completed their projects and 17 people who have resigned, making a current total of 125 researchers in ASTRI.

There was a team of 7 researchers from CSIRO's Manufacturing and Minerals Flagships who came as a team to develop the drop-in heliostat concept under the guidance of Manuel Blanco. This CSIRO team have contributed significantly to the cost analysis for the other heliostat concept development. There were 17 people who joined ASTRI from UQ's geothermal research centre. This included 8 post-graduate students, 5 postdoctoral follows and 4 researchers. The full list of ASTRI researchers is in ASTRI People.

Of the 144 researchers involved in ASTRI, the number of staff/postdocs/PhDs recruited considered new to CST is 122, being:

- 4 of the ASTRI Leaders not involved in the development of ASTRI
- 44 post-graduate students
- 25 post-doctoral fellows
- 49 of the researchers are considered new to CST.

KPI: Accumulative number of postgraduate student completions

Two Masters' students have completed industrial placements within ASTRI at CSIRO in 2014. One student played a crucial role in the design of the reference heliostat field, while the other undertook a preliminary cost study for storage using PCMs. The first ASTRI PhD completions are not expected until 2016 with many completions expected the following year 2017.

Collaboration Involving Research Training

Objective: to strengthen institutional capability by providing high-quality training environments for the next generation of researchers.

KPI: Number of student/staff visits between partner institutions

To promote collaboration, ASTRI has committed to student/staff visits between partner institutions. Exchanges between institutions have become commonplace, with kick-off meetings, co-supervision, use of research infrastructure, and learning activities accounting for most of the visits. Monthly team meetings more commonly occurred by video or telephone conferencing. The visits are occurring across the nodes now that the projects are established. The collaboration within ASTRI has increased with 40 visits between institutions in the last year, double target metric.

Postgradaute students and Postdoctoral fellows

Industry Engagement

Objective: to partner with and engage industry stakeholders to identify and provide pathways for commercialisation of technology.

ASTRI Economic Workshop in February 2015




KPI: Funding from external sources

An example of early stakeholder engagement is an award to UQ from the Queensland State Government Futures Co-Investment Fund for hybrid cooling research infrastructure. There is a direct contribution of $391,923 from the grant of $1.5M to design, commission and evaluate this infrastructure for ASTRI.

Other stakeholder engagements include in-kind contributions in the form of dust monitoring equipment and staff to conduct the dust monitoring requirements from an industry stakeholder. This is equivalent to $15,360 per annum.

In 2014, CSIRO was contracted to deliver a 10-day intensive training course to a multinational company that was fully costed at $65,800. The company paid for the ASTRI Director to make a follow-up visit, which reinforced the company’s intent to enter the CST industry. These was also a $38,885 contribution through Carlos III University for the ASTRI Director as a Chair of Excellence, providing funds allowing Dr Blanco to make contact with a range of companies in Spain and Europe. ASTRI has also looked to Europe for collaboration, with potential linkages through SolarPACES and STAGE-STE. Discussions have been held about further interactions with China, India and South Africa, who are all emerging players in CST.

Knowledge Transfer

Objective: to facilitate the transfer of knowledge through public education about solar energy technologies and research outcomes, and the provision of support for policy development.

KPI: Number of conference presentations

ASTRI is excelling in sharing knowledge created through conferences, having a total of 55 conference presentations compared to the proposed target of 15. A number of these were presented to solar thermal audiences with 9 presentations at SolarPACES 2015. Most presentations were made to non-solar thermal audiences, being disciplines such as fluid mechanics, heat transfer, thermodynamics and mechanical engineering. There is diversity, not only in the research areas, but also in the mix of the development of analysis techniques for CST technologies versus exploring opportunities for further research. This demonstrates the essential mix of creativity and rigorous analysis that leads to good research is a part of ASTRI.

In February 2015, ASTRI hosted two public events; a public symposium and the economic workshop were both held in Brisbane after the internal ASTRI workshop day. The public symposium had 121 people register, with 43 being from industry or government. The economic workshop was by invitation only, with 10 of the 32 attendees from industry or government.

A presentation targeted to a broader Australian energy audience was a Australian Institute of Energy (AIE) Solar Seminar held in Newcastle on 3 September 2015 titled “Concentrating Solar Thermal: Developments and Research Needs”. This Solar Seminar attracted an audience of 50 people with live stream that included attendees from Europe and a video recording available to all 1200 AIE members.

Power blocks Project Review in June 2016

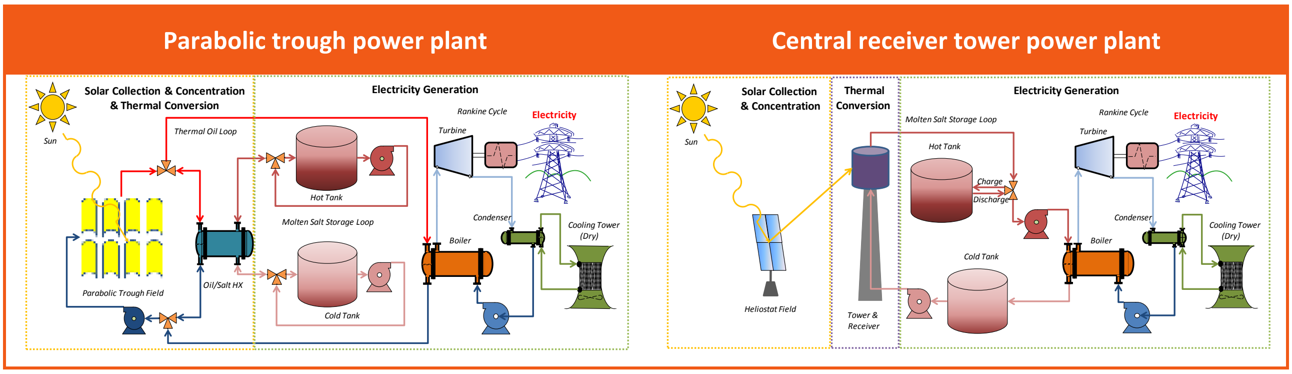
Specific Research and Education Activities

CST Technical Progress and Performance

ASTRI will deliver cost reductions and dispatchability improvements to CST in Australia in terms of LCOE (c/kWh), through:

- Improvements in overall annual efficiency
- Reductions in capital expenditure
- Increases in capacity factor
- Reductions in O&M costs.

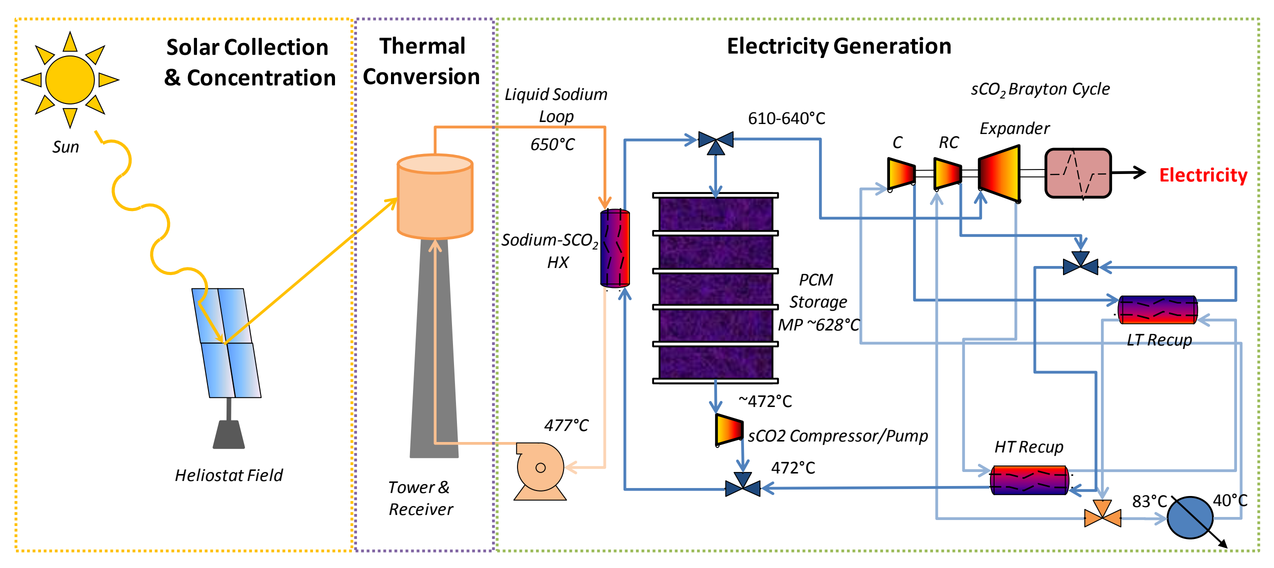
More than 90% of the world's commercial CST power plants operate using parabolic trough technology. They are typically centralised-grid-connected generators with nominal power ratings of 50–250 MWe and storage capacity of 3–6 hours. For Australian energy market conditions in 2012, the baseline plant for ASTRI was defined as a state of the art 100 MWe parabolic trough plant with four hours' storage. A sensitivity analysis of the ASTRI parabolic trough reference plant suggested that shifting from parabolic trough to central receiver tower technology could facilitate the substantial LCOE reductions that ASTRI is targeting. A similar conclusion was found during the development of the United States concentrating solar power (CSP) SunShot program.



ASTRI has developed a CST plant configuration that is expected to achieve a LCOE of 12.9 c/kWh at 100MWe and 14.2 c/kWh at 25 MWe. The proposed central receiver tower power plant design is based on a closed-loop sCO_2 Brayton cycle power block, with a single-tank phase change material (PCM) thermal storage and sodium receiver. The sCO_2 power block under development in ASTRI is intended for an operating temperature of 600-650 °C, with partial recompression (RC) and recuperation units, as well as a hybrid cooling tower.

The optimum performance to cost balance was achieved with a turbine inlet temperature of approximately 610 °C. At higher temperatures, the cost of materials of construction increased significantly, particularly as temperatures approach 700°C, without significant gains in efficiency. As this would also extend to influence the materials of construction for the storage, it appeared that the cost effectiveness of the system design would benefit from the use of temperatures below 650 °C.

Central receiver tower system with sodium receiver, phase change material for thermal storage and supercritical CO_2 power block



The storage system selected is a shell-and-tube design from the reliable low-cost phase change material thermal storage systems project (P22) that uses the phase change material (PCM) with a melting point around 628 °C. Due to concerns about catastrophic failure if the PCM comes into contact with liquid sodium, sCO_2 is used as a heat transfer fluid for both charging and discharging of the storage. The hot sCO_2 will range in normal operating conditions from 640 °C during charging to 610 °C during discharge, although it is considered in modelling of the system that the power block will continue to operate at reduced efficiency with temperatures as low as 590 °C. The cold sCO_2 exiting the storage and the power block is expected to be approximately 472 °C under normal operations, but modelling allows for this to increase to 500 °C before charging of the storage is deemed complete.

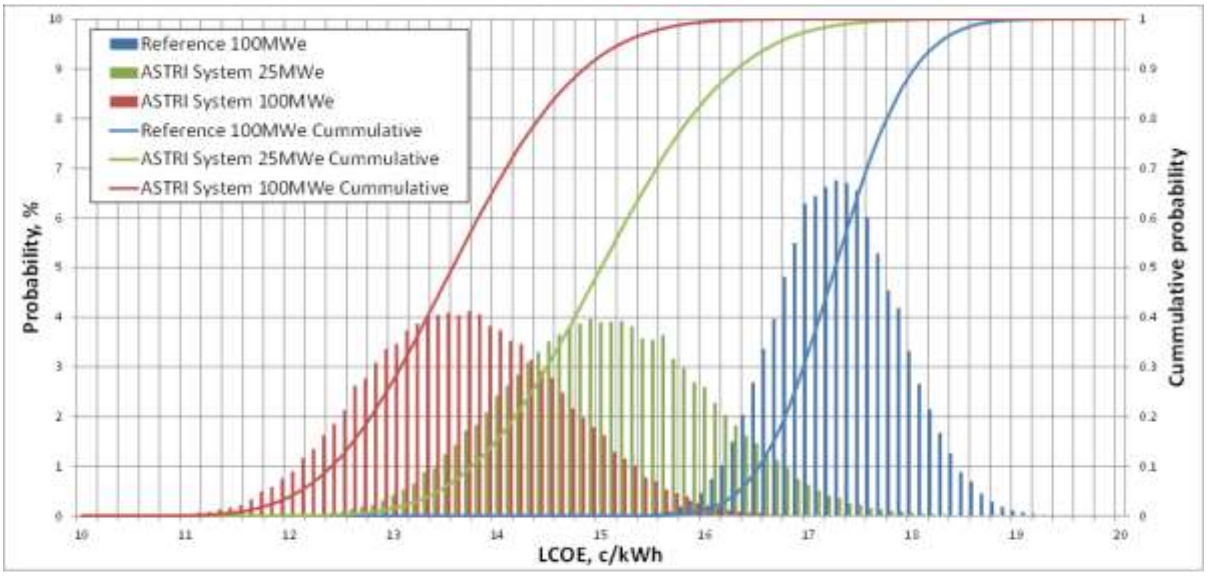
One unusual piece of equipment that is required is a sCO_2 compressor/pump to increase the pressure of the sCO_2 leaving the storage during charging up to the same pressure as the stream leaving the power block. This compressor/pump does not have a large duty, as it is only overcoming losses in the storage unit, but the relatively high temperature of the sCO_2 results in low efficiency and high cost for a relatively small device. An alternative process design that utilises a different heat transfer fluid is being considered for subsequent developments. The cold sCO_2 stream is heated by heat exchange with hot liquid sodium that has been pumped through the solar receiver and heated to a temperature of 650°C, as is being developed in the receiver performance project (P12).

The sodium loop and receiver are analogous to the conventional molten salt system, but liquid sodium has considerably better heat transfer properties, is stable at temperatures up to 882 °C and has a lower solidification point. The improved heat transfer properties allow higher fluxes to be used and this can be used to reduce the size and cost of the receiver, if the heliostat field can target the receiver accurately. Field designs for the 100MWe and 25MWe plants were designed in the heliostat field project (P11) using heliostats of dimensions 12.2m x 12.2m and 6.1m x 6.1m, respectively, as the size of the heliostats was considered a key item in ensuring that the heliostat numbers and accuracy were balanced to provide a cost effective, efficient and practical outcome. A heliostat design based on the analysis being performed in the heliostat field project (P11) to developed more cost effective heliostats was also used, although this analysis was primarily directed at the smaller size heliostat.

Many of the concepts have not been tested at pilot plant scale and typically do not have detailed engineering designs for cost analysis, so until those occur it is difficult to reduce the uncertainty ranges in the cost and performance inputs to the assessment. If a 95% confidence is used, the LCOE would be approximately 15.2c/kWh at 100MWe, 16.7c/kWh at 25MWe, with 18.3c/kWh for the original tower Reference Case. It would, therefore, be difficult to achieve the final target value on the basis of 95% probability without a full pilot plant development or component prototype design, construction and testing of all the new technologies.

The LCOE deemed to have the highest probability or most likely for this CST plant configuration is 12.9 c/kWh at 100MWe and 14.2 c/kWh at 25 MWe, with 16.8c/kWh for the original tower Reference Case. While the 12c/kWh final ASTRI target has not been achieved at this stage, it is considered that continued optimisation of the plant designs will enable more cost reductions and performance improvements.

