ASTRI
AUSTRALIAN SOLAR THERMAL RESEARCH INITIATIVE

ASTRI Annual Report

Australian Solar Thermal Research Initiative

November 2013 – October 2014

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-2013 to 31-Oct-2014

ASTRI at a Glance

ASTRI – Australian Solar Thermal Research Initiative

ASTRI is a consortium of leading Australian research institutions collaborating 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 create 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 deliver leading-edge solar thermal concepts and profit from the growing CST sector.

Approach and Innovation

ASTRI's innovations will be 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 will achieve 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 economic model. Together, the collaborating ASTRI organisations will produce a large-scale collaboration on CST across Australia, serving as a platform for new 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 cost reductions to produce solar electricity at 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.

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 has brought together an array of impressive people to exploit one of Australia's most abundant and under-utilised natural resources: solar energy.

Without doubt, now is the right time for investment in energy research. A range of political and energy market drivers have forced our renewable energy industry into a state of uncertainty. Indeed, it has been a turbulent year for all of our ASTRI partners, be they energy businesses, CSIRO or the higher education sector.

In this continuing period of uncertainty and change, public and private sector investment in energy sector research is particularly important.

The 2014 *Australian Industry Report*[1] identified oil, gas and energy resources as one of the sectors of strategic importance to Australia's economic prosperity and that "our future economic success depends on finding new sources of growth".

Similarly, our Chief Scientist's *Draft Science and Research Priorities for Australia*[2] emphasises energy systems research as a priority area: "A desirable energy future is one that progressively reduces carbon emissions and is economically attractive for consumers and other stakeholders. A diversity of energy sources and suppliers will be important to ensure energy security".

ASTRI's programme is well aligned with these sentiments. ASTRI's ambitious cost reduction research will have a dramatic impact on future energy supply economics. These results will help build Australia's national competitiveness and energy security. The ASTRI team understands that the energy domain has changed significantly over recent years; and those changes underpin the importance of the work we do.

A year ago ASTRI was half the size it is today. I am greatly encouraged by its rapid growth and the acceleration of project work. The education program is having some early important successes in training ASTRI researchers. I am also pleased with the focus on safety and adherence with safe work practices at each of the campuses. ASTRI's primary asset is its people.

It is good to hear everyone in the ASTRI team communicating their important research achievements, meeting or exceeding their KPIs, and collaborating effectively. It is also good to meet and hear from ASTRI's many new students and postdoctoral fellows.

Looking forward, it is pleasing to hear about the move to a whole-of-ASTRI systems approach to help ensure projects do not develop subs-systems in isolation, but integrate with the others in the ASTRI group.

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

Kieran Jacka
Chair, ASTRI Advisory Committee.
Senior Manager, Engineering, ACCIONA Energy Australia.

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[1] http://www.industry.gov.au/industry/Office-of-the-Chief-Economist/Publications/Documents/AIR-Highlights.pdf
[2] http://www.chiefscientist.gov.au/2015/03/draft-science-and-research-priorities-for-australia/

Message from the Director

CST technologies have the potential to become one of the pillars of the future world energy system – a system that must and hopefully will necessarily be much more sustainable than the current one. The core purpose of the ASTRI research program is to develop technological proof-of-concepts with the potential to drastically improve the cost competitiveness of these CST technologies and to position Australia among the leading countries in this global and promising industrial sector and technological field.

The move towards a more renewable energy supply started some years ago, and is gaining momentum by the day – based upon very serious and realistic climate change, sustainability, geopolitical and local environmental concerns. In the electricity sector, for instance, although the contribution of renewable energy systems to electricity generation worldwide is still relatively low, annual growth in the installed capacity of RES around the world has been speeding up in recent years. In 2011 for the first time, then again in 2012, worldwide investment in additional renewable power capacity exceeded the investment in additional fossil-fuel generating capacity. In 2012, the difference was $100 billon[3].

For CST to fulfil its promise of becoming a pillar of the future energy system – and contribute to the provision of firm, affordable, and environmentally friendly electricity to a large fraction of the world population – the CST industry and research community unanimously agree that CST needs to rapidly improve its cost competitiveness by reducing cost and increasing efficiency and overall value. This agreement is reflected in the 2014 edition of the International Energy Agency Solar Thermal Electricity Technology Roadmap. The roadmap envisions 1000 GW of installed CST power plant capacity worldwide by 2050, contributing to 11% of global electricity needs. To fulfil this vision, two of the key actions that the roadmap considers must be taken within the next five years are the strengthening of *'research, development and demonstration (RD&D) efforts to further reduce costs'* and the strengthening of *'international collaboration on RD&D and exchanges of best practices.'*

The urgency of the need for CST technologies to improve their cost competitiveness was one of the motivations for starting ASTRI. It is the reason why ASTRI has such a strong focus on cost reduction and efficiency improvements. Other programs that have also been motivated by this need for cost competitive CST technologies. These include the United States SunShot and the European Union STAGE-STE[4]. The solar industry, through the Euro-Mediterranean Solar Thermal Electricity Association (ESTELA), is promoting a research agenda with similar objectives.

ASTRI stands out from these other initiatives in its structure and focus. Our highly targeted and co-ordinated research, in combination with the critical range of expertise from the seven different institutions, is a highlight of ASTRI's collaborative research program. ASTRI has balanced the need for project

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[3] Frankfurt School of Finance & Management gGmbH, UNEP Collaborating Centre for Climate & Sustainable Energy Finance (2013) "Global Trends in Renewable Energy Investment 2013" www.unep.org/pdf/GTR-UNEP-FS-BNEF2.pdf

[4] STAGE-STE is the Scientific and Technological Alliance for Guaranteeing the European Excellence in Concentrating Solar Thermal Energy

management, which co-ordinates the research direction, with the importance of innovative research from relevant disciplines. Within the research program, all participating institutions are focusing their research expertise and know-how on developing a plethora of innovative technologies that can be combined to create complete CST system configurations with the potential to reach the long-term LCOE target of ASTRI. This adaptation of research expertise and resources for CST research is starting to pay dividends. As is shown in this annual report, an interim CST system has been configured and modelled to demonstrate how technical improvements researched in ASTRI can lead to CST power generation with a lower LCOE than the current state of the art of commercial plants.

Manuel Blanco Ph.D., Dr.Ing
Director, Australian Solar Thermal Research Initiative (ASTRI)
Science Leader, CSIRO Solar Energy Systems Research Group

Concentrating Solar Thermal Technologies

Concentrating solar thermal (CST) technologies can produce high-temperature solar thermal energy and can drive chemical reactions. The most proven CST technologies generate electricity using sunlight.

Reflectors concentrate the solar radiation by directing the sun's rays, which fall over a large area, towards 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 produced in a heat transfer fluid. The thermal energy in the heat transfer fluid can then either be stored, or converted into mechanical energy and ultimately into electricity through a power cycle.

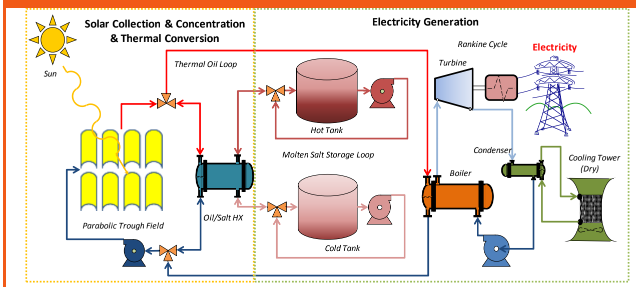
The most significant advantage of CST technologies over other renewable energy technologies is their ability to store thermal energy and convert it to electricity when needed; dispatchable power generation.

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 or nuclear power stations, but CST technologies can 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.