Distribution of LCOE for 100MWe Reference Case in comparison with ASTRI systems of 25 & 100 MWe



Overarching Economic Model Project

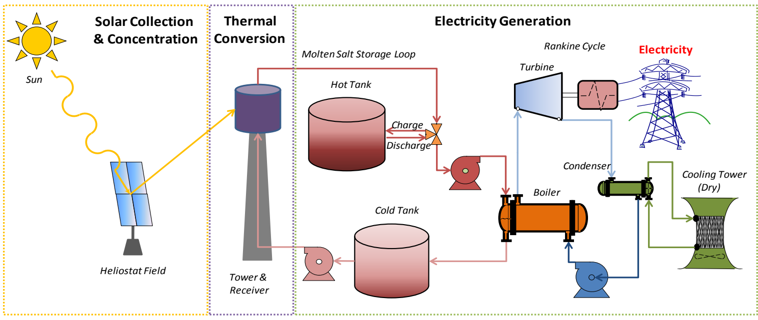
Project P01	Overarching economic model to evaluate ASTRI CST system performance and costs
Project leader: Dr Andrew Beath (CSIRO) **Collaborating & Contributing Institutions:** CSIRO Australian National University University of Queensland University of Adelaide University of South Australia Queensland University of Technology Flinders University NREL **Start Date:** May 2013	The Overarching Economic Model is a central modelling framework for use within ASTRI to predict and evaluate technical progress. The primary objective of the project is to ensure the framework maintains relevancy, through capability and currency, to demonstrate that the technical KPIs are being met. The model calculates the annual performance of CST technologies along with the associated costs to determine the LCOE. The initial framework has been based on the System Advisor Model (SAM) available from NREL, which is capable of simulating the annual performance of conventional CST technologies. ASTRI is developing a suite of new technologies within an integrated systems approach to ensure it can deliver its LCOE cost reduction of 12 c/kWh. It is essential that the central modelling framework is flexible to incorporate performance models from the novel technologies being developed. This flexibility facilitates an integrated system design that can be optimised and compared with conventional CST plants. Some of the new technologies may require more complex performance modelling than SAM. However, where possible, simplified predictive methods will be incorporated in the modelling framework to extend its performance and cost prediction capabilities. The expansion of the project scope has improved the accuracy of the system performance and economic analysis capabilities of the model. This in turn has increased confidence in demonstrating the progress of ASTRI. Details of the trough baseline case and tower reference case were endorsed by representatives of the CST industry at an ASTRI Economic Modelling Workshop in February 2015. There was a minor discrepancy about insurance costs and agreement that a simple financial model was appropriate.
Trough baseline case:	ASTRI's baseline CST plant is a nominal 100-MWe oil parabolic trough plant with four hours of molten salt thermal storage. The reference meteorological site, chosen in 2012, is Alice Springs. This baseline was chosen because it represented the most proven and common CST technology in commercial use worldwide in combination with a proven storage technology. ASTRI assumed a dry cooling system to condense the residual steam in the power block back to water, resulting in a more realistic (but lower power cycle) efficiency than a wet cooling system. This baseline provides a basis for comparison for ASTRI developments.
Tower reference case:	A central receiver tower technology provides higher cost reduction opportunities than parabolic trough technology. This is mainly due to the tower's potential for operating at much higher concentration ratios and, therefore, at higher temperatures. This leads to higher overall light-to-work

Project P01 — **Overarching economic model to evaluate ASTRI CST system performance and costs**

efficiencies and relatively inexpensive high-temperature and high-energy density thermal storage solutions.

A central receiver tower system has been adopted as a reference case to understand the state of the art in solar tower concepts upon which ASTRI technology developments can be compared. The solar tower reference case is a nominal 100-MWe molten salt central receiver plant with four hours of molten salt thermal storage, with the reference meteorological site being Alice Springs.

Central receiver tower reference case



Review and Update of Australian O&M costs:

Initial ASTRI estimates of O&M costs were based upon literature values such as the Australian Energy Technology Assessment (2013) which did not breakdown these costs. ASTRI has moved to the US NREL detailed breakdown of material and labour costs for different sections of the conventional CST power plants. ASTRI also performed an assessment of real Australian labour costs on the Electrical Power Industry Award 2010 and the Kelly Services Australia and New Zealand 2014 Salary Guide. While the overall impact of these changes is minor, some significant differences in professional salaries compared to the US were identified.

Improved Modelling of Lifetime Solar Conditions:

ASTRI began its analysis of plant performance utilising a single representative year of weather data. This was improved to analysing variations over 13 discrete ‘real’ years, based on the high quality one-minute solar data set available from the Bureau of Meteorology (BOM) for Alice Springs.

A new synthetic one-minute solar data set for 100 years has been created to match the measured mean and standard deviation statistical profile. This allows more robust prediction of the likely plant performance over its lifetime, which includes the probability distribution and range of variability in LCOE that can be expected.

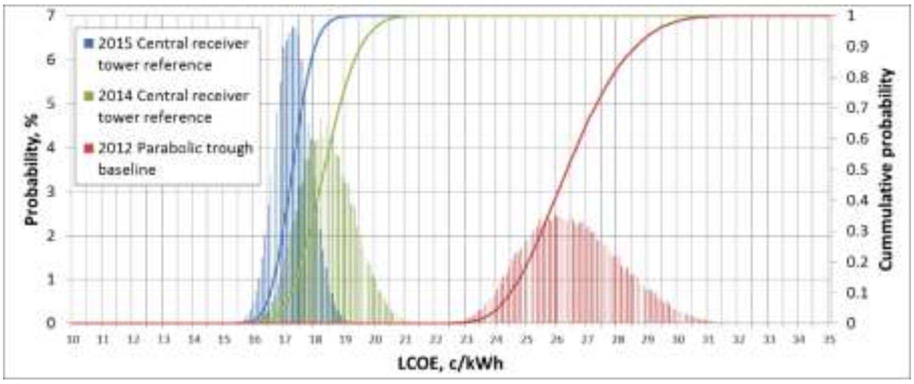
Annual Review of Molten Salt Central Receiver Reference Case:

The annual review of the Molten Salt Central Receiver Reference Case is to track the changes in cost and performance of current commercial ‘best practice’ that have occurred internationally. LCOE estimates are based on 30 year project life, including 3 years of construction and 27 years of operation. Costs are in 2012 Australian dollars with a simple discount rate of 7% applied over the entire project life.

Project P01	Overarching economic model to evaluate ASTRI CST system performance and costs
	In 2012, the most likely LCOE for the parabolic trough baseline case was 26.4 c/kWh with 90% confidence that LCOE value was less than 28.6 c/kWh. In 2014 the most likely LCOE for the tower Reference case was 18.3 c/kWh, with 90% confidence that the value is less than 19.9 c/kWh. In 2015, the most likely LCOE is 17.3 c/kWh, with a 90% probability that it will be less than 18.1 c/kWh.

LCOE probability distribution for the ASTRI baseline and reference plants

2012 Parabolic trough baseline
2014 Central receiver tower reference
2015 Central receiver tower reference



All plants: 100MWe (net) conventional Steam Rankine cycle with 4h storage at Alice Springs

Influence of Site, Size and Storage Capacity on LCOE:

The influence of plant scale, the size of the storage and site solar characteristics on the performance and cost of the tower reference plant has been examined:

- Larger plants have lower LCOE
  - the impact of plant size, in terms of power block output, is important as larger steam turbines are more efficient and the overall plant has economies of scale
- Large storage capacity reduces the LCOE
  - at three sites with considerably different annual DNI (kWh/m²/y) LCOE is reduced by expansion of the storage to 14 hours or greater
- Large storage capacity and larger power blocks may increase financial risk
  - increased electricity production during low demand periods may be surplus to the network requirements
- Sites with higher annual DNI have lower LCOE
  - Alice Springs has lower LCOE than Kalgoorlie or Mildura

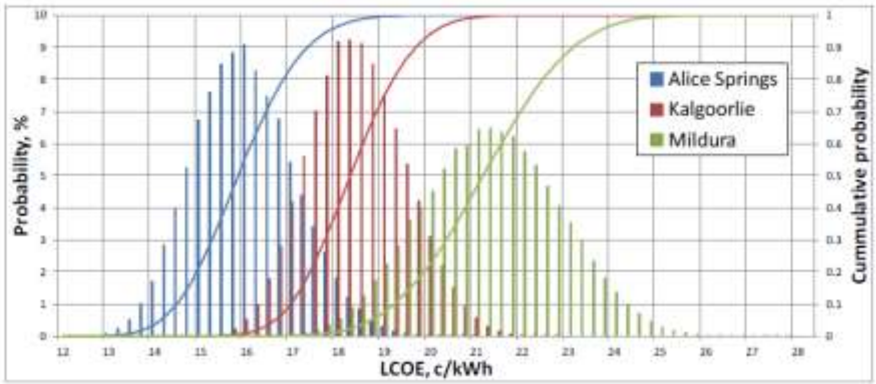
Project P01	Overarching economic model to evaluate ASTRI CST system performance and costs

LCOE for three different Australia locations

Plant size: 100MWe,

Plant storage: 14 h

DNI (kWh/m²/y)
Alice Springs: 2600-2800
Kalgoorlie: 2400-2600
Mildura: 2000-2200



Integrated Process Designs:

The methods developed in the Overarching economic model have been used to identify the performance and cost requirements for different plant sections. This has led to three different plant configurations, intended to guide technology development by establishing operating conditions where component designs will be compatible. These configurations are not intended to limit the development of other process options and alternative components are already being examined in some projects.

As research has continued it has been possible to identify more precisely the suitability of utilising specific operating conditions and working fluids in combinations to develop a set of potential process designs that can be used as targets for further refinement of the technologies.

Key findings

Development of the overarching economic model has continued to improve the detailed assessment of costs and expand in capability with respect to both solar conditions modelling and incorporation of new component technologies. The model is being used to both analyse process designs incorporating both conventional and new technologies, plus to provide assessments of prospective technology developments that have the potential to meet the ASTRI technical targets.

A key outcome has been the development of several process configurations that incorporate prospective ASTRI technologies from a range of projects. The central receiver tower system with sodium receiver, phase change material for thermal storage and supercritical CO_2 power block demonstrates potential to meet the ASTRI LCOE target.

Future direction

Over the past year there has been increased interaction between the ASTRI projects, both formally through regular meetings and also through other dialogues, to improve planning of the process development. The regular meetings have improved the collective understanding of the issues in development of the component technologies and the requirements of an overall process analysis.

Project P01	Overarching economic model to evaluate ASTRI CST system performance and costs
	It is inherent in an innovative research program that the project outcomes will result in changes in the plant component designs at irregular intervals. Mechanisms for continual improvement are ongoing to address the fundamental challenge of obtaining input from projects to ensure complete process design analysis. Activities to identify the most prospective areas for cost reductions and propose alternative process configurations are ongoing.

ASTRI Economic Workshop in February 2015

Node 1: Reduce Capital Expenditure

Node 1 Leader:	**Dr John Pye (ANU)**	**Node 1 Co-Leader:**	**Professor David Lewis (Flinders)**

The highest cost in CST plants is the capital expenditure (CapEX) for design, development and construction of CST components and systems. This capital expenditure can be further amplified by high financing costs due to the perception of risk, which then reduces investment opportunities. By reducing the capital expenditure and proving the reliability of CST components and system technologies, the technical and investment risk is reduced. The CST researchers and industry need to address such risks by creating CST technologies that area fundamentally cheaper, as well as by proving their reliability as they are developed.

Improvements in CST design with the objective of reducing the capital costs are being addressed in ASTRI by modelling, design, and industry engagement. The preferred options, assessed in terms of attractiveness and feasibility, will be developed through to a proof-of-concept stage. Proof-of-concept projects will then lead to the development of pilot-scale demonstration projects in conjunction with industry.

Key leverage points for reducing capital expenditure were identified following scoping studies and robust discussion on the breadth of possibilities available to meet the overall ASTRI targets. The concepts are focused around cost reduction specifically for central receiver tower systems, because of their relatively larger potential for cost reduction in this technology compared with parabolic trough systems. The major areas for cost reduction are in the cost of heliostats, improvements in the optical efficiency of the heliostat field, and the thermal efficiency of high-temperature receivers.

Heliostat cost is critical, because many thousands of heliostats are installed in a tower system. They must be as cheap as possible while maintaining required optical accuracy. Reduction of heliostat cost requires novel manufacturing techniques, integrated structural and optical design, and careful consideration of wind loads. The Heliostat Field Cost Down project (P11) addresses these areas, and has strong links with the Receiver Performance project (P12), the Cost-Effective Operations and Maintenance project (P41) and Solar Fuels project (P42).

Receiver optical and thermal efficiency is also critical. Any increases in these receiver efficiencies immediately reduce the number of heliostats required for delivery of a specified amount of energy and, therefore, leads to substantial cost savings. Achieving high receiver efficiency at elevated temperature is also necessary to use of higher-efficiency power cycles. These higher-efficiency power cycles also enable smaller heliostat fields for a defined energy output, hence higher temperature receivers also contribute to reducing capital costs. The Receiver Performance project (P12) has strong connections and interactions with the, the thermal storage projects (P21 and P22) and Solar Fuels project (P42).

Project P11	Heliostat Field Cost Down Project

Project Leader:

Joe Coventry (ANU)

Collaborating & Contributing Institutions:

ANU

Flinders University

CSIRO

University of Queensland

University of Adelaide

University of South Australia

Queensland University of Technology

Sandia National Laboratory

NREL

Start Dates:

Scoping study 2013

Project 2014

Improvements in heliostat fields are expected to reduce the overall LCOE of CST, due to their substantial capital and operating costs and the variables in their design. Therefore, we must identify and prioritise the factors that contribute to the cost of heliostat fields.

The heliostat field cost down project aims to demonstrate proof-of-concept for a new, low-cost heliostat field designs, combining novel heliostat concepts with field layouts of high optical efficiency.

The measurable performance target of this project is to develop a heliostat design that could be manufactured, installed and operational at a cost of \$120/m^2. This is 46% less than to the baseline cost, and contributes to an overall 17% reduction in solar field capital expenditure. In addition, the project will aim for a stretch target of \$90/m^2 for the heliostat design. Measurable performance targets regarding improved heliostat field concepts are yet to be defined.

The design concept stream has a product development focus underlying the core technological research. Four heliostat design concepts were recommended in the Scoping Study, and three of these continued into this project. The technology development stream allows research in areas considered common to all heliostat design concepts. Six research themes will be investigated: mirror facet development, aerodynamics and wind loads, heliostat field optimisation, manufacturing systems, design and testing tools, and O&M systems.

Heliostat design concept:

Each heliostat concept has a champion responsible for its vision, opportunities and challenges. The progress of each concept is:

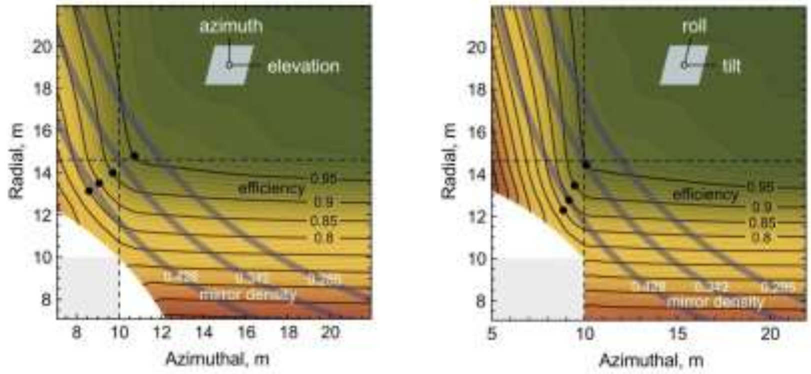
- A sandwich panel heliostat concept with a preliminary total cost estimate of 116 AUD/m^2 continues to look promising
- A drop-in heliostat has been put forward for patenting. The preliminary total cost estimate was higher than the target cost of 120 AUD/m^2 but correcting inconsistencies in the costing methodology and are expected to improve the cost estimate
- A mini-facet heliostat concept based on automotive wing mirror systems appears unlikely to reach performance and cost targets. The development has ceased.

Four-panel heliostat and tracking/actuation system

Project P11	**Heliostat Field Cost Down Project**
Mirror facet development:	Sandwich panels may hold significant potential for future heliostat cost reduction. The focus thus far has been on selection of core materials including manufacturing methods, prototyping small mirror panels with the various core materials, and finite element analysis of mirror panels in a full scale heliostat to refine design. The core materials have been reduced from three to two options. The cost of both materials appears to be under 10 AUD/m^2 of heliostat area, within the upper bounds agreed for the core material costs in a panel.
Aerodynamics and wind loads:	An important aspect of cost reduction for heliostats is to avoid being ‘over-designed’. A major emphasis is on understanding the properties of wind gusts, and how they interact with heliostat structures. One key finding is that gust period and integral length scales of turbulence in the atmospheric surface layer (ASL) need to be considered for structural design at the maximum height of the heliostat structure. This is because although the maximum gust wind speed and gust factor increase closer to the ground, the integral length scales increase linearly with height. Therefore the size of gusts can be larger than the chord length of the heliostat mirror, which causes larger correlated wind loads and can lead to structural failure from overstressing when the peak wind stresses exceeds the material capacity of the structure.
Flapping plate vortex generator and brass model heliostat mounted on load cell	 A ‘flapping plate’ vortex generator for testing some large-scale turbulence structures that can be expected in the upstream wind within heliostat fields
Heliostat field optimisation:	Optical modelling tools are being established to determine the annual efficiency of standard and novels solar fields. The tools for examining blocking and shading losses at local points within the field have been further developed, and a thorough comparison of two different heliostat tracking configurations, altitude-azimuth and tilt-roll has been conducted. Tilt-roll heliostats have been shown to achieve higher annual efficiency and higher mirror density in most cases. The aspect ratio for heliostats was also analysed, and it was found that wide heliostats are better than tall or square heliostats in most cases, especially for altitude-azimuth heliostats.

Project P11	Heliostat Field Cost Down Project

Comparison of altitude-azimuth and tilt-roll heliostat tracking



Annual visibility as a function of azimuthal and radial separations for azimuth-elevation (L) and tilt-roll tracking (R)

Key findings

The heliostat and the mirror facet development research show the drop-in and sandwich panel heliostat concepts show excellent promise for meeting ASTRI cost target. The development of the mini-facet heliostat is being discontinued due to general doubt over its ability to meet cost targets. Optical modelling shows tilt-roll heliostats achieve higher annual efficiency and higher mirror density in most cases.