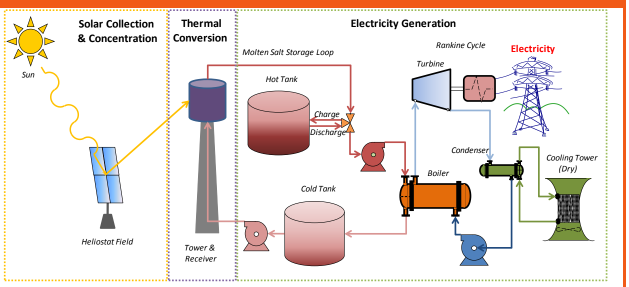
Parabolic troughs are linear focusing technologies, with a concentration ratio of 50–80. The trough reflects the sun's rays onto a linear receiver fixed at the focus on the parabola, and tracks the sun in one direction – normally from east to west. The receiver usually consists of an absorber metal pipe 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 tower some distance away. The receiver can therefore be considered as a point. 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.

Parabolic trough power plant



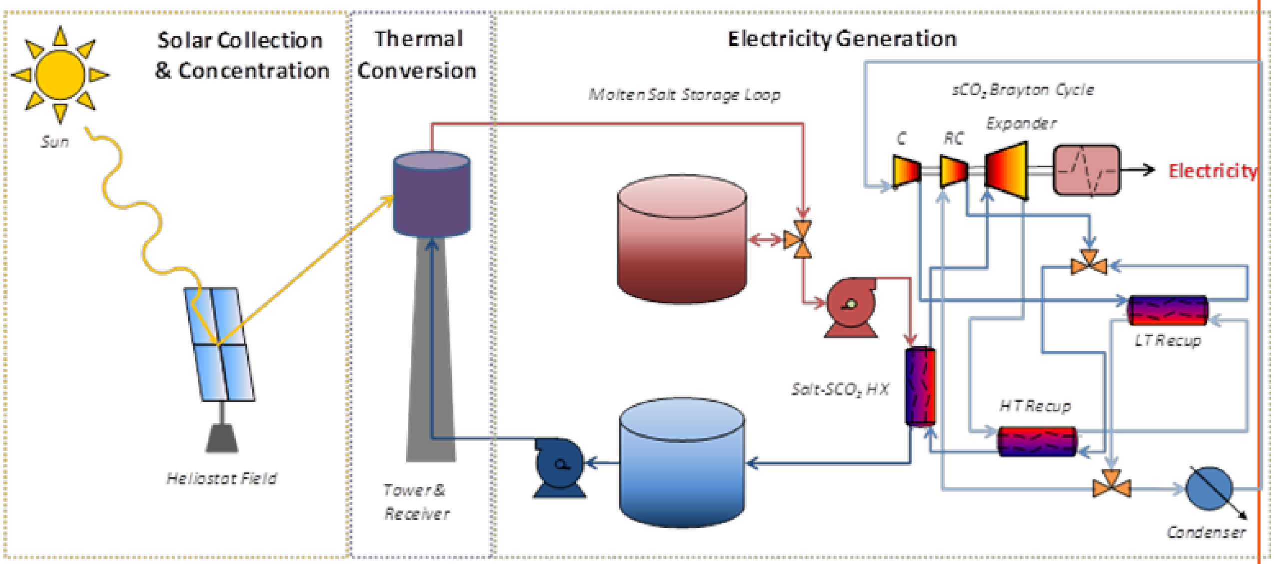
Central receiver tower power plant



Highlights and Achievements

ASTRI has developed a concentrating solar thermal (CST) power plant configuration that could achieve a levelised cost of energy (LCOE) of 21.9c/kWh, with an overall annual efficiency of 15.6%. The proposed central receiver tower power plant design is based on a 120-MWe closed-loop supercritical carbon dioxide (sCO_2) Brayton cycle power block, with molten salt two-tank thermal storage. This interim configuration reflects research outcomes to date and will be further improved.

Central receiver tower system with molten salt storage and supercritical CO_2 power block



Our research into adding value to CST plants has established cost targets for solar fuels. We believe this sets a world benchmark, and 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 Concentrating Solar Power and Solar Chemistry Technologies. In its most recent executive committee meeting, this international organisation discussed establishing cost targets for solar chemistry technologies to help assess the development of those technologies.

The targets already established by ASTRI as levelised cost of fuel (LCOF) were:

- \$1.20/L for fossil fuel feedstock with a life-cycle emission of CO_2 that is at least 10% lower than conventional diesel
- \$2.50/L for future renewable feedstock with a life-cycle emission of CO_2 that is at least 50% lower than conventional diesel.

People

ASTRI has attracted a diverse array of quality researchers. After some recruitment delays, most positions have been filled, allowing research to be undertaken on schedule. There has been particular growth in the number of students and postdoctoral fellows. While some students (namely two Master's students) have completed their work and left ASTRI, most students are continuing. In total, 29 students and 14 postdoctoral fellows have worked on ASTRI projects. Currently 97 researchers are involved in ASTRI projects, which contribute a total of 38 full-time equivalent staff to the projects.

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

Large-scale Collaboration

The second year of ASTRI has been devoted to developing a systems approach, and refining the portfolio of research project proposals to ensure system interconnectivity to meet the our objectives.

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. The topics researched and the different disciplines involved in this program rely on communication between researchers and between projects. The node structure has been essential to ensure research topics are synergistic and produce relevant research outputs with potentially commercialisable outcomes.

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.

Engagement and Linkages

ASTRI continues to develop its international connections. The Director of ASTRI, Manuel Blanco, has spent significant effort to network with other leaders in CST and to search for potential partnerships. Dr Ranga Pitchumani, the Chief Scientist of SunShot, has joined the ASTRI Advisory Committee as the United States representative. 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.

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 part of the supercritical carbon dioxide (sCO_2) project. As part of the education project, a 10-day training course was run for a multinational company. The total value of support from these funding partners has been $420,000. Currently, ASTRI is seeking more direct and technical involvement with particular projects, as well as more general support.

Knowledge Sharing

ASTRI's knowledge sharing has been gaining momentum, with an increase in publications and conference presentations along with the development of our website. Through these mediums, the research community, industry and the wider public have become more aware of the objectives of ASTRI and its work. ASTRI researchers have had a strong presence, both as presenters and as delegates, at seven prestigious conferences in 2014. Through collaboration tools, the knowledge gained through these events has been disseminated throughout ASTRI.

ASTRI System Workshop, October 2014

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:

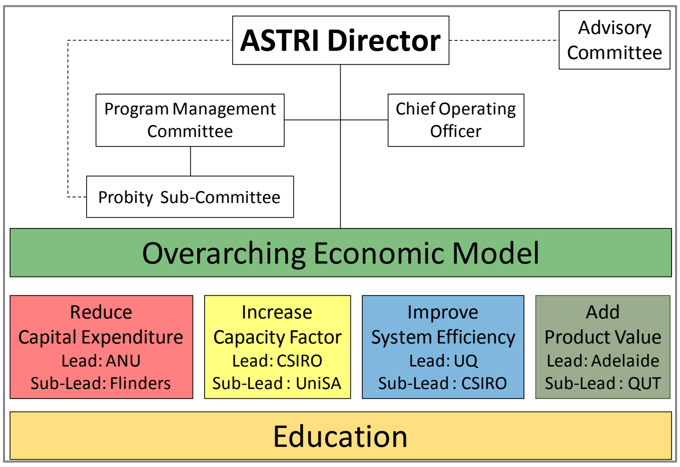
- a Funding Agreement between the Australian Renewable Energy Agency (ARENA) and CSIRO as the ASTRI lead party
- a Collaborative Research Agreement between CSIRO and the Australian partner Universities to pass through required terms and provide a framework for the conduct and management of the Program.

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, University of South Australia (UniSA), Queensland University of Technology (QUT) and Flinders University.

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.