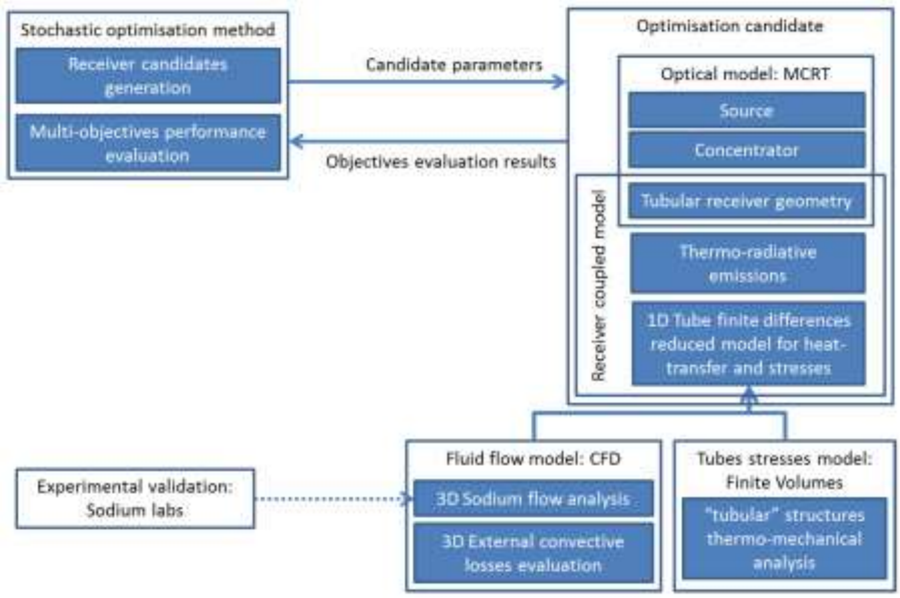
Wind turbulence in the atmospheric surface layer (ASL) needs to be considered for structural design at the maximum height of the heliostat structure. If the size of gusts is larger than the chord length of the heliostat mirror, then the wind loads can lead to structural failure from overstressing when the peak wind stresses exceeds the material capacity of the structure.

Future direction

The research on the heliostat and the mirror facet development, along with wind load and aerodynamics and heliostat field optimisation will continue with:

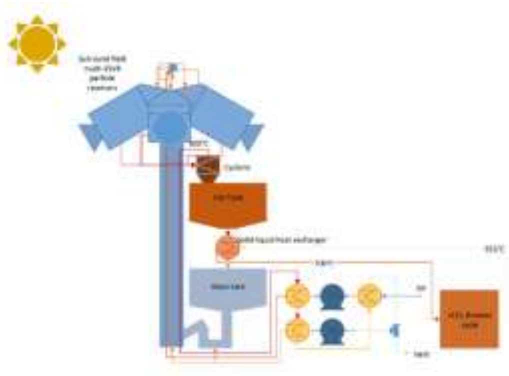
- Further refinement of the Heliostat concept development will proceed to proof-of-concept with targeted testing of heliostat sub-systems and components
- Wind load and aerodynamics testing and model validation of static and dynamic wind loads on a single heliostat, proceeding to two tandem heliostats
- The mirror facet development will involve optimising the structure to minimise materials. Construction and characterisation of small prototypes
- The heliostat field optimisation will analyse the effects of factors such as number and size of towers on heliostat design, layout and optical efficiency.

Project P12	Receiver Performance Project
Project Leader: Joe Coventry (ANU) **Collaborating & Contributing Institutions:** ANU Flinders University CSIRO University of Adelaide Sandia National Laboratory **Start Dates:** Scoping study 2013 Project 2014	The ASTRI reference central receiver tower system is a tubular molten salt receiver with an operating temperature of 580 °C and thermal efficiency of 90%. Improvements in receiver efficiency will reduce solar field capital expenditure, because less solar energy would be necessary to provide the optimal energy requirements for the CST. This project aims to contribute to overall capital cost reduction and LCOE savings by demonstrating proof of concept for two different high-efficiency receivers, which are able to supply heat at elevated temperatures compared with the current state of the art. A tubular receiver with a sodium working fluid is the first concept, with a target of 91% annual thermal efficiency at design conditions of 700 °C. A particle receiver is the second concept, with a target of 85% efficiency at design conditions of 800 °C. The project includes modelling and laboratory experimental work, but excludes on-sun testing. On-sun testing of either or both of the concepts is expected to be undertaken in years 5–8 of ASTRI, pending successful concept development, technical evaluation and due diligence.
Tubular receiver:	There are several benefits associated with using sodium as the receiver heat-carrier in a tubular receiver. One of the possible major advantages is that sodium tubular receivers could work at higher incoming radiative flux than their molten salts and steam counterparts. Higher flux on the receiver aperture generally allows a reduction of the receiver size for the same thermal energy output. A smaller receiver comes with a series of advantages: • Lower heat losses • Cheaper receivers if significantly less material is needed, and • Ease of procurement and installation. Several conceptual designs for a tubular sodium receiver have been prepared based on optimisation of the sodium flow-path to maximise exergy efficiency, accounting for the varying incident solar flux on the receiver aperture. Minimising the thermal stress on receiver tubes which appears to be quite a severe constraint at the temperatures in consideration. Modelling of individual tubes in the sodium receiver has been undertaken to evaluate these stresses, with suitable boundary conditions applied for the circumferentially-varying incident solar flux and the internal convection heat transfer to the liquid sodium. A novel approach to receiver multi-objective optimisation has also been developed, and once tube-level studies are complete, it is expected that the receiver-level design optimisation will make use of that tool. A preliminary scale-up study for the tubular sodium receiver indicated that a receiver efficiency of 88% is achievable with a uniform-flux cylindrical receiver at the

Project P12	Receiver Performance Project
	145 MWt scale. It is expected that the 91% performance target will be achievable once non-uniform flux and possibly a cavity geometry is incorporated into the design.
Tubular receiver optimisation model structure	
Particle receiver:	The particle receiver concepts being pursued are directly irradiated involving particles swirling in a vortex reactor or particle falling. The indirectly irradiated particle receiver concepts are not being pursued. The particle vortex receiver concept has two attractive features: • Longer residence time for large particles, addressing the key concern of exergy destruction when varying-temperature particles are mixed at the receiver outlet. • Less particle loss; the concept appears to offer a solution that avoids particle deposition on an aperture window, or avoids particle loss in the case of a windowless receiver. The falling particle receiver has been further advanced by: • Computational fluid dynamics modelling • Ray tracing combined with analysis based on radiative transmissivity of the particle 'screen', in order to arrive at estimates of receiver efficiency as a function of particle size and flow rate. Our models currently predict a falling particle receiver efficiency of over 89% at summer midday, suggesting that the performance targets for this concept are achievable.

Project P12	Receiver Performance Project
Key findings	A preliminary scale-up study for the tubular sodium receiver indicated that a receiver efficiency of 88% is achievable with an expectation that the 91% performance target will be achievable once non-uniform flux and possibly cavity geometry is incorporated into the design. Both particle receiver concepts are advancing well and appear to have a good prospect of meeting project performance targets, although more work is required to produce efficiency estimates for the vortex receiver in particular.
Future direction	For the tubular receiver the development will involve: • Flux optimisation of the sodium receiver concept • Testing of a first prototype mini-module sodium receiver on the solar simulator at ANU • Concept design of a suggested full-scale sodium receiver, including cost estimations. The particle receiver activities leading to concept design of a full-scale particle receiver, including cost estimation will involve: • Development of a new methodology for the heat transfer analysis of a particle receiver • Development of the particle receiver with a comprehensive analysis of its hydrodynamics leading to a prototype design for investigating the hydrodynamics.

Conceptual layout of a vortex receiver CST plant



Node 2: Increase Capacity Factor

Node 2 Leader:	Mr Wes Stein (CSIRO)	Node 2 Co-Leader:	Professor Wasim Saman (UniSA)

The ability to dispatch electricity on demand continues to grow as one of the most valuable features that CST can contribute to the renewable energy mix. Dispatchability – and in particular, storage – is recognised throughout the community as a ‘mandatory’ requirement in most future scenarios. This is because storage creates the potential for a better commercial business proposition through an increased internal rate of return, as well as a reduction in the LCOE.

Thermal storage is now well-commercialised in the form of two-tank molten salt operating at temperatures suitable for sub-critical steam turbine cycles and the lower temperature end of sCO_2 cycles. It provides an excellent reference point upon which to improve. In order to allow the new emerging higher temperature cycles such as sCO_2 to operate at their full efficiency, storage temperatures must correspondingly increase also. This introduces a number of key research challenges including reduction of exergetic losses that arise as a result of heat exchange between the receiver fluid and storage fluid, and the storage fluid and turbine working fluid, bulk storage materials, and containment materials. Where feasible, it is desirable to use the same fluid in the storage as in the receiver or power block to remove the cost and performance reduction associated with heat exchangers.

The projects in this node interact closely with the work undertaken in receiver project (P12) and supercritical CO_2 power block project (P31A). The key receiver heat transfer fluids under consideration for temperatures beyond molten salts include sodium and particles. Thus the storage technologies under development are targeted towards interaction with these materials. For example particle storage, both sensible and thermochemical, is under development in the High Temperature Storage project (P21).

The thermodynamically optimum method of transferring heat is through phase change to create an isothermal heat exchange and minimise exergy destruction. A break-through in high temperature phase change storage would represent a quantum leap for the sCO_2 cycle economics. Thus the reliable low-cost phase change material thermal storage systems for CST project (P22) is developing high temperature phase change materials and storage systems which are compatible with the sCO_2 turbine being developed in the supercritical CO_2 power block project (P31A).

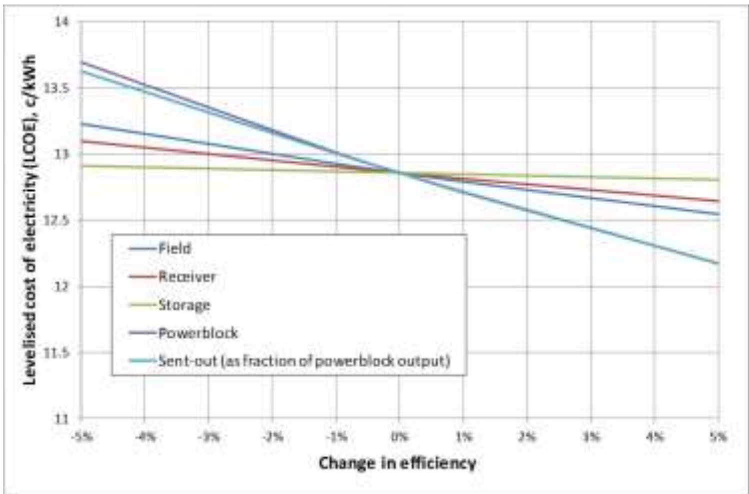
A key attraction of storage is its ability it affords to increase internal rate of return which is the key measure used by project financiers. ASTRI will develop a comprehensive, techno-economic model to optimise storage size in a CST power project (P21) and in doing so will interact with the overarching economic model project (P01). Both projects under this node (P21 and P22) are also the main contributors to the increase of capacity factor to which we have committed.

ASTRI
AUSTRALIAN SOLAR THERMAL RESEARCH INITIATIVE

Project P21	**High-Temperature Thermal Storage Project**
Project Leader: Jim Hinkley (CSIRO) **Collaborating & Contributing Institutions** CSIRO University of South Australia ANU University of Adelaide **Start Date:** 2014	This project aims to advance the state of the art in high-temperature energy storage for CST. Several specific technology concepts will be developed in parallel with common-basis performance assessment and materials development. The project focuses on those concepts most likely to work at the temperature levels demanded by high-efficiency cycles such as sCO_2. As such cycles are most likely to produce an LCOE below 12 c/kWh, storage designed for these cycles will play an important role in the future. As well as interacting thermodynamically the higher-temperature cycles, these thermal storage systems will offer low cost in terms of $/kWh$_t$, due to the potential for high energy density of the storage medium compared to molten salt. Specific objectives of the high-temperature thermal storage project are to: • Identify and develop storage technology that leads to a 20% increase in capacity factor above the parabolic trough ASTRI baseline case • Undertake targeted experimental evaluation of materials and heat transfer processes to support system-level storage concept development • Develop a common-basis modelling platform to support annual performance and techno-economic analysis of a range of candidate storage technologies, together with alternative power-cycle options where relevant, including optimisation of design and operation strategy.
Overall Storage Technology Model:	A Modelica-based annual performance storage model is being developed using the OpenModelica framework. Overall, for the simple systems being currently considered, a single annual performance calculation takes a few seconds using one processor on standard hardware. It is anticipated that quite fast simulations will still be possible even as the system complexity increases.
Overall cost methodology of storage systems and tanks:	A parametric analysis of the impact of thermal storage unit cost on LCOE indicated that the unit cost of storage has relatively less impact on LCOE to the cost of other components. Thus it is important to concentrate on overall cycle efficiency, especially as this lowers the capital cost of all components. Since the overall cycle efficiency is improved by temperature, storage technologies that provide higher temperatures without loss of round-cycle efficiency.

Project P21 — **High-Temperature Thermal Storage Project**

Impact of thermal storage unit cost on LCOE



High temperature sensible heat storage:

Since decomposition of conventional ‘solar salt’ limits the temperature of efficient power cycles, low-cost salt mixtures with higher thermal stability are being investigated. The initial focus for these novel high temperature molten salts is on chloride salts, rather than carbonates and fluorides, because of their relatively low cost and favourable melting temperatures. The starting material is a eutectic mixture with a relatively low melting point of 380 °C that is stable at temperatures above 700 °C. This material has a cost of 250 USD/tonne specific energy storage cost of AUD 14.07/kWh_t.

Sensible heat can also be stored in high-temperature particles. Our initial scalability analysis suggests commercially available equipment and hardware can be adapted for the intended CST application. The ongoing analysis is to evaluate the efficacy, efficiency and extent of adaptation.

Latent heat storage:

While latent heat storage in solid-liquid phase change materials (PCMs) is a relatively well known concept, the concept of solid-solid is relatively unexplored. Several potential large advantages of solid-solid PCM storage are less potential for corrosion, less volume expansion and greater long-term stability. Lithium Sulphate is being investigated as a thermal storage material where the crystal structure changes from monoclinic to cubic. This expected to give an operational range from 150-655 °C at a cost of $23.40/$kWh_t$.

Thermochemical heat storage:

Thermochemical energy storage utilises reversible chemical reactions to store thermal energy in chemical form. To be cost effective, materials are required that combine high energy density with moderate cost. Particles must also exhibit high reactivity, and appropriate charge and discharge temperatures compatible with the power cycles. In this project only the likely cost effective alternatives are being evaluated.

The carbonate looping thermochemical storage system under consideration involves three main blocks: gas storage block, reaction cycle block and

ASTRI
AUSTRALIAN SOLAR THERMAL RESEARCH INITIATIVE

Project P21	**High-Temperature Thermal Storage Project**

power cycle block. Carbon dioxide from the storage block is heated by the reaction cycle block and then generates power in the power cycle block, assumed to be a sCO_2 Brayton cycle. In the reaction cycle block, there are two reactors, calciner and carbonator, which operate alternatively during day and night. The products from the reactors are stored in the storage tanks. The system is expected to have an operational range from 650-980°C at a cost of \$9.34/kWh$_t$.

Other systems under consideration are:

- Indirectly-heated hybrid chemical looping combustion thermochemical energy storage system using molten sodium heated in a central receiver to drive a reaction in a fixed or fluidised bed.
- Directly-heated hybrid thermochemical energy storage where a solid oxygen carrier passes through a vortex receiver reactor.
- Both of these systems achieve exergetic leverage to deliver a higher temperature to the power cycle than that of the solar receiver by releasing the stored chemical energy in such a way as to increase the temperature of the working fluid above that of the receiver.

Estimated unit cost (\$/kWht) of selected storage technologies

TYPE OF TECHNOLOGY	SYSTEM	TEMPERATURE RANGE	ESTIMATED COST (\$/kWh$_t$)	APPLICABLE POWER CYCLES
Sensible Heat	Molten Salts (60/40)	235-565	24.79	SSR
Sensible Heat	Sensible Iron Sand	700-900	15.60	sCO_2/CC
Sensible Heat	High Temperature Molten Salts	385-800	14.90	sCO_2/SSR
Latent Heat	Li_2SO_4	150-655	23.40	SSR/sCO_2
Thermochemical Energy Storage	Perovskites	500-1000	TBA	sCO_2/CC
Thermochemical Energy Storage	$CaCO_3$	650-980	9.34	sCO_2/CC
Thermochemical Energy Storage	Iron CLC	800-950	16.50	CC
Thermochemical Energy Storage	Nickel CLC	900-1100	40.00	CC

Legend for power cycles applicable to each storage technology are:
SSR = subcritical steam Rankine cycle; CC = combined cycle; sCO_2 = supercritical CO_2

Key findings

The main findings have involved the selection of materials for investigation and the planning of the investigation based on reviews and leveraging relevant work in other ASTRI projects. The estimated unit cost of selected storage technologies ranges from \$9/kWh$_t$ to \$40/kWh$_t$.

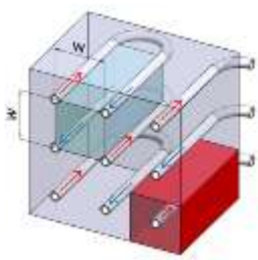
The main preliminary outcomes include:

- Proof of concept system modelling tool based on OpenModelica, with annual performance evaluation, parameter sensitivity 'sweeps', and optimisation already implemented
- Identification of the technical and economic characterisation requirements for candidate materials for different storage systems

Project P21	High-Temperature Thermal Storage Project
	• The identification of several potential thermochemical cycle systems that are compatible with the temperatures proposed in the receiver project and the sCO_2 power cycle project. • Preliminary costing of materials for thermochemical cycles and an understanding of the costs associated with other particle storage media. • Preliminary concept design of novel storage systems and plans for their investigation
Future Direction	The future direction of this project involves a matrix of the following research activities: • Refine subsystem technical models • Techno-economic evaluation to justify the system concepts • Design of storage tank system configurations for concept demonstration, • Fundamental experimental evaluation for each of: • High temperature sensible storage • Solid-Solid PCMs • Thermochemical Energy Storage based on • Calcination-Carbonation Chemical Looping • Hybrid Chemical Looping Combustion.

Reliable, low-cost, phase-change material thermal storage systems Project Review in June 2015

Project P22	Reliable, Low-Cost, Phase-Change Material Thermal Storage Systems
Project Leader: Wasim Saman (UniSA) **Collaborating & Contributing Institutions** University of South Australia CSIRO Queensland University of Technology NREL **Start Date:** 2013	PCM thermal storage systems target the latent thermal energy characteristics of materials that may be exploited to match the thermal behaviour of the heat transfer fluids involved. However, most PCM research has focused on low-temperature applications and research is needed to understand the potential for incorporating PCMs into a high temperature CST plant. This project aims to develop a practical PCM storage system costing less than $25/kWh (thermal) that is designed high-temperature sCO_2 central receiver tower system. We will investigate a thermal storage system that uses an encapsulated PCM and compare it to the systems that use bulk PCM.
Economic analysis of storage:	With cost reduction being a high priority outcome, an overview of the costing of various configuration alternatives has been carried out. The latest costing, based on today's market prices for the chemicals and materials, and all other costs (such as construction and engineering) based on equations which are published in the literature, is as follows: • Encapsulated PCM- $19.40/kWh$_t$ (Based on 2-PCM cascade system with chlorides, and 90% effectiveness) • Coil-in-tank: $24/kWh$_t$ using PCM with melting point around 628 °C These estimates are based on the assumptions of using liquid sodium as the HTF in the system, 390MWh$_t$ storage capacity, 650 °C as high temperature point, and 472 °C as low temperature point. Even though the encapsulated PCM system appears to be technically attractive and cost effective, there is considerable more research necessary to reduce the associated technical risks. It is too premature to proceed with a prototype as insufficient testing has been done to evaluate the durability and performance on a system based on geopolymer encapsulation.
Geopolymer encapsulations made from fly ash and black slag	

Project P22	Reliable, Low-Cost, Phase-Change Material Thermal Storage Systems
Encapsulated PCMs:	Development of encapsulated PCMs is being investigated to promote high thermal response of PCM storage systems. This has seen the manufacture of geopolymer shells from fly ash and black slag to encapsulate a molten chloride PCM. The geopolymer shells were initially tested at 650 °C and then at 900 °C, for 72 hours without the PCM, with no degradation of the samples observed. Results from a differential scanning calorimeter showed that the PCM has a latent heat of 211kJ/kgK and a melting onset temperature of 530 °C and it has survived one hundred cycling tests. Initial testing of the geopolymer encapsulation with the 540 °C PCM has shown phase change was achieved in the capsule with no loss of PCM material. A new computer model has been developed for high temperature encapsulated PCMs using Python allowing simulations to be carried out many times faster than currently-available commercially software. The model can handle a variety of inputs such as the type of PCM, shell material and heat transfer fluid used in the system as well as other user-defined inputs such as capsule size, operation time and capsule geometry. The model developed has been validated with experimental data obtained from the literature.
Tube-in-tank PCM system:	An investigation into the optimal configuration for a coil-in-tank storage system has been conducted. Using a validated computational fluid dynamics (CFD) model, this work has examined how five different arrangements of pipes in a PCM storage system affects the latent energy extracted from the PCM. The results show that the two-dimensional counterflow pipe arrangement delivers the highest effectiveness and therefore extraction of latent energy. A two-dimensional transient computer model to simulate the heat transfer in shell-and-tube PCM storage systems has also been developed. Compared to CFD modelling, this numerical model requires much less computation time with good accuracy. This will be used in the design of future prototypes.
Two dimensional counterflow tube PCM storage arrangement	 End view showing the direction of the heat transfer fluid

Project P22	Reliable, Low-Cost, Phase-Change Material Thermal Storage Systems
Testing of PCM thermal properties:	An extensive literature review on current data of thermophysical properties of PCMs and their methods for measurement has been completed. Test rigs are being constructed that will employ two novel measurement techniques at high temperature; one using a calorimeter and the other based on the temperature-history relationship during cooling. Based on experimental results, the most promising high temperature PCMs investigated are:

PCM	MELTING POINT (^{0}C)	LATENT HEAT (KJ/KG)
Aluminium (Al)	660	397
88% Al-12% Si	576	567
59.45% Na_2CO_3-40.55%NaCl	638	278
52.2% Na_2CO_3-47.8% K_2CO_3	710	140
53% BaCl, 28%KCl and 19% NaCl	540	211

Key findings

Key findings are:

- Five candidate PCMs have been identified, with storage temperatures ranging from 540 °C up to 710 °C
- A new encapsulation system comprising a geopolymer made from fly ash and black slag is being developed. This is ideal for corrosive PCMs such as those based on chloride salts as well as providing high rates of heat transmission
- The tube-in-tank flow configuration which maximises latent energy extraction is the two-dimensional counterflow arrangement

Future direction

The immediate future direction will focus on constructing and testing a coil-in-tank type storage unit using the PCM with a melting point around 628 °C for further proof-of-concept evaluation. To support the focus on cost-effective PCM thermal storage systems, activities to measure and develop PCMs will continue, along with compatibility of PCMs, heat transfer fluid and construction materials.

Node 3: Improve Efficiency

Node 3 Leader:	Professor Hal Gurgenci (UQ)	Node 3 Co-Leader:	Dr Andrew Beath (CSIRO)

CST plants involve a variety of interacting processes and systems, all of which must be considered when improving the efficiency of generating electricity and other products derived from CST technologies. A key subsystem that affects annual efficiency is the power block. This requires development of advanced power cycles and power conversion technologies, not only at the design point, but also at part-loads or at other off-design conditions, such as ambient temperature.

Achieving optimal efficiencies will require a systematic analysis of the inherent trade-offs in internal systems and operation. The research in this node focuses on improved efficiency through novel high-temperature cycles, advanced dry and hybrid condensers, and poly-generation, as well as significant interaction with the thermal storage system developments.

The development of sCO_2 power cycles is a particularly ambitious aspect of the work, given that it is aimed at a 100-MWe CST power plant, as well as a realistic commercialisation path in Australia due to demand for smaller-scale systems suitable for remote area standalone applications and hybrid power generation.

The sCO_2 power block project is developing both a radial expander and hybrid cooling. The expander is a critical missing power block component that prevents the adoption of sCO_2 cycles. The power block also requires a compressor or pump to recycle the sCO_2, and a recuperator to preheat the sCO_2 after compression. Our researchers are confident that an appropriate compressor and other components for the target power plant size can be sourced commercially from other applications. The hybrid cooling research for the power block addresses the cooling challenges when water availability limits the siting or performance of the CST plant.

Another project aims to investigate opportunities beyond the baseline steam cycle and high-temperature sCO_2 cycles. We will evaluate alternative power block equipment and configurations that may offer significant cost and performance benefits compared with current steam Rankine cycle systems.

To account for annual system efficiency improvements, the entire CST plant needs to be considered. The systems approach in ASTRI allows the improvements in the power block to be evaluated:

- within a conventional framework, such as the central receiver tower reference case, or
- along with developments in other parts of the CST plant that have been designed to interface with the power block to maximise its efficiency gains.

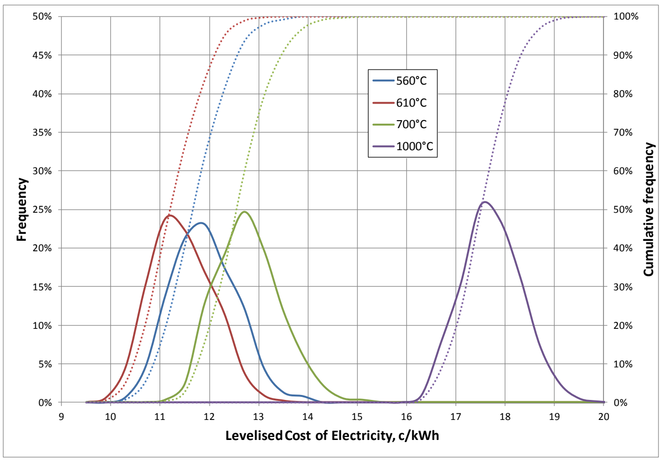
Achieving both cost and efficiency improvements in the CST plant will require careful balance between the flow-on benefits in capital cost reductions arising from higher efficiency, and the extra costs arising from new equipment and materials.

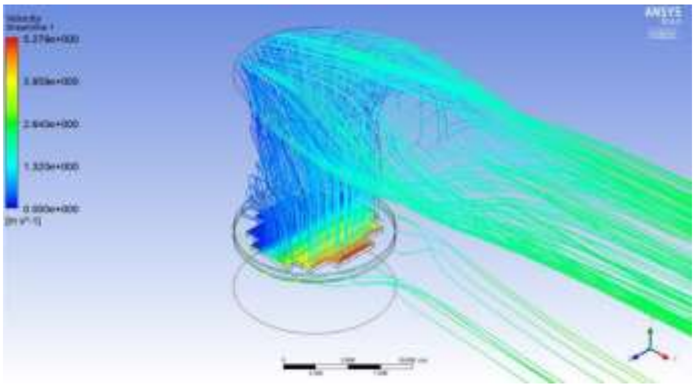
The projects in this node interact most with the Overarching Economic Modelling project (P01) and thermal storage projects (P21 and P22).

Project P31A	Supercritical CO_2 Power Block
Project Leader: Kamel Hooman (UQ) **Collaborating & Contributing Institutions:** University of Queensland CSIRO Queensland University of Technology Sandia National Laboratory NREL Queensland Government **Start Date:** 2013	The overall objective of this project is to develop a sCO_2 power block designed and optimised around a radial turbine. The project aims to deliver both a 100 MWe centralised CST power plant, and a 25–30 MWe remote area standalone and/or fringe-of-grid hybrid power generation application. As part of the project, the team expects to deliver a sCO_2 radial expander and high-efficiency power block concept with the potential to substantially contribute to reducing the LCOE of CST power plants. The project is structured along three research activities: • Development of a sCO_2 power cycle, including turbine technology and dynamic modelling. • Development of hybrid cooling technologies to minimise the water consumption while maintaining efficient power generation, particularly in arid areas. • Techno-economic optimisation of power cycles for future sCO_2 plants. The first two streams are aimed at the development of specific component technologies to make a supercritical CO_2 CST plant possible. The third stream will develop a techno-economic optimisation framework to develop the optimum centralised and smaller configurations for a future sCO_2 plant. In a sCO_2 power block, ambient air is used to dispose of waste heat by cooling the CO_2 fluid with a dry cooling technology. The efficiency of a power block is highly sensitivity to the temperature of the ambient air. ASTRI central receiver tower reference case is based on a design ambient temperature of 40 °C. The effective ambient temperature can be lowered by hybrid cooling, which involves evaporative cooling of inlet air on very hot days. The major critical missing technology for a future sCO_2-based CST plant is the turbine and compressor/pump. Nobody manufactures sCO_2 turbines commercially, although some commercial companies are involved in the development of compressor-expander turbines for CST applications.

Opening of the hybrid cooling tower facility

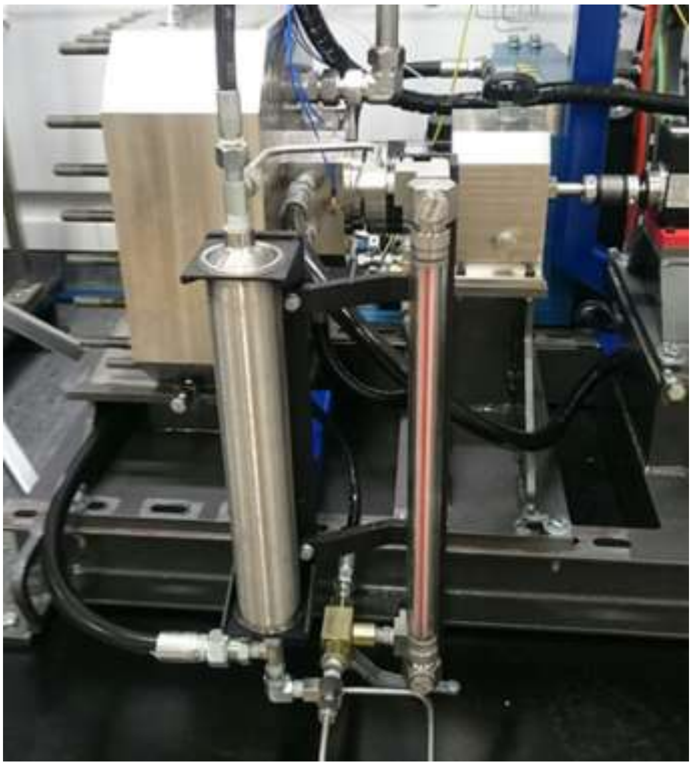
Queensland Science Minister Leeanne Enoch, centre, and UQ Pro Vice Chancellor Professor Alan Rix, right, UQ staff Hugh Russell, Stephen Gwynn-Jones, Kamel Hooman, Zhiqiang Guan

Project P31A	**Supercritical CO_2 Power Block**
Supercritical CO_2 power cycle techno-economic model:	A detailed techno-economic analysis was conducted of a 25-MWe CST power plant using a sCO_2 power block, based on a recuperated cycle with partial recompression. A design sweep conducted across turbine inlet temperatures (560 °C, 610 °C, 700 °C and 1000 °C) was utilised in conjunction with Monte Carlo cost modelling tools in the overarching economic project (P01) to identify the configuration that minimises the levelised cost. The trade-off between the higher efficiency and the capital cost is captured in this analysis. A power block with a turbine inlet temperature of 610°C has a higher probability of achieving 12c/kWh than the other options. While systems designed for higher turbine inlet temperatures yielded higher efficiencies, the benefits of this were counteracted by high capital costs and resulted increased probability of higher LCOE resulting
Probability distribution of LCOE for CST systems using power blocks with different inlet temperatures	
Detailed Off-Design Modelling:	While design point modelling is a good indicator of how to set cycle conditions, it is also necessary to assess the highest probability cycle on an annual average basis. This includes modelling of the heat transfer under supercritical conditions through Printed Circuit Heat Exchangers (PCHE) and off-design performance of the expander. This type of detailed undertaking has not been found in published literature for sCO_2 power blocks. Detailed off-design model results matrix is now underway, to be utilised in predicting the annual average LCOE for the 610 °C turbine inlet temperature sCO_2 power cycle.
Turbine design:	A laboratory-scale (7 kW) subcritical radial turbine has been manufactured. The design, installation and commissioning process has provided significant learnings in the areas of turbomachinery design and manufacture. This turbine is capable of generating shaft work out of 5 kW and operating at speeds of up to 30,000 RPM. The aerodynamic data collected from experiments creates the ability to validate the aerodynamic simulation and design tools.

Project P31A	**Supercritical CO_2 Power Block**
	The next step of the turbine development is a 100 kW sCO_2 turbine. Selection of the operating point has allowed a preliminary turbine geometry to be defined and detailed design of the turbine is now underway. A concept design has been produced for a 1 MWe sCO_2 turbine in collaboration with a Chinese manufacturer. This is a configuration that can be scaled up to larger sizes in the future to serve CST power plants up to 30 MWe.
Hybrid cooling:	The natural draft hybrid cooling tower funded by an additional grant of $1.5M obtained from the Queensland State Government has been completed and opened. This new 20m hybrid cooling research tower is equipped with industrial heat exchangers similar to air-cooled heat exchangers to be used in future sCO_2 plants. The facility is fully instrumented to measure the air velocity and the temperature distribution in the tower. Early testing results confirm that the tower has sufficient capacity to provide air cooling for a 1 MWe supercritical CO_2 plant. The performance modelled using computational fluid dynamics (CFD) under different ambient conditions, including cross winds, support the premise that it is possible to design short cooling towers with natural draft levels sufficient to provide cooling for renewable power plants. CFD models to understand hybrid cooling design options are in progress.
CFD modelling of hybrid cooling tower	
Key findings	Completion of the techno-economic analysis identified that using a temperature of approximately 610 °C offers the best development target for achieving low cost electricity. Development of a radial turbine through a staged scale-up of size and conditions is proceeding to this design temperature. Development of the hybrid cooling tower has been proceeding with spray dispersion modelling conducted and pilot plant commissioning underway.