ASTRI Governance Reporting Structure



Advisory Committee Members

Chairman and Industry Advisor

Mr Kieran Jacka

Acciona

Senior Manager, Engineering

Industry Advisor

Mr Anthony Wiseman

AREVA

Regional Director & General Manager Australia

ARENA Representative

Ms Louise Vickery

Renewable Futures

General Manager

ARENA Representative

Ms Veronica Heard

Renewable Futures

Team Leader

CSIRO Representative

Dr Jim Smitham

CSIRO Energy Flagship

Science Director

Program Management Committee Representative

Prof Paul Meredith

University of Queensland

Principal Investigator

US DOE Representative

Dr Ranga Pitchumani

SunShot

Chief Scientist

Program Management Committee

Chairman

Dr Manuel Blanco

CSIRO

ASTRI Director

Mr Wes Stein

CSIRO

Principal Investigator

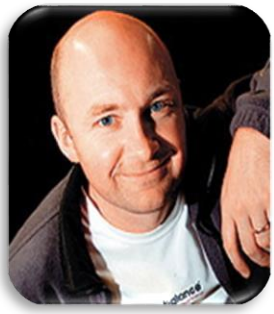
Node 2 Leader

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 John Barry

Queensland University of Technology

Principal Investigator

Node 4 Co-Leader

Chairman of Probity Sub-committee

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 Bassam Dally

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

Progress towards Program Outcomes

The ASTRI Program Outcomes stem from the USASEC Strategic Research Initiative Objectives. Our progress against these outcomes are as follows:

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

The Program 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. For example, in the second round of project approvals, the new O&M activities were added to the first-round mirror cleaning project to minimise the project management overheads for the Project Leader. This focus on significant projects has also encouraged two other projects to have a postdoctoral fellow and a senior research fellow assist with project management. This has widened the experience of these researchers within ASTRI and increased their preparedness for leadership within an Australian CST industry and the research community. Project Leaders applauded having their project reviewed and seeing this as a benefit arising uniquely from such a large-scale collaboration.

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

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

- By taking a systems approach, 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 2014, the reduction in LCOE was achieved by advances in the supercritical CO_2 power block and heliostat field cost down projects. In the future, we expect more drastic LCOE reductions to be achieved by advances in these and many other ASTRI projects. This will be helped by the development and optimisation of new CST power plant configurations, which will combine those advances in innovative and efficient ways
- In August, ARENA announced that three new CST projects would be funded, with one project involving three ASTRI partners. ARENA can see the influence of ASTRI on the quality of solar thermal submissions in the Solar Excellence round, 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, believed to set a world benchmark, addresses an issue identified at the international level by the IEA SolarPACES. In its most recent executive committee meeting, this international organisation discussed establishing cost targets for solar chemistry technologies to help assess the development of those technologies. ASTRI has already established two LCOF targets:
  - $1.20/L for fossil fuel feedstock with a life-cycle emission of CO_2 that is at least 10% lower than conventional diesel
  - $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

ASTRI experienced a major growth spurt with the initial of project approvals, and **continues to grow with quality staff, postdoctoral fellows and students**. We are developing education modules to inform highly trained graduates of CST who will deliver success in CST industries. Several ASTRI researchers attended the Annual International SolarPACES Conference for the first time. After the conference, ASTRI held a knowledge-sharing webcast open to all ASTRI partners to analyse the implications of the keynote speeches, technical presentations and posters.

A CST training course run within ASTRI targeting researchers new to CST and/or ASTRI. Attendance exceeded initial expectations, with participants rated the course highly. They also valued the opportunity to network with other researchers with expertise in many different disciplines. The next annual workshop will include short presentations from PhD students, as well as other researcher development activities.

The postgraduate completion rate is expected to trend above the milestone requirements, with two Masters students having completed their projects, which are still being assessed. A high number of PhD students commenced with the first round of ASTRI projects. PhD positions associated with new ASTRI projects are currently being filled.

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

The structure of ASTRI as a large-scale collaboration with nodes ensures that research topics are synergistic and that 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 United States and many other countries. In August, ASTRI welcomed Dr Ranga Pitchumani, SunShot Science Director, as the United States representative on its Advisory Committee.

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 are 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 model is to enable researchers to understand how their specific areas of research will affect the LCOE, the overall system performance and the added value that CST technologies bring to the energy marketplace.

Performance against the ASTRI Objectives

The ASTRI objectives were formulated in terms of the USASEC Strategic Research Initiative 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, nine refereed journal papers have been published and two others have been accepted for publication in early 2015. Eleven other articles have been drafted and are in various stages of the review process.

The published 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 in progress include the topics of receivers and solar fuels, and future papers will come from a wider variety of projects and activities.

KPI: Percentage of joint refereed journal publications

The published papers have not yet shown a true reflection of the collaboration, with only two of the published papers being authored by multiple ASTRI partners. However, this is expected to change in 2015. As a measure of meaningful research collaboration between ASTRI partners we intend journal publications to have authors from more than one partner. Some of the measures in place to ensure this occurs are:

- All PhD students must have a co-supervisor from a different ASTRI partner to the main supervisor. This is becoming more strongly enforced within ASTRI and supervisors are using ASTRI networks to search for appropriate co-supervisors that will add value to the PhDs.
- Potential joint publications are being identified and discussed during monthly project meetings.
- The ASTRI office is asking project leaders for strategies to show they are planning for joint publications.

United States Collaboration

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

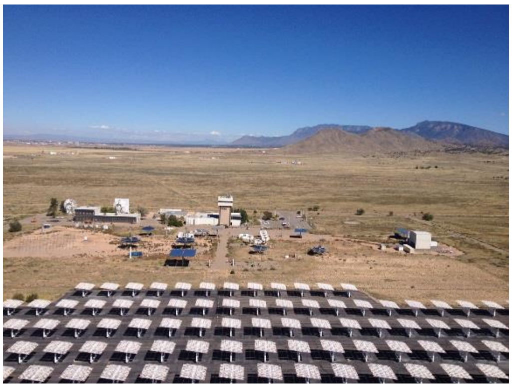
KPI: Visits to/from United States Collaborators

ASTRI researchers have had seven visits to or from United States collaborators and contributors over the year. This has occurred through:

- ASTRI researchers visiting United States research institutions and CST facilities
- ASTRI researchers attending conferences or summits in the United States for networking and knowledge sharing
- Researchers from the United States visiting ASTRI institutions for substantial stays.

While potential collaboration topics have been identified from these exchanges, funding opportunities to support United States researchers remain a hurdle.

Visit to Sandia National Laboratory, Albuquerque



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. Potential collaborations with the United States have been identified in a number in several projects, these including:

- a CST facility and research institution to gather data on O&M and to test improvements to mirror cleaning techniques
- a future CST demonstration project involving the University of Texas.

To ensure that ASTRI optimises its gains from these collaborations, we are developing a system to track exchanges with United States research partners and ensure effective co-ordination.

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

In 2014, 52 researchers were recruited to ASTRI. With several projects and project extensions being approved in late 2014, we expect further significant recruitment in early 2015. Most importantly, many of the new recruits have been PhD students and postdoctoral fellows. This shows true growth in ASTRI, with these young researchers being guided by the more senior researchers in their institution, as well as by other ASTRI researchers.

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.

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. Twenty-two such meetings were recorded for 2014. Monthly team meetings more commonly occurred by video or telephone conferencing.

Industry Engagement

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

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. This grant of $1.5M, which will be used within ASTRI, reflects a direct contribution of $337,500 from external sources to ASTRI. Most of the funds will be used to construct unique research infrastructure within 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.

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. The company wishes to look to ASTRI and/or CSIRO to be a research provider.

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

In 2014, ASTRI researchers attended the Solar 2014 conference in Melbourne in May and the SolarPACES conference in Beijing in September. They presented a wide variety of research papers at both conferences from each node of ASTRI. There was also diversity in the mix of analysis techniques developed for CST technologies versus exploring opportunities for further research. This demonstrates that the essential combination of creativity and rigorous analysis that leads to good research is a part of ASTRI. ASTRI also presented at five other conferences, making up twenty conference presentations in 2014.

Specific Research and Education Activities

CST Technical Progress and Performance

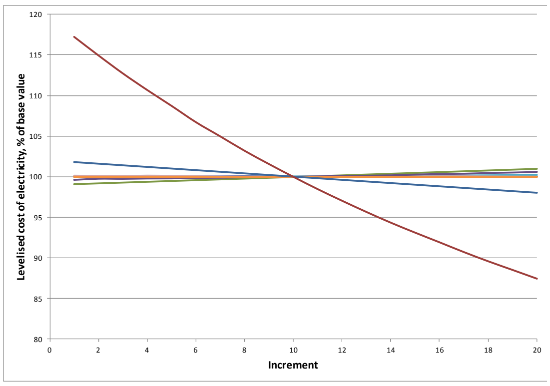
ASTRI will deliver cost reductions and dispatchability improvements to CST in Australia in terms of LCOE (c/kWh), through:

- improvements in overall annual efficiency
- reductions in capital expenditure
- increases in capacity factor
- reductions in O&M costs.

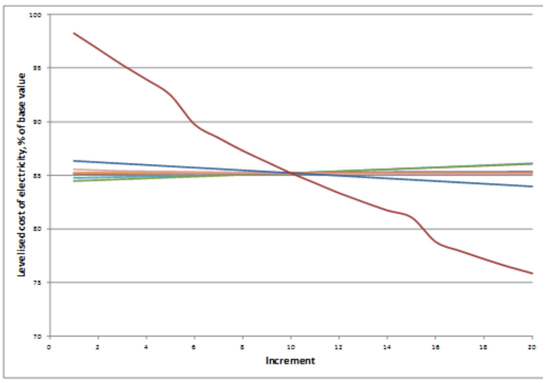
More than 90% of the world's commercial CST power plants operate using parabolic trough technology. They are typically centralised-grid-connected generators with nominal power ratings of 50–250 MWe and storage capacity of 3–6 hours. For Australian energy market conditions in 2012, the baseline plant 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.

Sensitivity of LCOE to changes in performance factors – in both systems the predominant factor which influences LCOE is the cycle efficiency (represented by the red line)

ASTRI base trough system



ASTRI reference tower system



ASTRI has developed an interim CST configuration that reflects research outcomes to date. The proposed central receiver tower power plant design is based on a closed-loop sCO_2 Brayton cycle power block with molten salt two-tank thermal storage. This system could achieve an LCOE of 21.9 c/kWh with an overall annual efficiency of 15.6%. The sCO_2 power block under development in ASTRI is intended for an operating temperature of 600-650°C, but these temperatures cannot be provided by proven conventional technologies. To overcome this, the interim power plant design uses conventional molten salt technology, limiting the operating temperature to 565 °C – a lower than optimal temperature for the sCO_2 power block.

The proposed power plant has partial recompression (RC) and recuperation units compared with a conventional superheated steam Rankine cycle. These units were added to increase the power generation efficiencies due to the design temperature limitation.

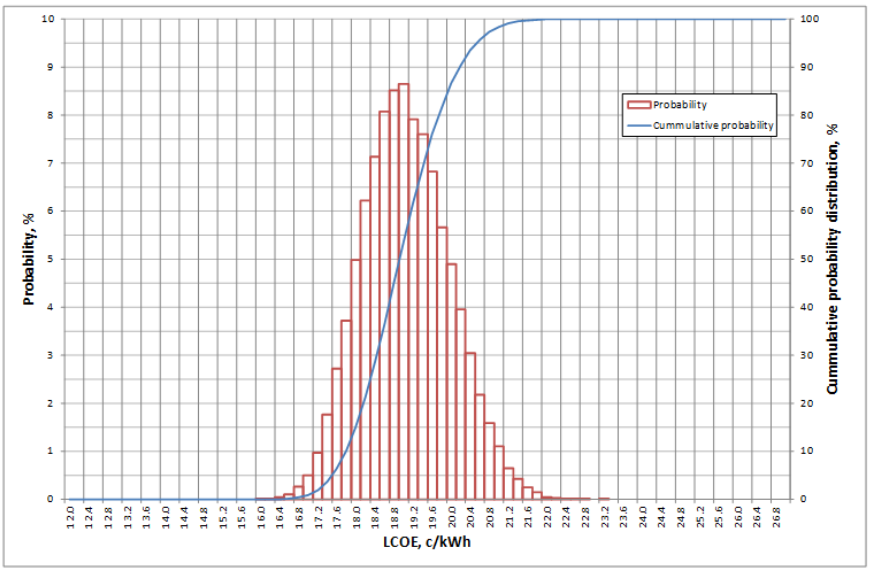
The 120-MWe sCO_2 power plant costs were estimated by aggregating costs up from a similarly detailed cost breakdown for the 100-MWe reference tower plant. The detailed cost breakdown was determined using a combination of conventional equipment cost models and cost estimates for the new technologies that have been developed within ASTRI. Cost ranges for the conventional plant items have been developed from a broad range of published values, but since this is not possible for the new technologies, we have applied error ranges comparable to similar conventional plants.

A statistical approach to LCOE is needed to account for the likely range in annual performance based on variable weather and solar data. We used a stochastic approach based on Monte Carlo simulation. Since the baseline case in ASTRI used the cost analyses from engineering assessments and represents a quite conservative view of the LCOE, a 95% confidence limit has been assumed.

LCOE predictions have been made for 13 years of weather and solar data for Alice Springs to produce the probability distribution of LCOE. The LCOE at the 95% confidence limit is approximately 20.5 c/kWh. This differs from the likely LCOE, which is determined from a simple LCOE analysis or that has the highest probability from the Monte Carlo analysis (approximately 19.3 c/kWh for this analysis). The model assumes the improvement in overall annual efficiency would reduce capital expenditure (CapEx) and O&M without any increase in capacity factor since these cost parameters are scaled based on the power and/or energy values. Being conservative, with an overall annual efficiency of 15.6% without any CapEx or O&M changes, the LCOE would be 21.9 c/kWh.

The full benefits of a central receiver tower power plant with a sCO_2 power block have not yet been realised in this interim plant design. They will arise at higher temperatures, with better thermal storage systems, receivers, heliostats and heliostat fields.

LCOE probability distribution from Monte Carlo simulation for 120-MWe sCO_2 power plant



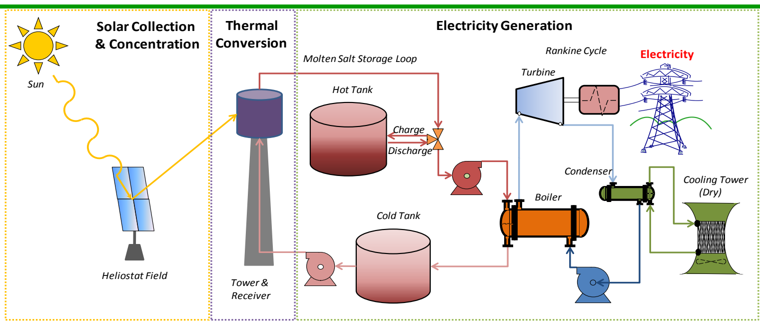
ASTRI
AUSTRALIAN SOLAR THERMAL RESEARCH INITIATIVE

Overarching Economic Model Project

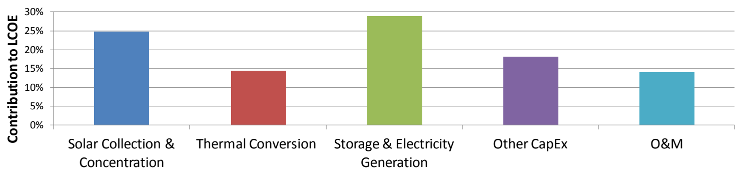
Project P01	**Overarching economic model to evaluate ASTRI CST system performance and costs**
Project leader: Dr Andrew Beath (CSIRO) **Collaborating & Contributing Institutions:** CSIRO Australian National University University of Queensland University of Adelaide University of South Australia Queensland 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.
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 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

Project P01	Overarching economic model to evaluate ASTRI CST system performance and costs
	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.
Plant component cost assessment:	A detailed review of published data on the cost of components within both trough baseline and tower reference cases has established the likely ranges of costs for use in probability analyses. The review of central receiver tower systems included a high number of international and Australian studies. The tower cost review identified that the published cost values varied considerably, requiring expert judgement about the reasonable typical plant cost values and ranges for Australian conditions.