Project P31A	Supercritical CO_2 Power Block
Future directions	The development of a modular design has been recommended, where power block modules of a fixed size can be used in multiples to produce plants of large capacities. More detailed techno-economic design assessments need to be performed to optimise such plant performance and encourage better integration with the related plant items (e.g. thermal storage and cooling systems). This modular concept will potentially offer reduced costs through increased production volumes of equipment items. Evaluation of the hybrid cooling system using saline waters is proposed. This will allow the use of lower quality water, potentially waste water from other processes in inland areas, which are less expensive.

Expander test rig



Project P32 — Alternative Power Block

Project Leader:

Emilie Sauret (QUT)

Collaborating & Contributing Institutions:

Queensland University of Technology

CSIRO

Start date:

2014

The Alternative Power Block project aims to evaluate power block equipment and configurations that may offer significant cost and performance benefits compared with current steam Rankine cycle systems.

A broad range of cycles will be considered, including Rankine, Brayton and combined cycles, with a variety of different working fluids (e.g. helium, air, organics, supercritical steam) and engine types (e.g. steam, gas). As well as standalone power blocks, the project scope also includes bottoming or topping cycles, in which efficiency may be improved for conventional cycles in a cost-effective manner.

The analysis will also consider integration with different storage types that are currently available or proposed. This will rely heavily upon the findings of other ASTRI projects or external studies. An assessment of the process options will be conducted at the end of the first year to establish the options suited for more detailed analysis. The assessment will consider the appropriate size for the system for different cycle configurations, types of turbine or engine, temperature of operation and type of working fluid used.

The initial approach to generating new designs for the effective generation of solar thermal electricity considers:

- Alternative thermodynamics cycles that can be used to generate power
- Performance of the turbomachinery, or turbine, since it is central to the design of a thermodynamic cycle.

Selection of the best cycle also requires economic considerations, with the target of achieving the lowest possible LCOE and delivering solid performance for the predicted life cycle of a CST power system.

Alternative Thermodynamics Cycles:

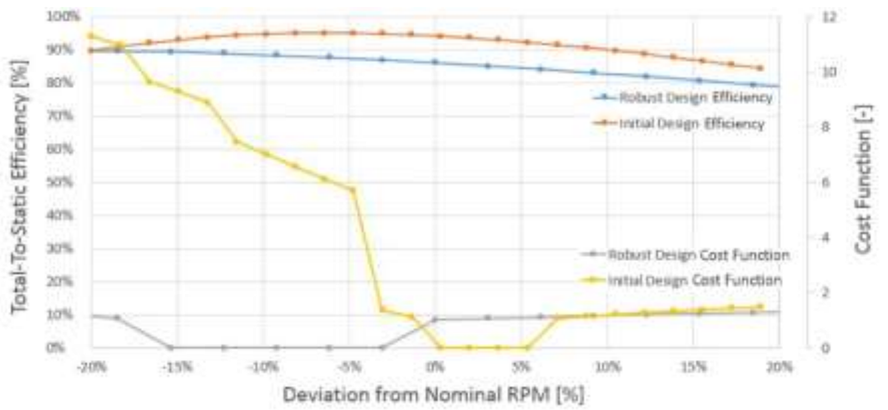
Review of alternate power cycles has focused on:

- Optimisation of gas and vapour cycles including a comparison of different cycle modifications such as intercooling, re-heating, multiple turbine stages, regeneration
- Scoping of a range of more exotic or novel power cycles for potential use in CST. The ten cycles considered featured a range of mid-size turbine cycles, high temperature solid state conversion methods, and low temperature cycles such as organic Rankine.

Although there is a clear a relationship between cycle configuration and performance, there is very little literature on optimisation and design approaches. However, it is clear that there is a correlation between the use of recuperation and system efficiency. While recuperation is a common technique used to boost steam Rankine cycle performance, increasing the number of regeneration steps improves the efficiency and cost. Three regeneration power cycles have been identified for further investigation.

Turbomachinery Modelling

It is highly desirable for CST power systems to work well under varying conditions and turbomachinery models that include off-design performance are critical to this. Performance and model validation are being performed

Project P32	Alternative Power Block
	including uncertainty quantification and sensitivity analysis. The goal of evaluating the off-design performance is to ensure that the operating cycle is able to continue operating without a significant performance penalty. Review of existing methods to evaluate the off-design performance of radial turbomachinery shows there are only a few. CFD is the most robust method for computing off-design performance based on changes in operating conditions and fluid properties. There are some other empirical methods that base the performance changes on a subset of the most highly sensitive parameters. Such empirical models typically use the ideal gas equation of state. Given the preferred fluids for alternative power cycles are not ideal, improved equation of state need to be incorporated into the calculations.
Turbine robust design with more consistent design efficiency and cost function compared to initial design	
Thermionics Developments	The potential of thermionics as a topping cycle for CST plants has been investigated. Some of the advantages of thermionics arise from being low-cost, modular, solid state devices that operate and reject heat at high temperatures. Although there is a reasonable worldwide research effort, especially for CST, efficiencies and power densities are still low, and must be increased if the technology is to become viable for CST. If high output currents are to be achieved, the options to negate space charge are either an extremely small inter-electrode gap or to utilise an ionised gas in the gap. Both options pose manufacturing challenges that are not being pursued.
Key findings	Development of sub/trans-critical Rankine and Brayton Cycles has reviewed regeneration and reheat and intercooling, showing that a Rankine cycle with reheat/intercooling provides a favourable efficiency. Since Rankine cycles appear to be well suited to utilising a wide operating temperature range with little change in efficiency, a cycle design can potentially be tailored to improve the economics of the combined solar heating and storage system. Analysis of regenerative Brayton cycles with a range of alternative working fluids suggested that sCO_2 was the most viable working fluid for efficient

Project P32	Alternative Power Block
	operation, with alternative working fluids having significantly lower efficiency.
Future directions	Future activities include: • Evaluation of novel combined cycles to improve the efficiency of using alternative working fluids to sco_2, potentially using higher operating temperatures with less corrosive fluids • Further technical and economic analysis on the identified potential cycles • Short listing of the most promising alternative energy conversion methods and initial study of these through coarse quasi-dynamic simulation

Project Review – June 2015

Node 4: Add Product Value

Node 4 Leader:	Prof Gus Nathan (Adelaide)	Node 4 Co-Leader:	Professor Ted Steinberg (QUT)

For the CST industry to fully emerge in Australia, it is important to realise competitive product values and capitalise on the various advantages CST can bring beyond electricity generation. Australia has unique local opportunities for CST applications in intensive industrial processes and resources. Adding product value will arise from minimising O&M costs, as well as developing new, high-value, solar thermal products.

CST plants can increase in value by reducing their substantial O&M costs, particularly within the Australian context, through design improvements based on experience and know-how. This involves dissecting the O&M costs with industry collaborators, and setting benchmarks for materials development and for best practice within the industry. The key areas of research are self-cleaning reflectors, efficient mirror cleaning, condition monitoring and reliability modelling of CST tower plants. Modelling and experimental studies are being conducted to optimise the cleaning system. To fully calibrate and measure O&M costs, condition monitoring and reliability modelling systems for tower CST plants are being created.

The Cost-Effective Operations and Maintenance project (P41) has important synergy to heliostat cost-down (P11) and receiver performance (P12) projects since the choice of these parts of CST plant will have significant and clear implications for ease of maintenance (access) and lifecycle costs. The thermal storage projects (P21 and P22) and power block projects (P31 and P32) also have significant O&M issues from the material challenges associated with containment, cycling and corrosion. The O&M also has an impact on the costings in the Overarching Economic Model project (P01).

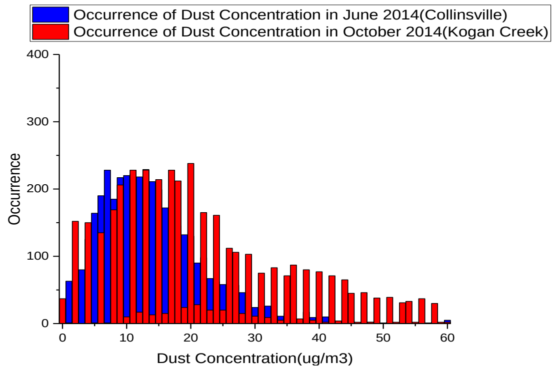
While ASTRI focuses primarily on electricity generation, its secondary emphasis on solar chemistry aims to produce fuels or provide a solar boost to Australian mineral and energy industry processes. The initial solar chemistry project within ASTRI is the development of solar fuels, with an LCOF being defined to prioritise this research. The Solar Fuels project (P42) has synergy with the receiver performance (P12) and high-temperature thermal storage projects (P21) in the irradiance of particles and storage of gases as well as benefiting from reduction in field costs from the heliostat cost-down project (P11).

Solar Fuels Project Review in June 2015

Project P41	Cost-Effective Operations and Maintenance
Project Leader: Ted Steinberg (QUT) **Collaborating & Contributing Institutions:** Queensland University of Technology Flinders University CSIRO University of Queensland **Start Date:** 2013	CST plants can increase their product value by reducing their O&M costs, which will become increasingly significant when CST plant and equipment capital costs are driven down. The O&M project adds value by developing processes and methodologies for establishing cost-effective operations and a maintenance regime for CST tower plants. This research will examine how to optimise O&M planning and practices for the most critical equipment of CST power plants. Particular attention is on the availability and cleaning of the heliostat field. For mirror cleaning operations, automatically controlled, high-pressure jet washing methods are considered most cost-effective and suitable for CST plants. To optimise mirror-cleaning, the strategy is to: • Monitor and characterise dust deposition and weathering of reflectors • Investigate surface coating to minimise soiling and • Develop spray cleaning through CFD models and experiments. The optimisation of maintenance and cleaning is based upon operational data from existing CST plants and on physical simulation models of the most critical degradation processes (e.g. mirror soiling). The mirror soiling rate is dependent upon dust type and weather conditions which are being monitored at two Queensland sites to estimate the type and frequency of mirror cleaning required for the O&M model. The same data will be used to validate and calibrate a soiling simulation model to predict the soiling of heliostats and thus enable optimisation of the cleaning schedule. The degradation of other critical equipment will be studied using reliability models based on historical failure and operational data from CST and other energy generation plants. The reliability models will allow prediction of the residual useful life of critical equipment in the plant. Condition monitoring information will be fed to the models to improve and correct their predictions. Weather data and operational data will also be crucial in assessing plant performance and equipment degradation rates, and in predicting weather opportunities for maintenance/cleaning.
Dust monitoring:	The dust characterisation has been completed based on two year's data collected from the dust monitor installed in Collinsville and about one year data collected from the second dust monitor installed in Kogan Creek. Kogan Creek showed higher dust concentration than Collinsville in all seasons except in autumn. Kogan Creek appeared to have a bi-modal dust distribution that is yet to be fully explained.

Project P41	Cost-Effective Operations and Maintenance

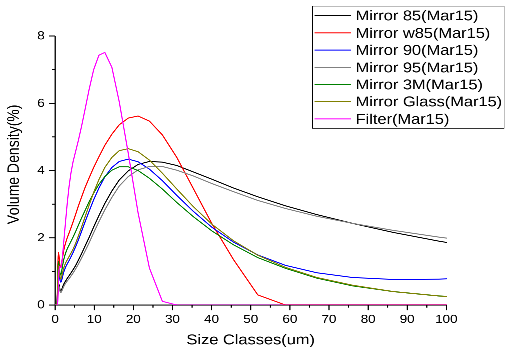
Bi-modal dust concentration distribution for Kogan Creek (blue) compared to Collinsville (red)



Correlation of airborne dust and dust deposition on mirror:

To understand what airborne components are deposited on the solar collectors, the dust on a number of mirror samples installed at Collinsville were compared to a co-located dust monitor. The larger particle sizes deposited on the mirrors may be caused by coalescence due to the humidity, dew and other ambient or atmospheric conditions. A preliminary dust correlation model requires more dust and weather data to develop a more accurate model.

Airborne dust and deposition



Spray cleaning experimentation:

Initial spray cleaning experimental tests have demonstrated the need for a more complex experimental arrangement which will allow automated traversing of the spray nozzle across the mirror surface. A spray traversing system is currently being designed for fabrication and use at a dedicated spray facility being established. A mirror supporting system which will change the mirror positions and angles to optimise the nozzle orientation for the effective cleaning is also being manufactured

Initial nozzle spray images

Project P41	**Cost-Effective Operations and Maintenance**
CFD spray modelling:	In order to purchase shear stress sensor and pressure pads for the spray cleaning experimental system, verification of the existing CFD model has been carried out. Two models adopted from the literature were: • Shear stress and particle removal by air jet impingement over horizontal flat plate (Young et al, 2013), and • Entrainment of fine particles from surface by normal gas jets impingement (Smedley et al, 1999). There was good agreement of the shear stress profiles for both horizontal and vertical water spray-jet impingement and those of Young et al. A comparison of these results Smedley at al. showed similar trends and reasonable agreement
Measurement of properties for surfaces and surface coatings:	Procedures for the synthesis of raspberry-shaped particles of silica on silica have been achieved to provide dual scale roughness for hydrophobic films. The issues being currently addressed include: • Consistency of coverage in the films • Improve in transparency • Reliability of the particle synthesis.
Physical degradation processes:	In the absence of real degradation data, physical models of degradation dynamics are being developed, in order to surrogate simulated data. This modelling phase is initially focused on the heliostat field and the receiver A comprehensive literature review focused on dust deposition onto a heliostat surface revealed the most relevant parameters influencing degradation processes had five degradation steps: • Dust generation • Dust deposition by gravity and turbulence • Adhesion • Removal • Mirror reflectivity loss. The simulation of dust soiling so far has demonstrated physical degradation with sound results and is eventually planned to generate (predict) reflectivity loss of heliostats over time.
Schema for soiling degradation process simulation	
O&M cost analysis:	Published O&M costs are limited to 'rolled-up' costs only, and details on cost breakdown for O&M activities at CST power plants are difficult to

Project P41	Cost-Effective Operations and Maintenance

obtain. Conversations with industry representatives and researchers reveal some willingness to review O&M costs data and collaborate.

A Failure Modes and Effects Analysis (FMEA) is an important technique of reliability analysis that evaluates designs and identifies all possible failure modes in the functioning of a system for the purpose of condition monitoring, reliability modelling and maintenance optimization. FMEA can be applied to CST plants to systematically measure and understand the impacts of failures on each component in the whole plant.

The five major subsystems identified and analysed for the ASTRI reference tower system: collector system, receiver system, thermal storage subsystem, steam generation subsystem and electrical generation subsystem.

An FMEA is underway for all components of the system, with the completed analysis for the receiver system highlighting a loss of absorptivity due to coating degradation is one of the major failure modes.

Overall fraction breakdown O&M cost for tower power plants

SUBSYSTEM	PERCENTAGE OF O&M COST
Solar collector	36 %
Receiver tower	22 %
Thermal Storage system	18 %
Power block system	15 %
Others	9 %
Total	100 %

Key findings

The key Mirror Cleaning findings are:

- Parameters affecting mirror cleaning have been identified
- The test facility to validate the models and measure the cleaning efficiencies of various techniques requires improvement to change the mirror positions and angles to optimise the nozzle orientation for the effective cleaning
- Procedures for the synthesis of raspberry particles of silica on silica to achieve dual scale roughness for hydrophobic films have been developed and demonstrated.