Central receiver tower reference case



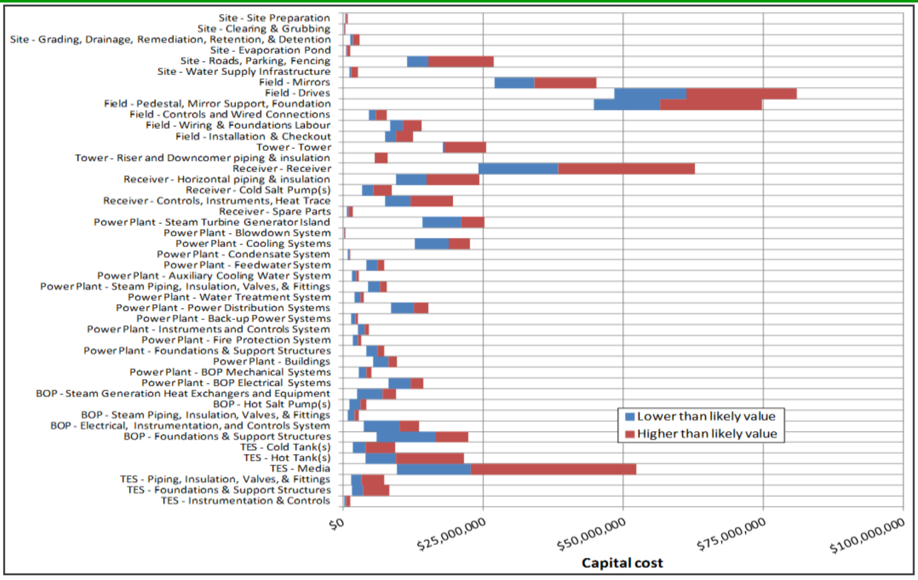
Contributions to LCOE for central receiver tower reference case



Revision of LCOE calculation:	The LCOE calculation is based on a general scheme proposed by the IEA, which allows consistent comparison of technologies. To ensure a realistic comparison between ASTRI achievements and the current commercial status of CST, new studies published by other organisations worldwide have been analysed using the ASTRI model to produce assessments of the current LCOE of conventional CST plants. This analysis indicates that CST is becoming a more cost-effective power generation technology as new large-scale plants are installed overseas. ASTRI technology improvements can build upon this to produce greater LCOE reductions.
Extension of solar data sets:	A standardised process was developed for the conversion of high-quality, one-minute solar data sets from the Australian Bureau of Meteorology with associated weather data into a format that is compatible with SAM. The data sets are for 13 real years at Alice Springs and six real years at both Kalgoorlie-Boulder and Mildura.
LCOE sensitivity analyses:	Since the costs of components within CST plants do not have single correct values, the likely ranges of costs have been used in sensitivity analyses to

Project P01	Overarching economic model to evaluate ASTRI CST system performance and costs
	determine their impact on the ultimate LCOE. The sensitivity analyses performed have used full Monte Carlo probability techniques for both the range of components costs identified from literature and solar variability based on the 13 years of real data for Alice Springs.

Examples of central receiver tower component capital cost ranges

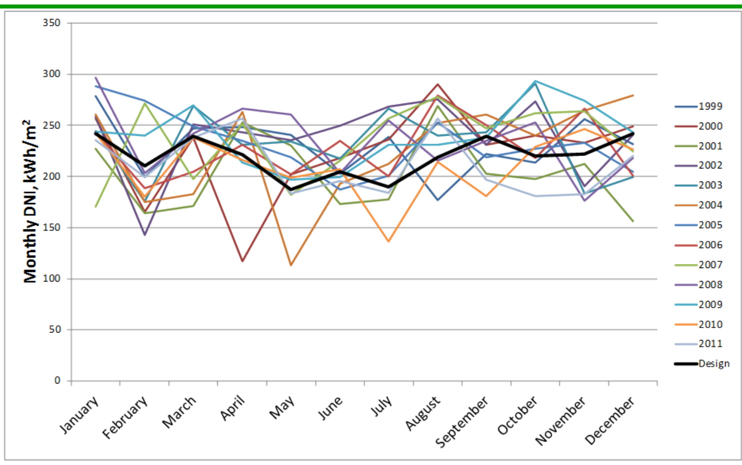


Evaluating new ASTRI technologies:

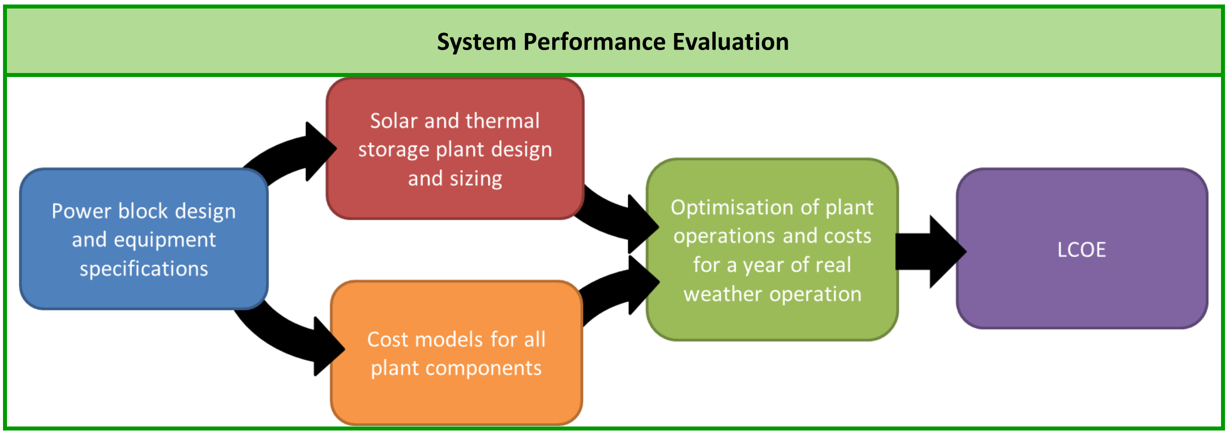
The central modelling framework provides an integrated systems modelling approach for evaluating ASTRI performance and progress. This framework involves energy analysis of the systems under the one-minute variable solar conditions for 13 years of real meteorological data for Alice Springs, as well as capital cost estimates and ultimately probabilistic calculation of LCOE.

This framework has been used to document the performance of the trough baseline and tower reference cases to be reviewed by Australian and international CST experts. The framework was also used to evaluate an interim system design based upon a conventional molten salt central receiver with a sCO_2 power block replacing the steam Rankine system.

Alice Springs Direct Normal Irradiance (DNI) by month varies randomly



Project P01	Overarching economic model to evaluate ASTRI CST system performance and costs
Key findings	Implementing the detailed component cost and performance modelling framework has resulted in a robust methodology for evaluating the most likely LCOE resulting from plant modifications. Using this in combination with the multiple years of solar data provides a more realistic view of the real-world viability of CST systems and the probability that the system design has been optimised efficiently. Preliminary results suggest that the selection of optimum storage size and operating philosophy is quite complex and can vary considerably between sites.
Future direction	The key role of the Overarching Economic Model project will be to drive system development of the overall plant configuration, incorporating emerging technology developments to achieve the target LCOE of 12 c/kWh. This requires ongoing development within the central modelling framework to optimise component integration, plant sizing, operating regimes and conditions, and costs. New ASTRI developments will be incorporated into the model as they arise.



Node 1: Reduce Capital Expenditure

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

The highest cost involved in CST plants is the CapEx to design, develop and construct the plant's components and systems. This expense is compounded by the emerging nature of the CST industry and the perception of risk, which can reduce investment opportunities. By reducing the CapEx and proving the reliability of CST components and systems technologies, the technical and investment risk is reduced. This improves bankability and effectively reduces CapEx. With this in mind, improvements in CST design to reduce the CapEx are being addressed 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 CapEx 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.

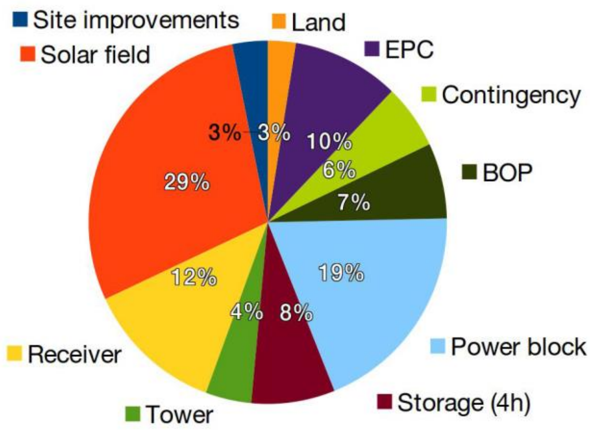
Heliostat cost is critical, because many thousands of heliostats installed in a tower system. They must be as cheap as possible while maintaining critical optical performance levels. Reduction of heliostat cost requires novel manufacturing techniques, integrated structural and optical design, and careful consideration of wind loads.

Heliostat field optical efficiency and receiver thermal efficiency are also critical. Any increase in those efficiencies immediately reduces the number of heliostats required for delivery of a specified amount of energy and, therefore, makes substantial cost savings. Maintaining high receiver efficiency at elevated temperature is also critical for facilitating the use of higher-efficiency power cycles. This is another way that receiver efficiency directly reduces costs.

Capital cost distribution

BOP = balance of plant

EPC = engineering procurement company



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 CapEx. 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.

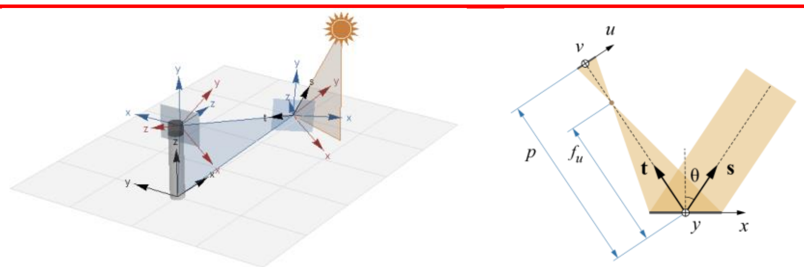
The design concept stream has a product development focus underlying the core technological research. Four heliostat design concepts were recommended in the Scoping Study, and three of these continued into this project. The technology development stream allows research in areas considered common to all 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. To date, the team has:

- documented a framework for the concept design process and heliostat design requirements. The structured, system-level set of technical requirements is helping to ensure a consistent design approach is taken across all the heliostat concepts
- commenced scoping options for linear actuators and heliostat autonomy for a medium-sized heliostat concept
- performed a feasibility and preliminary cost analysis for a multi-facet concept with industry input to determine both the facet size and overall size of the heliostat.

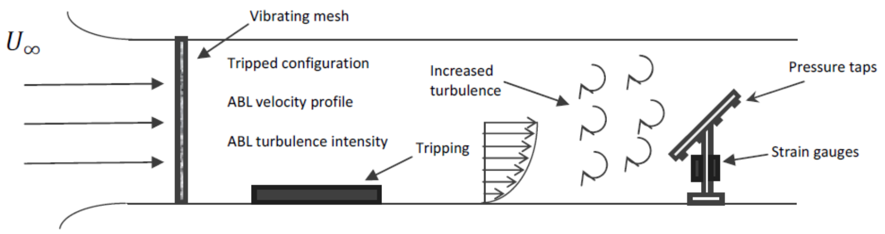
Cone optics for flux distribution



The co-ordinate systems explained (left) and the focus and image on target on the reflective plane for given sun position and target (right)

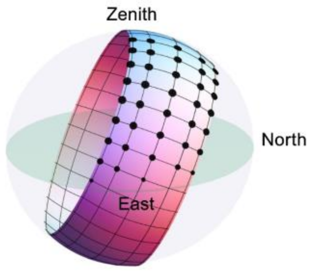
Project P11	Heliostat Field Cost Down Project
Mirror facet development:	A review of core materials of mirror facet materials and construction has identified that many core materials are marketed on the basis of their high-quality engineering properties that justify their cost rather than their optimum cost. Other important considerations are moisture resistance and core sealing, thermal stability, weight, stiffness, strength, and manufacturing processes to form the core and achieve the desired curvature.
Aerodynamics and wind loads:	The effect of aerodynamic loads on operating heliostats and the effect of wind loads on heliostats in stow position are being investigated. The literature has primarily focused on static loading rather than dynamic loading of heliostats. Gap analysis of the present state of the art technology has identified the issues that are most likely to lead to cost and performance breakthroughs in heliostat design. For dynamic loading, the heliostat vibration behaviour due to atmospheric boundary layer (ABL) characteristics, heliostat geometry and wake turbulence within heliostat fields have been identified as issues for optimum heliostat design. Peak loads in heliostats are typically associated with peak wind gusts when the heliostat is in a stow position. Current standards are inadequate for heliostat design and the influence of wind velocity gradient on heliostats in stow positions needs to be investigated.

Wind tunnel experimental set-up



Schematic of wind tunnel "tripped" boundary layer profile and increased turbulence

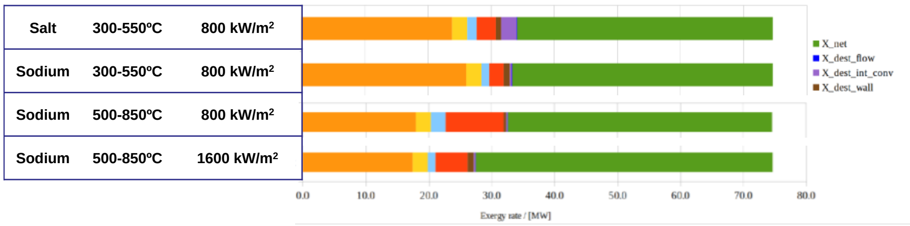
Heliostat field optimisation:	Optical modelling tools are being established to determine the annual efficiency of standard and novels solar fields. A method of estimating annual efficiency using a reduced number of hour-angle/declination cases that span the range of sun positions has been proposed. Methods of determining the solar flux profile are being investigated, using the ray-tracing software Tonatiuh and an analytical approach using new software based on cone optics. These investigations are necessary precursors to developing heliostat field concepts with an annual optical efficiency substantially better than the current state of the art.

Project P11	Heliostat Field Cost Down Project
Apparent motion of Sun	 Path of the sun around a terrestrial location with sampling points for simplifying calculations
Key findings	The heliostat and the mirror facet development research has so far focused on cost, performance and manufacturing process information to allow selection of core materials for new panel and facet structures. Core materials that have a nearly homogenous density may absorb impact stresses better than non-homogenous options. Polymer materials can be cheap, but are likely to require careful formulation to ensure the correct properties are achieved, while the high cost of high-performance materials rules them out from further consideration. The dynamic loading of heliostats is not well understood, and we need to determine the impact of aerodynamics and wind loads on heliostat vibrations. Peak wind loads in heliostats typically occur when the heliostat is in a stow position, and current standards do not adequately allow for heliostat design under these conditions.
Future direction	This research is at an early stage following the Scoping Study and the project has commenced strongly. In the next year we will continue the heliostat concept developments, with detailed design and concept specifications for review. The review will require knowledge from parallel research on mirror facet development, aerodynamics and wind loads, heliostat field optimisation, manufacturing systems, design and testing tools and O&M systems. Several reviews, involving comparative evaluations, are planned as part of a stage-gate selection process.