The main progress in Operations and Maintenance are:

- A Failure Modes and Effects Analysis (FMEA) has been implemented for the five major subsystems of CST power plant:

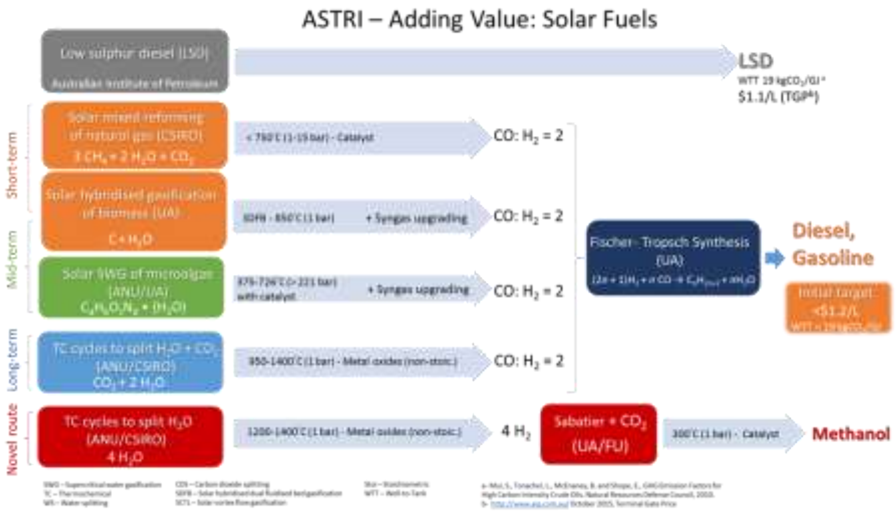
Project P41	**Cost-Effective Operations and Maintenance**
	– Collector system, receiver system, thermal storage subsystem, steam generation subsystem and electrical generation subsystem – The completed receiver system analysis highlighted a loss of absorptivity due to coating degradation is one of the major failure modes • Dust produced at several Australian sites has been characterised – Allowing development of physical models for the degradation processes, starting with the mirror soiling model and – Includes correlation analysis of dust concentration vs. environmental conditions for the development of a mirror fouling model using existing data.
Future direction	The on-going project activities include further development of: • Mirror cleaning involving dust monitoring • Spray cleaning, CFD modelling and validation • Anti-soiling mirror coatings • Failure Modes and Effects Analysis (FMEA) for CST power plants • Physical models for the degradation processes. • A CST plant industry partner is being sought to allow the modelling being developed to be trialled on actual CST plant data.

Cost-Effective Operations and Maintenance Project Review in June 2015

Project P42	Solar Fuels
Project Leader: Gus Nathan (University of Adelaide) **Collaborating & Contributing Institutions:** CSIRO Australian National University University of South Australia Flinders University Arizona State University University of Colorado ETH Zurich **Start dates:** Preliminary 2013 Project 2014	The solar fuels project is directed at a new market for CST, adding value by demonstrating the potential to produce high-grade fuels such as synthetic diesel. As a commodity, diesel has a commercial value typically twice that of electrical power on a $/GJ basis. The preliminary project has established a realistic cost target CST-based production of solarised diesel-grade liquid fuels. A levelised cost of fuel (LCOF) for solarised production of diesel-grade liquid via synthesis gas (syngas) and Fischer–Tropsch (FT) liquids pathway was estimated in the range of $0.9–2.5/L, depending on feedstock cost and the carbon footprint of the fuel. Solarised syngas production requires high temperatures that can be achieved by CST technologies. The project focuses on developing of reactors with cavity receivers for central receiver tower systems. It considers the whole CST system, including the downstream processing of syngas and an FT-type process, which requires adaptation to perform with the solarised syngas production. The project also capitalises on the other developments within ASTRI in particle receiver technology, heliostat design and thermal storage. The techno-economic analyses consider how to optimise each of these components to lower the LCOF for each of the chosen systems. The solar fuel technologies and feedstock being considered are: • Solarised hybridised dual-fluidised bed gasification of coal or biomass • Solar hybridised coal to liquids with a vortex flow reactor • Solar supercritical water gasification of micro-algae • Solar mixed reforming of natural gas • Joint splitting of water and carbon dioxide using reduction-oxidation cycling • Ft synthesis for liquids fuels production • The Sabatier process to enable the conversion of CO_2 by-product to valuable products, such as propane and methanol. • The key activities to date have been development of: • The techno-economic model reference conditions and methodology • A qualitative assessment methodology.

Project P42	Solar Fuels

Proposed solar fuel technologies to high value liquid fuels



Techno-economic model for solar to liquids fuels:

The qualitative matrix reported in the scoping study has been revised to develop a quantitative matrix for comparing solar fuels from all available CST technologies and feedstocks. The updated criteria are:

- Economic feasibility (33%)
- Sustainability (33%)
- Stage of development (34%)

Solar hybridised dual fluidised bed gasification:

A process modelling performance assessment of FT liquid production by solar hybridised dual fluidised bed gasification of lignite found the annual reduction of well-to-tank CO_2 emission of the solar coal-to-liquids system relative to its non-solar system was 34%.

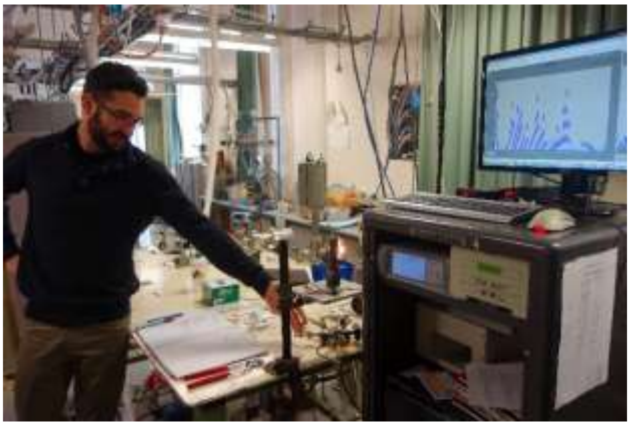
Since LCOF depends strongly on the cost of the feedstock, a greater range of feedstocks is being considered. Many of the sources of low-cost biomass are residues from other agricultural processes, such as forest residue, which tend to have lower availability and lower yields per hectare. To access them in a way that is both economically and environmentally feasible, it is necessary to upgrade their energy density prior to transportation. Torrefaction is one method by which this can be achieved since torrefaction generates:

- A higher energy density, to reduce transportation cost
- A unified the output from a diverse range of sources of biomass feedstocks
- A lower storage cost.

Project P42	Solar Fuels
Solar supercritical water gasification of algal biomass:	A steady-state quasi-equilibrium reactor model has been prepared for immediate use in design of the experimental apparatus, as well as for future use in full-scale system models. The model incorporates compositional data for real algae will be refined in future by incorporating our own kinetics data for microalgae gasification. The thermodynamic equilibrium prediction is done using a Gibbs free energy minimisation approach. This reactor model has been instrumental in developing a good level of understanding of some of the critical design aspects of the benchtop apparatus. These include temperature difference between the supercritical medium and reactor wall; behaviour of the heat-exchanger with a mixture of sub- and supercritical fluid; preheater and furnace lengths for specific residence times; radiative vs conductive heating options.
Redox syngas production:	Flame-made nano-structured and commercial micro-structured ceria powders have been assessed for two-step carbon dioxide splitting (CDS) driven by a reduction step of methane partial oxidation (MPO). The results suggest the reaction rates are strongly dependent on the structural properties of the ceria powders. The nano-structured material show higher reaction rates than the micro-structured commercial ceria and are attributed to the higher specific surface area. The results findings indicate that thermal and chemical stabilization of nano-scale structural features is the key to achieving long-term cyclability of ceria in high temperature solar thermochemical fuel production.
Fisher-Tropsch catalyst development:	The Fisher-Tropsch (FT) process involves the conversion of hydrogen and carbon monoxide to methane and higher hydrocarbons. The Fisher-Tropsch catalyst development has focused on iron oxide / graphene aerogels. Five different phases of iron oxides magnetite, maghemite, hematite, akaganietite and goethite were embedded on to the three dimensionally arranged graphene aerogels. The carbon monoxide conversion and reaction rate were significantly greater for hematite aerogels than for magnetite aerogels.
Advanced Sabatier process:	The Sabatier process involves the conversion of hydrogen and carbon dioxide to methane and higher hydrocarbons. We have demonstrated CO_2 reduction to methane, ethane, and carbon monoxide over various nanoscale catalysts supported on anatase nanoparticles. Increased hydrogen calcination temperatures results in a significant reduction of RuO and clear impact on the catalytic performance. In some experiments, small amounts of propene, propane, hexane, and methanol are produced, but typically in amounts that are difficult to consistently reproduce.

Project P42	Solar Fuels
Key findings:	The qualitative solar fuels evaluation matrix devised in a scoping study has been revised to a quantitative matrix for comparing solar fuels from all available CST technologies and feedstocks. A published performance assessment of Fischer-Tropsch (FT) liquid fuels production using solar hybridised dual fluidised bed gasification of lignite showed the annual solar share depends of the char conversion and quality of the solar resource. For a solar multiple of 3 and bed material storage capacity of 16 h, assuming a char conversion of 100%, the annually averaged utilisation factor of the heliostat field was 40.8% and annual solar share was 21.8%.
Future direction:	The development of the techno-economic assessment will continue to demonstrate that the LCOF targets can be met by 2020 to the ASTRI LCOF targets. In parallel, the following reactor technologies will be developed to a proof-of-concept: • Solar hybridised gasification of biomass and/or coal • Solar mixed reforming of methane • Solar supercritical water gasification of algae • Thermochemical splitting of H_2O and CO_2, as well as advancement of solar thermal production of high value fuels from development of a Fischer-Tropsch catalyst and CO_2 reduction to hydrocarbons via the Sabatier process

Solar Fuels Project Review – June 2015



Education Program Project

Project P02	Project to develop a CST education program
Program Leader: Professor Maziar Arjomandi **Collaborating & Contributing Institutions:** All ASTRI partners **Start Date:** May 2013	To strengthen Australia's ability to provide efficient and affordable CST power, we need to build human capacity in CST research and development. High-quality education tools and environments are therefore needed for the next generation of CST researchers and professionals. The objective of this project is to develop specialised educational material in a broad range of CST-related topics. The program will improve access to educational material focused on CST, because it will be shared among the ASTRI partners and made available to interested professional practitioners. A staged approach has been chosen, with preliminary work to develop short, online education modules. These will be disseminated to enrich and broaden the knowledge base of existing and future university students. The proposed modules are classified as either 'core' or 'enriching'. The core modules will cover collection, concentration and use of solar energy, which includes applications beyond electrical power generation, such as solar fuels. The enriching modules will examine the details of technology development, maintenance and the specialised use of solar energy. The long-term approach is to develop a detailed CST course for undergraduate and postgraduate students that will become a reference course in Australia. The proposed course will keep engineers, students and researchers up to date in this field.
ASTRI education and training	
Module content:	The modules are structured around core content and enriching content. The core content includes CST fundamentals; solar resource; linear focus technologies; point focus technologies; thermal storage; power blocks; solar chemistry; and process heat.
Progress:	Four lectures completed and available to ASTRI partners are: Solar Energy Storage, CST Utilisation - power block fundamentals, CST Utilisation – supercritical CO_2 Cycle), and Solar Hybridisation. Each lecture comprises a series of flash-based interactive presentation slides with a narrative, which is

Project P02	Project to develop a CST education program
	controlled by the user, as well as a short quiz at the end. The lectures are independent and can be used for formal assessment if required.
Feedback on modules:	During the ASTRI 2015 Annual Workshop the module on storage for CST systems was run and early career researchers from ASTRI were asked for their feedback on the content and delivery of the course. There was some key feedback, particularly considering the delivery style, where more animation and diagrams were suggested. In addition, each module has a three member panel to review their content once recoded and before being finalised. The review has taken place recently and feedback is being sent to the module authors. Most modules still need to be changed to an ASTRI template
Key findings	The project is progressing with 'core' and 'enriching' modules of the ASTRI CST course make it adaptable to different needs. There are four lectures completed and available to ASTRI partners.
Future direction	The key activities for the education program are developing the modules, creating practical activities and resolving platform issues. Tasks within these activities are to: • Continue to develop syllabi for modules and possibly combine courses by adapting existing and recording new modules • Peer review of produced modules • Ensure future modules incorporate tools such as animation and graphics to engage students and help explain CST.
ASTRI training and networking	 Explaining sunpaths with a balloon

Knowledge Sharing Activities

ASTRI has significantly increased the focus on communications in the last year with the appointment of a dedicated Communications Advisor.

Key communications highlights include::

- Development and ongoing execution of a communications strategy and activity plan with objectives, timelines, tactics, targets and ownership;
- Increased level of media engagement through briefings, news updates and liaison with industry, environment and renewables media;
- Social media strategy defined and implemented;
- New brand and marketing tools developed to increase profile and engagement with ASTRI through banners, models and educational video; and
- Website additions and enhancements.

Implementation of the first phase of ASTRI’s Communications strategy in this reporting period has seen an increase in media engagement, briefings, ASTRI news, knowledge sharing (through new tools and approaches) and enhancements to existing brand and communications platforms to help achieve ASTRI’s communications objectives.

A broad range of communications tactics will be employed in the next reporting period to continue the momentum established and further develop ASTRI’s reputation and profile.

The ASTRI Annual Workshop in February 2015 was a major success, bringing together researchers, industry, government, as well as international experts. The internal workshop highlighted the achievements of 2014, with the ASTRI Economic Workshop being an inaugural dialogue between the researchers, CST industry, and government; ultimately providing endorsement for ASTRI’s economic modelling that underpins the demonstration of technical progress.

The economic workshop was held with selected key industry representatives and researchers and was designed to establish common ground within the CST community in Australia, particularly for issues regarding the economic value of CST. It proved to be insightful with many interesting queries and ideas being raised, both in preparation of the workshop and on the day. The preparation was facilitated by an external Yammer network so that all participants could share material, write their opinions and start online discussions. This tool was seen as a great way to communicate within the CST community in Australia and the way in which ASTRI should use external Yammer networks in the future is now being planned. The Australian industry representatives invited to the ASTRI Economic workshop endorsed the need for ASTRI to have a long-term, cost-reductions focus and to pursue a large, centralised, national grid-connected size, such as the 100MWe baseline.

The public symposium was organised to facilitate the sharing of knowledge and to foster connections amongst the stakeholders within the CST community in Australia. The symposium included presentations from two high profile international guests, one form the US and the other from Europe. They gave a global perspective on the research and industry efforts to introduce CST in countries across the world in cost-competitive ways. There was a strong emphasis on the role of reducing the cost of CST technologies and building relationships between researchers and industry. This highlighted the contribution ASTRI plays in progressing CST technologies and building relationships with industry. This event proved to be highly valuable as was noted in a media release by ARENA.

Publications and Presentations

Publications

#	PAPER	PARTNERS	DOI*
J001	Singh, R., Miller, S.A., Rowlands, A.S., Jacobs, P.A. "Dynamic characteristics of a direct-heated supercritical carbon-dioxide Brayton cycle in a solar thermal power plant" Energy 50 (2013) 194-204	2	http://dx.doi.org/10.1016/j.energy.2012.11.029
J002	Singh, R., Miller, S.A., Rowlands, A.S. "Effects of relative volume-ratios on dynamic performance of a direct-heated supercritical carbon-dioxide closed Brayton cycle in a solar-thermal power plant" Energy 55 (2013) 1025-1032	2	http://dx.doi.org/10.1016/j.energy.2013.03.049
J003	H.Gurgenci " Supercritical CO2 cycles offer experience curve opportunity to CST in remote area markets" Energy Procedia	1	http://dx.doi.org/10.1016/j.egypro.2014.03.125
J004	J. Coventry and J. Pye "Heliostat cost reduction – where to now?" Energy Procedia	1	http://dx.doi.org/10.1016/j.egypro.2014.03.007
J005	Ming Liu, Martin Belusko, N.H. Steven Tay, Frank Bruno, Impact of the heat transfer fluid in a flat plate phase change thermal storage unit for concentrated solar tower plants, Solar Energy, Volume 101, March 2014, Pages 220-231, ISSN 0038-092X.	1	http://dx.doi.org/10.1016/j.solener.2013.12.030
J006	Suoying He, Zhiqiang Guan, Hal Gurgenci, Ingo Jahn, Yuanshen Lu, Abdullah M. Alkhedhair, Influence of ambient conditions and water flow on the performance of pre-cooled natural draft dry cooling towers, Applied Thermal Engineering, Volume 66, Issues 1–2, May 2014, Pages 621-631, ISSN 1359-4311	1	http://dx.doi.org/10.1016/j.applthermaleng.2014.02.070
J007	Suoying He, Zhiqiang Guan, Hal Gurgenci, Kamel Hooman, Yuanshen Lu, Abdullah M. Alkhedhair, Experimental study of film media used for evaporative pre-cooling of air, Energy Conversion and Management, Volume 87, November 2014, Pages 874-884, ISSN 0196-8904	1	http://dx.doi.org/10.1016/j.enconman.2014.07.084
J008	M.H. Sadafi, I. Jahn, A.B. Stilgoe, K. Hooman, Theoretical and experimental studies on a solid containing water droplet, International Journal of Heat and Mass Transfer, Volume 78, November 2014, Pages 25-33, ISSN 0017-9310	1	http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.06.064
J009	Lu, Y.S., Gurgenci, H., Guan, Z., and He, S., The influence of windbreak wall orientation on the cooling performance of small natural draft dry cooling towers. International Journal of Heat and Mass Transfer, Volume 79, December 2014, Pages 1059–1069	1	http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.09.012
J010	Suoying He, Zhiqiang Guan, Hal Gurgenci, Kamel Hooman, Yuanshen Lu, Abdullah M. Alkhedhair, Experimental study of the application of two trickle media for inlet air pre-cooling of natural draft dry cooling towers, Energy Conversion and Management, Volume 89, 1 January 2015, Pages 644-654, ISSN 0196-8904	1	http://dx.doi.org/10.1016/j.enconman.2014.10.031

#	PAPER	PARTNERS	DOI*
J011	M.H. Sadafi, I. Jahn, A.B. Stilgoe, K. Hooman, A theoretical model with experimental verification for heat and mass transfer of saline water droplets, International Journal of Heat and Mass Transfer, Volume 81, February 2015, Pages 1-9, ISSN 0017-9310	1	http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.10.005
J012	Abdullah Alkhedhair, Zhiqiang Guan, Ingo Jahn, Hal Gurgenci, Suoying He. Water Spray For Pre-Cooling Of Inlet Air For Natural Draft Dry Cooling Towers – Experimental Study. International Journal of Thermal Sciences	1	http://dx.doi.org/10.1016/j.ijthermalsci.2014.11.029
J013	Jacob, R. and F. Bruno (2015) "Review on shell materials used in the encapsulation of phase change materials for high temperature thermal energy storage." Renewable and Sustainable Energy Reviews 48(0): 79-87	1	http://dx.doi.org/10.1016/j.rser.2015.03.038
J014	Liu, M., J. C. Gomez, C. S. Turchi, N. H. S. Tay, W. Saman and F. Bruno (2015) "Determination of thermo-physical properties and stability testing of high-temperature phase-change materials for CSP applications." Solar Energy Materials and Solar Cells 139(0): 81-87	1	http://dx.doi.org/10.1016/j.solmat.2015.03.014
J015	Sadafi, M. H., I. Jahn and K. Hooman (2015) "Cooling performance of solid containing water for spray assisted dry cooling towers." Energy Conversion and Management 91(0): 158-167	1	http://dx.doi.org/10.1016/j.enconman.2014.12.005
J016	J. Toster and D.A.Lewis (2015) “Investigation of Roughness Periodicity on The Hydrophobic Properties of Surfaces”, Aust J. Chem (special issue invited), 68, 1228-1232	1	http://dx.doi.org/10.1071/CH15310
J017	Kueh, K., Nathan, G.J., Saw, W. (2015) "Storage capacities required for a solar thermal plant to avoid unscheduled reductions in output" Solar Energy, 118, 209–221	1	http://dx.doi.org/10.1016/j.solener.2015.04.040
J018	J. Coventry, C. Andraka, J. Pye, M. Blanco, J. Fisher (2015) “A review of Sodium receiver technologies for central receiver solar power plants” Solar Energy, 122, 749–762	2	http://dx.doi.org/10.1016/j.solener.2015.09.023
J019	V. Grigoriev, M. Blanco, C. Corsi (2016) “Fourier sampling of sun path for applications in solar energy” American Institute of Physics	1	Accepted on 7-Oct-2015 with SolarPACES ID 36017
J020	Emes, M. J., M. Arjomandi and G. J. Nathan (2015) "Effect of heliostat design wind speed on the levelised cost of electricity from concentrating solar thermal power tower plants." Solar Energy v115: 441-451	1	http://dx.doi.org/10.1016/j.solener.2015.02.047
J021	Guo, P., P. J. van Eyk, W. L. Saw, P. J. Ashman, G. J. Nathan and E. B. Stechel (2015) "Performance Assessment of Fischer–Tropsch Liquid Fuels Production by Solar Hybridized Dual Fluidized Bed Gasification of Lignite." Energy Fuels, 29(4), 2738–2751	1	http://dx.doi.org/10.1021/acs.energyfuels.5b00007
J022	He, S., H. Gurgenci, Z. Guan, X. Huang and M. Lucas (2015) "A review of wetted media with potential application in the pre-cooling of natural draft dry cooling towers." Renewable and Sustainable Energy Reviews v44: 407-422	1	http://dx.doi.org/10.1016/j.rser.2014.12.037
J023	Lu, Y., Z. Guan, H. Gurgenci, K. Hooman, S. He and D. Bharathan (2015) "Experimental study of crosswind effects on the	1	http://dx.doi.org/10.1016/j.enconman.2014.12.018

#	PAPER	PARTNERS	DOI*
	performance of small cylindrical natural draft dry cooling towers." Energy Conversion and Management 91: 238-248		
J024	P. Guo, W. Saw, P. J. van Eyk, P. J. Ashman, G. J. Nathan and E. B. Stechel (2015). "Fischer–Tropsch liquid fuel production by co-gasification of coal and biomass in a solar hybridized dual fluidized bed gasifier." Energy Procedia v69, 1770–1779	1	http://dx.doi.org/10.1016/j.egypro.2015.03.147
J025	W. Saw, A. Kaniyal, P. J. van Eyk, P. J. Ashman, G. J. Nathan and E. B. Stechel (2015). "Solar hybridized coal-to-liquids via gasification in Australia: techno-economic assessment." Energy Procedia v69, 1819–1827	1	http://dx.doi.org/10.1016/j.egypro.2015.03.158
J026	Liu M., Tay N.H.S., Belusko M., Bruno F. (2015) Investigation of Cascaded Shell and Tube Latent Heat Storage Systems for Solar Tower Power Plants, Energy Procedia, v69, pp 913-924, 2015	1	http://dx.doi.org/10.1016/j.egypro.2015.03.175
J027	Belusko M, Tay N.H.S., Liu M., Bruno F. (2016) Effective tube-in-tank PCM thermal storage for CSP applications, Part 1: Impact of tube configuration on discharging effectiveness, Solar Energy, Available online 20 October 2015	1	http://dx.doi.org/10.1016/j.solener.2015.09.042
J028	Belusko M, Tay N.H.S., Liu M., Bruno F. (2016) Effective tube-in-tank PCM thermal storage for CSP applications, Part 2: Parametric assessment and impact of latent fraction, Solar Energy, Available online 20 October 2015	1	http://dx.doi.org/10.1016/j.solener.2015.09.034
J029	Liu, M., Tay, N.H.S., Bell, S., Belusko, M., Jacob, R., Will, G., Saman W., Bruno, F. (2016) Review on concentrating solar power plants and new developments in high temperature thermal energy storage technologies, Renewable & Sustainable Energy Reviews, v53, 1411–1432	2	http://dx.doi.org/10.1016/j.rser.2015.09.026

Presentations

ASTRI ID	PRESENTER	TOPIC	CONFERENCE	DATE
C001	Blanco, Manuel	Current status of CST	First Australian Workshop on Solar Thermal Chemical and Industrial Processes, Adelaide University	7-Feb-2013
C002	Blanco, Manuel	ASTRI Overview	SolarPACES, Newcastle	17-Apr-2013
C003	Blanco, Manuel	Solar Thermal’s Potential	Solar 2013 Conference and Expo, Melbourne Convention Centre	24-May-2013
C004	Miller, Sarah	ASTRI and CSP Overview	SOLAR SOLUTIONS The future of concentrating solar power in Australia: transitions and benefits, Institute for Sustainable Futures, UTS	24-Jun-2013
C005	Blanco, Manuel	Overview of CSIRO & ASTRI	EUROTHERM Seminar No. 98 - Concentrating Solar Energy Systems	7-Jul-2013
C006	Gurgenci, Hal	Supercritical CO2 Cycles Offer Experience Curve Opportunity to CST in Remote Area Markets	Poster Session 2, SolarPACES 2013, Las Vegas	18-Sep-2013

ASTRI ID	PRESENTER	TOPIC	CONFERENCE	DATE
C007	Coventry, Joe	Heliostat Cost Reduction – Where to Now?	Poster Session 2, SolarPACES 2013, Las Vegas	18-Sep-2013
C008	Blanco, Manuel	Plenary: Global CSP Initiatives	SolarPACES 2013, Las Vegas	19-Sep-2013
C009	Webby, Brian	Sensitivity analysis for concentrating solar power technologies	MODSIM Conference, Adelaide Australia	1-6 Dec 2013
C010	Blanco, Manuel	Overview of R&D activities in Solar Thermal Electricity technologies worldwide	Solar 2014, Melbourne	8-May-2014
C011	Sun, Yanping	Cost analysis of high temperature thermal energy storage for solar power plant	Solar 2014, Melbourne	8-9-May-2014
C012	Tay, Steven	Thermal performance of phase change thermal storage systems for concentrated solar power applications with different heat transfer fluids	Solar 2014, Melbourne	8-9-May-2014
C013	Gurgenci, Hal	Supercritical CO_2 Systems for Concentrating Solar Thermal Power	Solar 2014, Melbourne	8-9-May-2014
C014	Singh, Rajnesh	Impacts of collector receiver volume on dynamic performance of a direct-heated supercritical-CO_2 closed Brayton cycle in a solar thermal power plant	Solar 2014, Melbourne	8-9-May-2014
C015	Beath, Andrew	Improving the financial performance of concentrating solar thermal power	ASME 2014 8th International Conference on Energy Sustainability, Boston	30-Jun-2014
C016	Guan, Zhiqiang	Performance analysis of natural draft cooling tower with inlet air precooling	Int Symp on Ind. Chimneys and Cooling Towers	June 2014
C017	Guan, Zhiqiang	Design options of solar enhance natural draft cooling tower for solar thermal power plants	Int Symp on Ind. Chimneys and Cooling Towers	June 2014
C018	Liu, Ming	Investigation of cascaded shell and tube latent heat storage systems for solar tower power plants	SolarPACES, Beijing	Sep-2014
C019	Pye, John	An exergy analysis of tubular solar-thermal receivers with different working fluids	SolarPACES, Beijing	Sep-2014
C020	Coventry, Joe	Sodium receivers for solar power towers: a review	SolarPACES, Beijing	Sep-2014
C021	Saw, Woei	Solar hybridized coal-to-liquids via gasification in Australia: techno-economic assessment	SolarPACES, Beijing	Sep-2014

ASTRI ID	PRESENTER	TOPIC	CONFERENCE	DATE
C022	Guo, Peijun	Fischer-Tropsch liquid fuel production by cogasification of coal and biomass in a solar hybrid dual fluidized bed gasifier	SolarPACES, Beijing	Sep-2014
C023	Saw, Woei	Techno-economic evaluation of solar hybridised and non-solar gasification poly-generation plants	4th International Symposium on Gasification and its Application, Austria	Sep-2014
C024	Jacob, Rhys	Techno-Economic Analysis of Phase Change Material Thermal Energy Storage Systems in High Temperature Concentrated Solar Power Plants	1st Asia-Pacific Solar Research Conference (APSRC) 2014, Sydney, Australia	8-Dec-2014
C025	Odabaee, Mostafa	CFD simulation and FE analysis of a high pressure ratio radial inflow turbine.	19th Australasian Fluid Mechanics Conference	8-Dec-2014
C026	Sadafi, Hosein	An Investigation of Evaporation from Single Saline Water Droplets: Experimental and Theoretical Approaches	19th Australasian Fluid Mechanics Conference	8-Dec-2014
C027	Alkhedhair, Abdullah	Experimental Study on Inlet Air Cooling by Water Spray for Natural Draft Dry Cooling Towers Enhancement	19th Australasian Fluid Mechanics Conference	8-Dec-2014
C028	He, Zimeng	Experimental Study of Heat Transfer Coefficient and Pressure Drop of Cellulose Corrugated Media	19th Australasian Fluid Mechanics Conference	8-Dec-2014
C029	Kan, Qin (Jason)	Validation of a Three-dimensional CFD Analysis of Foil Bearings with Supercritical CO2	19th Australasian Fluid Mechanics Conference	8-Dec-2014
C030	Saw, Woei	Solar hybridised biomass-to-liquids via gasification in Australia: Techno-economic assessment	Bioenergy Conference Australia Adelaide, Australia	1-2 Dec-2014
C031	Guo, Peijun	Liquid fuel production via solar hybridized dual fluidized bed cogasification of biomass and coal	Bioenergy Conference Australia, Adelaide, Australia	1-2 Dec-2014
C032	Aghaeimeybodi, Mehdi	Variability in the estimated LCOE for CSP technologies arising from uncertainty in cost and solar data inputs	1st Asia-Pacific Solar Research Conference (APSRC) 2014	8-Dec-2014
C033	Hinkley, Jim	The challenges and opportunities for integration of solar syngas production with liquid fuel synthesis	SolarPACES 2015, Cape Town, R.S.A.	13-16 Oct-2015
C034	Persky, Rodney	Robust Design and Optimisation of a Radial Turbine Within a	11th World Congress on Structural and Multidisciplinary Optimisation, Sydney	7-12 Jun-2015

ASTRI ID	PRESENTER	TOPIC	CONFERENCE	DATE
		Supercritical CO2 Solar Brayton Cycle		
C035	Odabaee, Mostafa	Optimisation of a High Pressure Ratio Radial-Inflow Turbine: Coupled CFD-FE analysis	ASME Turbo Expo 2015	15-Jun-2015
C036	Lu, Yuanshen	Experimental Study On The Effects Of A Tri-Blade-Like Windbreak Wall On Small Size Natural Draft Dry Cooling Towers	17th IAHR International Conference on Cooling Tower and Heat Exchanger	7-11 Sep-2015
C037	Sadafi, Hosein	Contact of Droplets with Heat Exchanger Surfaces in Spray Assisted Dry Cooling Towers Using Saline Water – A Numerical Study	17th IAHR International Conference on Cooling Tower and Heat Exchanger	7-11 Sep-2015
C038	Yue, Lindsey	Solar thermochemical CO_2 capture via calcium oxide looping: thermal transport modeling and solar reactor design	Eurotherm Seminar 109/Numerical Heat Transfer 2015, Warsaw	27-30 Sep-2015
C039	Bell, Stuart	Development of Testing Systems for Corrosion in Molten Salts	SolarPACES 2015, Cape Town, R.S.A.	13-16 Oct-2015
C041	Miller, Sarah	Concentrating Solar Thermal: Developments and Research Need	Australian Institute of Energy (AIE) Newcastle Solar Seminar	3-Sep-2015
C042	Jiang, Yifeng	Development of High Temperature Phase Change Materials for the Supercritical Carbon Dioxide Power Cycle for Solar Power Plants	Greenstock 2015, Beijing	19-22 May-2015
C043	Bruno, Frank	Heat Transfer Study of a Coil-In-Tank Latent Heat Storage System for Solar Tower Power Plants	Greenstock 2015, Beijing	19-22 May-2015
C044	Odabaee, Mostafa	Computational Fluid Dynamics Simulation and Turbomachinery Code Validation of a High Pressure Ratio Radial-Inflow Turbine	10th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics (HEFAT2014)	14-Jul-2014
C045	Saman, Wasim	Numerical modeling of inward and outward melting of high temperature PCM in a vertical cylinder	SolarPACES 2015, Cape Town, South Africa, 2015	13-16 Oct-2015
C046	Bell, Stuart	Stability and corrosion testing of a high temperature phase-change material for CSP applications	SolarPACES 2015, Cape Town, R.S.A.	13-16 Oct-2015
C047	Raud, Ralf	Method for Systematic Comparison of Eutectic Salts for Latent Heat Solar Thermal Energy Storage	SolarPACES 2015, Cape Town, R.S.A.	13-16 Oct-2015
C048	Anglani, Francesco	CFD modelling of a water-jet cleaning process for concentrated solar thermal (CST) systems	SASEC 2015, Kruger Park, R.S.A	10-14 May-2015

ASTRI ID	PRESENTER	TOPIC	CONFERENCE	DATE
C049	Guan, Zhiqiang	Dust Characterisation for Solar Collector Fouling and Cleaning in a Concentrating Solar Thermal Power Plant	Heat Exchanger Fouling and Cleaning – 2015, Enfield, England	7-12 Jun-2015
C050	Anglani, Francesco	A Numerical study of a stationary water-spray cleaning system for concentrated solar Thermal (CST) reflectors	SuNEC 2015, Palermo, R.S.A	9-12 Oct-2015
C051	Pennetta, Selene	A case study on parameters influencing dust accumulation on CSP reflectors	SuNEC 2015, Palermo, R.S.A	9-12 Oct-2015
C052	Anglani, Francesco	A Numerical Study on High-Pressurized Water-Spray Cleaning for CSP Reflectors	SolarPACES 2015, Cape Town, R.S.A	13-16 Oct-2015
C053	Pennetta, Selene	An Investigation on Factors Influencing Dust Accumulation on CSP Mirrors	SolarPACES 2015, Cape Town, R.S.A	13-16 Oct-2015
C054	Saman, Wasim	A Numerical Model for Thermal Energy Storage Systems Utilising Encapsulated Phase Change Materials	SolarPACES, Cape Town, South Africa, 2015	13-16 Oct-2015
C055	Saman, Wasim	Geopolymer Encapsulation of a Chloride Salt Phase Change Material for High Temperature Thermal Energy Storage	SolarPACES, Cape Town, South Africa, 2015	13-16 Oct-2015