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	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:	The ASTRI reference central receiver tower system is a tubular molten salt receiver. To create a baseline upon which improvements can be measured, a computational fluid dynamic (CFD) model is being developed. The baseline receiver CFD model considers operating in combinations of forced and free convection conditions. It is being validated using data from forced convection experiments published in the literature. A thermal and optical efficiency analysis of tubular receivers has been performed. This analysis considered several different working fluids, but so far only for the uniform flux case. Sodium was shown to be a very attractive heat transfer fluid when working at elevated temperatures and solar flux. The net useful energy, or exergy, of salt and sodium receivers at 300–550 °C and flux of 800 kW/m^2 are similar but much greater for sodium at 500–850 °C and 1600 kW/m^2. Other results show that sodium offers higher exergy efficiency than CO_2, air or molten salt. Further work will add the effect of non-uniform flux, as well as greater detail in tube heat transfer, fluid properties and external paint coatings. The target heat transfer fluid for the ASTRI tubular receiver is sodium. To support planned sodium receiver experiments, the Solar Thermal Group at ANU is separately developing and funding new laboratory infrastructure for working with liquid sodium. They have received detailed advice and comment on the current proposed sodium work cell plans and safety procedures from collaborators at Sandia National Laboratories (United Sates), Karlsruhe Institute of Technology (Germany) and Vast Solar (Australia).

Project P12	Receiver Performance Project

Comparison of molten salt and sodium receivers



Comparison under various model temperature and solar flux conditions with more green being a higher net energy outcome

Particle receiver:

Development of the particle receiver concepts has commenced with selection of particle materials. Once short listed, experimental evaluation of particle properties (e.g. tendency to agglomerate at elevated temperatures) will be required. The particle receiver concepts being pursued include:

- an indirectly heated, dual-fluidised bed receiver
- a particle receiver based on a vortex reactor
- a dense, slowly moving bed of particles with indirect heat transfer through a tube or multiple tubes.

Thermal and CFD analyses are underway. Initial data gathering is focused on understanding the potential heat transfer from the tube and through the bed of particles, to understand its impact on the required receiver design. The initial results show thermal conductivity of a particle bed increases when it is densely packed (i.e. high solid fraction). This is consistent with increasing conduction heat transfer. When the solid thermal conductivity increases, the thermal conductivity of the particle bed increases, but its effectiveness is reduced, indicating a particle receiver needs to be designed to optimise the heat transfer processes.

The project team has agreed on initial design requirements for both tubular and particle receivers, as well as performance requirements.

Key findings

Thermal and optical efficiency analysis of tubular receivers with several different working fluids has identified sodium as a very attractive fluid for tubular receivers, if elevated temperatures can be attained.

Initial design and performance requirements for both tubular and particle receivers have been defined. This will allow informed screening of particles suitable for particle receivers and development of the set of proposed receivers. The receiver concepts include a vortex reactor, indirect dual-fluidised bed receiver, and slow-moving particle receiver.

Future direction

This research is at an early stage following the Scoping Study, and the project has commenced strongly. In the next year, we will continue the thermal and CFD modelling of each receiver concept.

Project P12	**Receiver Performance Project**

For the tubular receiver this will involve development of:

- CFD and radiative models for the reference central tower receiver operating in combined forced/free convection conditions, as well as for at least one cavity and/or quasi-cavity receiver configuration
- a conjugate heat transfer model of internal convection (tube wall to heat transfer fluid) and conduction through the tube for a simple tubular sodium receiver.

The particle receiver activities leading to assessment and prioritisation of receiver concepts for further development will involve:

- experimental suitability testing for agglomeration and durability of short-listed particle materials for use as the particle heat carrier
- CFD modelling of particle receivers to identify preferred configurations
- particle movement dynamics and heat transfer feasibility studies
- flow visualisation measurements in a cold-flow facility using laser diagnostics.

Useful energy accounting for a 100 m² molten salt receiverusing a Sankey diagram

inlet 300°C, outlet 550°C, under 800 suns uniform flux

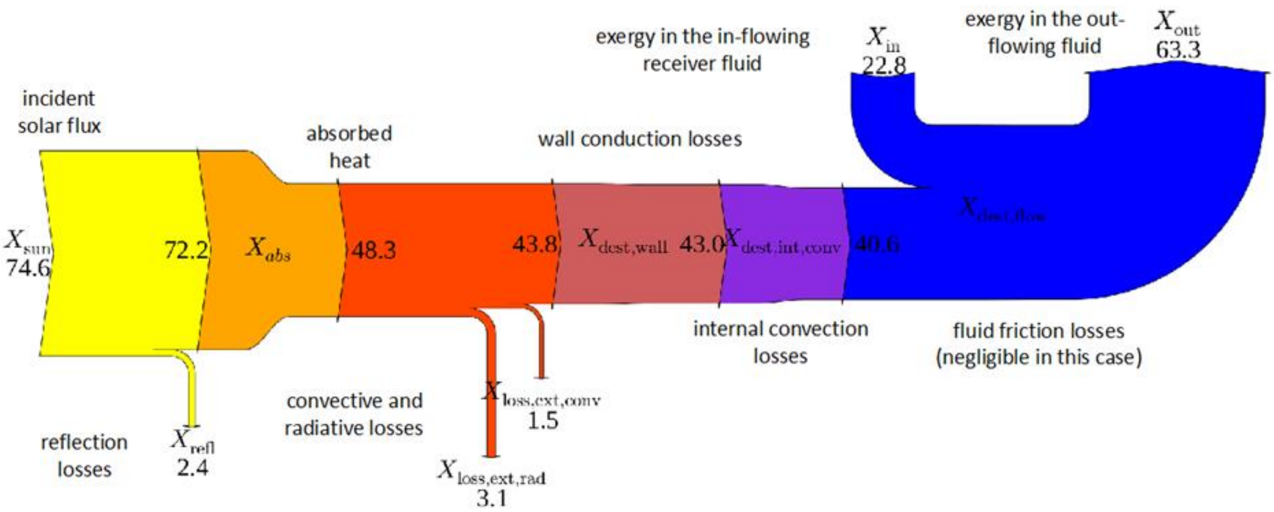


Diagram showing the loss of useful energy in a molten slat receiver due to reflcetion, radiation, convection, conduction. Note the fluid coming into the receiver has useful energy.

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.

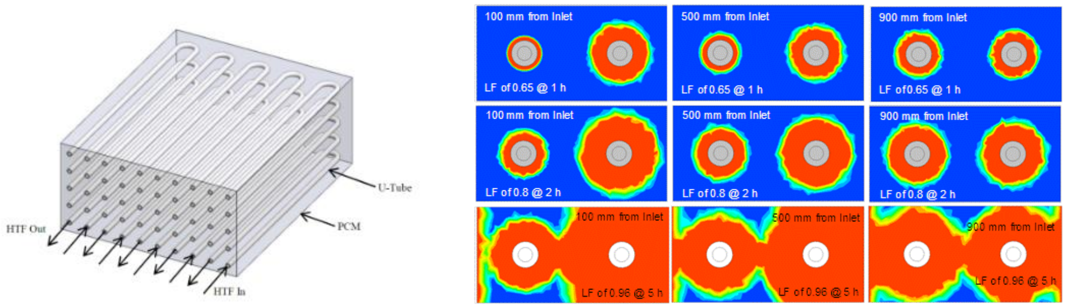
Thermal storage is now well commercialised, in the form of two-tank molten salt operating at temperatures suitable for subcritical steam turbine cycles. However, to allow the emerging higher-temperature cycles such as sCO_2 to operate at their full efficiency, storage temperatures must also increase correspondingly. This introduces a number of key research challenges to find both the most appropriate storage mediums and developing systems to reduce the loss of useful energy, or exergy.

One source of exergy loss (loss of useful energy) occurs when heat is exchanged between the different materials involved in the storage process. This includes the receiver fluid (or particles), the storage fluid (or particles) and the working fluid for the turbine. Making use of the same fluid in the storage and receiver or power block removes the cost and performance reduction associated with heat exchangers.