ASTRI People

ASTRI OFFICE

CSIRO BUSINESS SUPPORT

NAME	ROLE	NAME	ROLE
Dr Manuel Blanco	Director	Ms Brooke Horton	Finance
Ms Sarah Miller	Chief Operating Officer	Ms Kate Hines	Communications
Ms Jane Sherman	Administration	Mr Stephen O'Dowd	Business Development
Dr Jacqueline Hicks	Research Co-ordinator	Mr Juan Llorente	Project Support
Ms Min Ostini	Administration	Mr Geoff Taylor	Health & Safety
		Mr Andrew Lake	Legal

ASTRI PRINCIPAL INVESTIGATORS

OTHER ASTRI LEADERS

NAME	ASTRI PARTNER	NAME	ASTRI PARTNER
Wes Stein	CSIRO	Hal Gurgenci	University of Queensland
Wojciech Lipinski	Australian National University	Andrew Beath	CSIRO
Paul Meredith	University of Queensland	Maziar Arjomandi	University of Adelaide
Graham (Gus) Nathan	University of Adelaide	Joe Coventry	Australian National University
Wasim Saman	University of South Australia	Jim Hinkley	CSIRO
Ted Steinberg	Queensland University of Technology	Kamel Hooman	University of Queensland
Davis Lewis	Flinders University	Emile Sauret	Queensland University of Technology

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Abbasi, Ehsan	Australian National University	Modirshanechi, Mohsen	University of Queensland
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Aljawi, Raad	Queensland University of Technology	Odabaee, Mostafa	University of Queensland
Anglani, Francesco	Queensland University of Technology	Omaraa, Ehsan	University of South Australia
Asselineau, Charles-Alexis	Australian National University	Perez, Erond	University of Queensland

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Corsi, Clotilde*	CSIRO	Persky, Rodney	Queensland University of Technology
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Emes, Matthew	University of Adelaide	Rahbari, Alireza	Australian National University
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Fedunik-Hofman, Larissa	CSIRO	Riahi, Soheila	University of South Australia
Gao, Michael	Australian National University	Sadafi, Hosein	University of Queensland
Gowtham, Mohan	Australian National University	Salikhori, Mahyar	University of Adelaide
Guo, Peijun	University of Adelaide	Smith, Christine*	CSIRO
He, Zimeng	University of Adelaide	Sun, Yubiao	University of Queensland
Jacob, Rhys	University of South Australia	Vidal, Alejandro	Australian National University
Jiang, Yifeng	CSIRO	Viv, Bone	University of Queensland
Kan, Qin(Jason)	University of Queensland	Wang, Jianyong	University of Queensland
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Completed* = 2 Resigned = 1

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NAME	ASTRI PARTNER	NAME	ASTRI PARTNER
Aghaeimeybodi, Mehdi	CSIRO	Kumar, Apurv	CSIRO
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Ashtiani Abdi, Iman	University of Queensland	Maselli, Olivia	University of Adelaide
Bayon Sandoval, Alicia	CSIRO	Nagy, Andras	University of Queensland
Bell, Stuart	Queensland University of Technology	Rakshit, Dibakar	CSIRO
Czapla, Jason	University of Queensland	Saw, Woei	University of Adelaide
Davis, Dominic	University of Adelaide	Singh, Rajinesh	University of Queensland
Duck, Benjamin	CSIRO	Toster, Jeremiah	Flinders University
Gentleman, Alexander	University of Adelaide	Twomey, Braden	University of Queensland

Ghanadi, Farzin	University of Adelaide	Venkataraman, Mahesh	Australian National University
Grigoriev, Victor	CSIRO	Ventura, Carlos	University of Queensland
Jafarian, Mehdi	University of Adelaide	Xue, Yun Peng	University of Adelaide
Ji, Guozhao	University of Queensland		

Resigned = 7

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Andersson, Gunther	Flinders University	Knight, Chris	CSIRO
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Borghesani, Pietro	Queensland University of Technology	Lim, Seng	CSIRO
Bruno, Frank	University of South Australia	Liu, Ming	University of South Australia
Burgess, Greg	Australian National University	Losic, Dusan	University of Adelaide
Campbell, Jon	Flinders University	Ma, Lin	Queensland University of Technology
Chinnici, Alfonso	University of Adelaide	Martin, Scott	CSIRO
Cholette, Michael	Queensland University of Technology	Metha, Greg	University of Adelaide
Chumpia, Ampon	University of Queensland	Murphy, Peter	University of South Australia
Connor, Phil	CSIRO	Nann, Thomas	University of South Australia
Dally, Bassam	University of Adelaide	Nock, Ian	Australian National University
Dekkers, Wim	Queensland University of Technology	Pennetta, Selene	Queensland University of Technology
Dennis, Mike	Australian National University	Pratt, Rodney	University of South Australia
Di Pasquale, Berto	University of Queensland	Qiu, Ang	Flinders University
Doonan, Christian	University of Adelaide	Rowlands, Andrew	University of Queensland
Fairman, Philip	CSIRO	Russell, Hugh	University of Queensland
Farrant, David	CSIRO	Stevens, David	University of Queensland
Guan, Zhiqiang	University of Queensland	Stuart, Wayne	CSIRO
Gwynn-Jones, Stephen	University of Queensland	Sun, Yanping	CSIRO
Hall, Colin	University of South Australia	Tang, Youhong	Flinders University
Haque, Nawshad	CSIRO	Tian, Zhao Feng	University of Adelaide
Hughes, Graham	Australian National University	Veeraragavan, Anand	University of Queensland
Jacobs, Peter	University of Queensland	Venn, Felix	Australian National University

NAME	ASTRI PARTNER	NAME	ASTRI PARTNER
Jahn, Ingo	University of Queensland	Wang, Ruizi (Norman)	Queensland University of Technology
Kaniyal, Ashok	University of Adelaide	Webby, Brian	University of South Australia
Kaufer, Martin	Australian National University	Will, Geoffrey	Queensland University of Technology
Khare, Sameer	CSIRO	Zanatta, Ivan	University of South Australia
Kim, Jin-Soo	CSIRO		

Resigned = 6

Financial Summary

The following is a financial summary for the relevant reporting period (1-Nov-2014 to 31-Oct-2015) and also for the Program overall. Accounting in ASTRI is on a cash basis as this was the preferred method by all collaborators.

Total income with breakdown by funding source

INCOME BY FUNDING SOURCE	1-NOV-2014 TO 31-OCT-2015	PROGRAM OVERALL
Grant funding (ARENA)	$4,550,000	$9,287,500
Collaborator contributions	$5,520,743	$10,419,967
TOTAL CONTRIBUTIONS	$10,070,743	$19,707,467

Total expenditure with breakdown by heads of expenditure

HEADS OF EXPENDITURE	1-NOV-2014 TO 31-OCT-2015	PROGRAM OVERALL
Salaries	$8,204,698	$15,156,615
Equipment	$301,731	$456,794
Materials	$335,620	$572,485
Sub-contract	$0	$0
Travel	$334,438	$584,134
Other	$332,545	$893,372
TOTAL EXPENDITURE	$9,509,031	$17,663,400

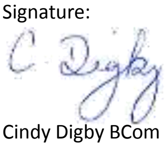
Statement of financial performance

FINANCIAL SUMMARY	1-NOV-2014 TO 31-OCT-2015	PROGRAM OVERALL
Total contributions	$10,070,743	$19,707,467
Total expenditure	$9,509,031	$17,663,400
OPERATING PROFIT (LOSS)	$561,712	$2,044,067

Declaration:

I hereby certify that the above statement covering the period from commencement to 31 October 2015 represents the financial transactions fairly and is based on proper accounts and records.

Signature:



Cindy Digby BCom MAcc CPA
Finance Manager, Energy Flagship
Date: 30 March 2016

Shortened forms

1D	1 dimension
3D	3 dimensions
ABL	Atmospheric boundary layer
AEMO	Australian Electricity Market Operator
AETA	Australian Energy Technology Assessment
AISI	American Iron and Steel Institute
ANU	Australian National University, Canberra
APA	Australian Postgraduate Award
APSRC	Asia Pacific Solar Research Conference
ARENA	Australian Renewable Energy Agency
ASTRI	Australian Solar Thermal Research Initiative
ASI	Australian Solar Institute
ASU	Arizona State University
AUD	Australian dollar
BAU	Business as Usual
BOP	Balance of Plant
BREE	Bureau of Resources and Energy Economics
CapEx	Capital expenditure
CCS	Carbon capture and storage
CDS	Carbon dioxide splitting
CFD	Computational fluid dynamics
CLC	Closed-loop cycle
CST	Concentrating Solar Thermal technologies
CSP	Concentrating Solar Power
CWG	Communications Working Group
DIISRTE	Department of Industry, Innovation, Science Research and Tertiary Education
DNI	Direct Normal Irradiance
DoE	Department of Energy
DOI	DOI is the Digital Object Identifier where replacing “doi:” by “http://dx.doi.org/” provides a web link
DSC	Differential Scanning Calorimetry
DRET	Department of Resource, Energy and Tourism
DSC	Differential scanning calorimetry
ELEMENTS	US DOE SunShot CSP: ELEMENTS funding opportunity for engineering new thermochemical storage
EOI	Expression of interest
EPC	Engineering Procurement Company
EPRI	Electric Power Research Institute
FTL	Fischer-Tropsch liquids
FTR	Fischer-Tropsch reactor
FOAs	Funding Opportunity Announcements
GDP	Gross domestic product
GJ	Giga-joule
GTL	Gas to liquids
GW	Gigawatt
ΔH_m	Latent heat of melting
ΔH_f	Latent heat of freezing
HAZID	Hazard Identification
HDR	Higher degree research
HTF	Heat Transfer Fluid
Hy-Sol	Hybrid thermochemical energy storage system
IEA	International Energy Agency
IP	Intellectual Property
IPCC	International Panel on Climate Change
IRENA	International Renewable Energy Agency
IRR	Internal rate of return
KPI	Key Performance Indicator
kW	Kilowatt
kWh	Kilowatt-hour
LCL	Limestone closed loop
LCOE	Levelised Cost of Electricity
LCOF	Levelised Cost of Fuel
MCW	Masters by Course Work
MENA	Middle East and North Africa
MJ	Mega-joule
MOE	Method of encapsulation
MPa	Mega-pascal
MPO	Methane partial oxidation
MW	Megawatt

NREL	National Renewable Energy Laboratory
NTU	Number of Transfer Units
O&M	Operation and maintenance
OECD	Organisation for Economic Co-operation and Development
OEM	ASTRI Overarching Economic Model project (P01)
ORC	Organic Rankine Cycle
P4VP	poly-4-vinylpyridine
PCHE	Printed Circuit Heat Exchangers
PCM	Phase Change Material
PDPA	Phase Doppler Particle Analyzer
PDMS	polydimethylsiloxane
PV	Photovoltaic Solar Cell
QUT	Queensland University of Technology
RD&D	Research, Development and Demonstration
RES	Renewable Energy Systems
RPM	Revolutions per minute
SAM	System Advisor Model
SCBTL	Solar coal-biomass–to–liquids
SDFB	Solar hybridised dual fluidised bed
SEGS	Solar Energy Generating System (CST trough plants in USA)
SEVR	Solar expanding vortex receiver
SNL	Sandia National Laboratories
SRI	Strategic Research Initiative
SROM	Supporting the Research Operating Model
SS316	Stainless Steel 316
STL	Solar to Liquid
ΔT	Temperature change
T_m	Melting point temperature
Tf	Freezing point temperature
TGA	Thermogravimetic analysis
TRL	Technology Readiness Level
UCB	University of Colorado at Boulder
UG	Undergraduate
UQ	The University of Queensland
USASEC	USA Solar Energy Collaboration
USD	US dollar
WCA	Water contact angle
WHS	Workplace health and safety

Glossary

Australian Electricity Market Operator (AEMO) – Australia's National Energy Market operator

Angle of incidence – the angle that a ray of sun makes with a line perpendicular to a surface. For example, a surface that directly faces the sun has a solar angle of incidence of zero, but if the surface is parallel to the sun (for example, sunrise striking a horizontal rooftop), the angle of incidence is 90°

Base load – the average amount of electric power that a utility must supply in any given period

Capacity factor – the fraction of a period, normally a year, which a plant operates at an equivalence to full capacity

Capital expenditure (CapEX) – the monetary or financial cost associated with long-term investment in physical assets, buildings or equipment.

Concentrating solar thermal (CST) – solar energy conversion systems characterised by the optical concentration of solar rays through an arrangement of mirrors or lenses, to create heat for process and chemical energy systems

Concentrating solar power (CSP) – solar energy conversion system characterised by the optical concentration of solar rays through an arrangement of mirrors or lenses, used to heat liquids or gases, which are then used to generate electrical power

Differential scanning calorimetry (DSC) – thermo-analytical technique

Direct Normal Irradiance (DNI) – synonym for beam radiation, the amount of solar radiation received per unit area by a surface perpendicular (normal) to the rays that come in a straight line from the direction of the sun at its current position in the sky

Electrical grid – an integrated system of electricity distribution, usually covering a large area.

Exergy - the maximum useful work that a system can deliver when it reaches thermodynamic equilibrium with its surroundings; the surroundings are considered anything outside the desired system boundaries, so any system process that does not deliver the desired work is an unintended process with losses to the surroundings, thereby reducing the useful work

Fischer-Tropsch – a process involving chemical reactions for converting syngas to liquid hydrocarbons

Funding Opportunity Announcements (FOAs) –refers to a notice received for federal grant funding opportunities

Gigawatt (GW) – a unit of power equal to 1 000 000 000 Watts, 1 000 000 kilowatts, or 1 000 megawatts.

Heliostat - a multi-component apparatus used to compensate for the sun's apparent motion in the sky which includes a reflective surface, usually a planar mirror, with a mechanically controlled range of motion used to reflect sunlight in a constant direction toward a predetermined target

Heat transfer fluid (HTF) – in high temperature systems a fluid agent (gas, liquid or emulsion) used to cool or transfer heat from one region or area to another

Kilowatt (kW) – a standard unit of electrical power equal to 1000 watts, or to the energy consumption at a rate of 1 000 joules per second

Kilowatt-hour (kWh) – 1 000 watts acting over a period of one hour. The kWh is a unit of energy. One kWh=3 600 kJ

Levelised Cost of Electricity (LCOE) – frequently used in reference to investment into electricity generation, it is the minimum price of electricity at which a technology generates enough revenue to pay all of the generation medium's costs, including sunk capital expenditure, and provide an investment return

Megawatt (MW) – 1,000 kilowatts or 1,000,000 watts; standard measure of electric power plant generating capacity

Overall annual efficiency – Efficiency of conversion of solar energy to net electrical energy output over a year

Phase-change material (PCM) – A substance with a high heat of fusion which, melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy. Heat is absorbed or released when the material changes from solid to liquid and vice versa. Also referred to as latent heat storage (LHS) units

Photon – a particle of light that acts as an individual unit of energy.

Receiver – or solar receiver is a type of furnace, either external or cavity, designed to absorb the energy being reflected from a heliostat field and transfer it into a heat transfer fluid where the furnace is placed at a predetermined point to intercept incoming reflected radiation most efficiently

Sabatier – a process involving chemical reactions for conversion of hydrogen and carbon dioxide to methane and higher hydrocarbons

Solar energy – electromagnetic energy transmitted from the sun (solar radiation). The amount of solar energy that reaches the earth is equal to one billionth of total energy generated, or the equivalent of about 420 trillion kilowatt-hours

Solar thermal electric systems – conversion technologies that convert solar energy to electricity by heating a working fluid to power a turbine that drives a generator. Examples of these systems include central receiver systems, parabolic dishes, and solar troughs

Strategic Research Initiative (SRI) – a term used by the Australian Solar Institute and refers long-term, strategic and collaborative national research programs to underpin the researcher capacity required to deliver 'over the horizon' technologies not yet commercially viable

Syngas – synthesis gas comprising predominantly hydrogen and carbon monoxide

System Advisor Model (SAM) - a performance and financial model designed to facilitate decision making for people involved in the renewable energy industry, developed by the USA National Renewable Energy Laboratory

USA Solar Energy Collaboration (USASEC) – used by the Australian Solar Institute and refers to the United States-Australia Solar Energy Collaboration as a funding mechanism to support collaborative research between the United States (US) and Australia that aims to fast-track cost reductions in capturing solar energy

Watt – the rate of energy transfer equivalent to one ampere under an electrical pressure of one volt. One watt equals 1/746 horsepower, or one joule per second. It is the product of voltage and current (amperage)

ARENA

Australian Government

Australian Renewable Energy Agency

This Program has been supported by the Australian Government through the Australian Renewable Energy Agency (ARENA). The Australian Government, through ARENA, is supporting Australian research and development in solar photovoltaic and solar thermal technologies to help solar power become cost competitive with other energy sources.

FOR FURTHER INFORMATION

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