The key receiver heat transfer fluids that we are considering for temperatures beyond molten salts include sodium and particles. Thus, we are developing storage technologies that interact with these materials. The optimal thermodynamic method of transferring heat is through phase change which creates an isothermal heat exchange and minimises useful energy losses. A breakthrough in high temperature phase-change storage would represent a quantum leap for sCO_2 cycle economics. ASTRI is therefore developing high-temperature PCMs and systems for storage that are compatible with the sCO_2 turbine.

A key attraction of storage is its ability it affords to increase internal rate of return – the key measure used by project financiers. ASTRI will develop a comprehensive, techno-economic model to optimise storage size in a CST power project, thereby ensuring an increase in both the internal rate of return and the capacity factor to which we have committed.

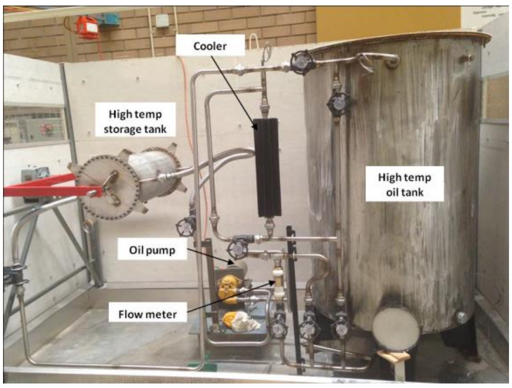
Shell and tube storage



Arrangement of tubing (on left) and results from CFD showing melting of the PCM around tubes as charging takes place (on right). Note that in each image obtained from CFD, the heat transfer fluid flows in the right tube and out of the left tube. LF is the total liquid fraction of the PCM at a specific time after charging started.

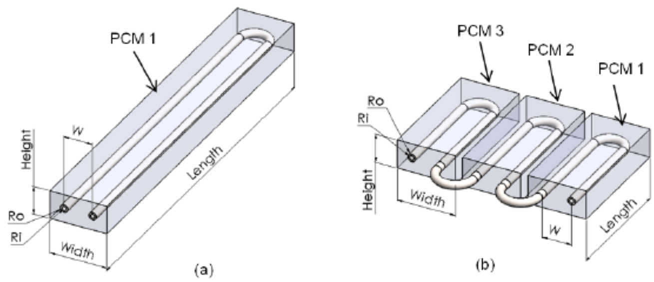
Project P21	High-temperature thermal storage project
Project Leader: Wes Stein (CSIRO) **Collaborating & Contributing Institutions** CSIRO University of South Australia ANU University of Adelaide **Start Date:** 2014	This project aims to advance the state of the art in high-temperature energy storage 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 $/kWh$_{th}$, due to the potential for high energy density of the storage medium compared to molten salt. The 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 – improve the accuracy of performance estimation for novel storage systems and materials – improve understanding of limiting design factors and materials constraints • Develop a common-basis modelling platform to support annual performance and techno-economic analysis of a range of candidate storage technologies. This will: – include optimisation of design and operation strategy – allow comparison and optimisation of different storage concepts and their associated operational strategies – provide high-fidelity assessment of new concept system performance not possible with currently available tools.
Future Direction	The next 12 months will establish model boundaries including the identification of a suitable model platform. The storage technology model will commence by establishing preferred properties for particles and heat exchange and conducting laboratory flow and heat exchange tests. Models of a thermochemical particle storage concept will be initiated, as well as three thermochemical cycles – a solar ammonia cycle, a closed-loop solar reforming loop and a solar chemical loop. The project will also review and start to model a high-temperature molten salt concept as a heat transfer fluid and storage media.

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:	A preliminary techno-economic analysis has helped to identify suitable concepts for latent heat thermal energy storage systems, and to justify research into PCMs as a feasible option to improve storage for the ASTRI system. PCM storage has the potential to be more economical than sensible storage in either the two-tank or thermocline tank configurations. While this conclusion is based on some simplifying assumptions, more detailed analysis with new PCMs and better containment options are expected to show more potential for being even more economic.
Encapsulated PCMs:	We have analysed the costs of potential encapsulated PCM storage systems based on single thermocline tank designs, taking into account the shell material, heat transfer fluid, PCM and method of encapsulation. The cost of encapsulation is largely dependent on the shell material used and the method of PCM encapsulation. The most cost-effective encapsulated PCM system had higher material costs but these were offset by a higher density which reduces storage tank size.

Project P22	**Reliable, low-cost, phase-change material thermal storage systems**
Tube-in-tank PCM system:	A tube-in-tank PCM system is being designed to accommodate sCO_2 at 20 MPa and 550 °C. The tubes must therefore have high strength and corrosion resistance, and be compatible with the PCM. The amount of tubing required was based on CFD modelling and using an effectiveness – number of transfer units method published by the project team. The cost analysis, which focused solely on just the PCM and tubing, identified two cost-effective solutions; one using an aluminium alloy PCM with titanium tubing and the using other low-cost carbonates with stainless steel tubing. We also investigated the effectiveness of a tube-in-tank PCM storage system as a function of the total thermal storage fraction, which includes both the sensible and latent thermal energy. During discharge, latent thermal energy was transferred first, followed by the sensible component. The usefulness of a single PCM to provide sensible heat to sCO_2 is limited once the PCM has changed phase. Therefore, we could potentially extract more of the stored sensible energy by using multiple tanks in series at different temperatures. Designing such a cascaded PCM storage system for an actual CST plant will involve considerably more thermal design research.
Prototype shell and tube storage system:	 This prototype is being built to test PCMs, initially with sodium nitrate (melting point 308 °C)
Experimental hot oil test rig:	 Test rig for measuring the thermal performance of a PCM thermal storage units such as the prototype shell and tube storage system (up to 400 °C)

Project P22	Reliable, low-cost, phase-change material thermal storage systems
Testing of PCM thermal properties:	A database of potential PCMs in the desired temperature range up to 600 °C has been established. We identified suitable PCMs from published literature and by using commercial thermochemical software, and tested six potential inorganic eutectic PCMs in collaboration with NREL. Some disagreement between the measured and published thermo-physical properties demonstrates the need for these and further measurements. Our results showed that the carbonate PCMs have very high degrees of sub-cooling in the initial cycles, which reduces as the number of cycles increases. Chloride PCMs have negligible degrees of sub-cooling. One carbonate PCM and one chloride PCM were recommended as promising latent heat storage materials. Measurement of the latent heat properties of high temperature PCMs using the 'Temperature–History' method has been problematic. We identified large temperature stratification in the oven, and subsequently developed a new test apparatus more suited to the required high temperatures.
Key findings	We need to focus on overall system cost in the selection of PCM/heat transfer fluid and container material combinations, as well as thermal and material properties. Metal alloys are the most likely PCMs for use in high-temperature CST applications, due to their superior heat transfer characteristics. Although system costs can be high, indications are that they can still be competitive.
Future direction	Although the project is being varied to ensure it fulfils the ASTRI system requirements, the planned activities will continue – but with a slightly different emphasis. The project will focus on cost-effective PCM thermal storage systems (encapsulated or bulk) with a view to designing at least one prototype for further proof-of-concept evaluation. Supporting activities to measure and develop PCMs will continue, along with compatibility of PCMs, heat transfer fluid and construction materials.

Cascaded PCM storage



Comparison of a single unit shell and tube PCM storage system (left) with three shell and tube PCM units connected in series (right), allowing three different PCMs.

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 all be considered when improving the efficiency of electricity and other products derived from CST technologies. Efficiency can be improved throughout the CST plant by examining how all the different subsystems affect the plant's other requirements and efficiencies. A key subsystem that affects annual efficiency is the power block. This requires development of advanced power cycles and power conversion technologies for the design point, as well as so they may also be operate efficiently at part-loads below the design point.

Achieving optimal efficiencies will require a systematic analysis of the inherent tradeoffs 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 power block requires a compressor to recycle the sCO_2, and our researchers are confident that an appropriate compressor and other components for the target power plant size can be sourced commercially from other applications.

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.

Project P31A	Supercritical CO_2 Power Block
Project Leader: Hal Gurgenci (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 sCO2 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 sCO2 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 streams: 1. Development of a sCO_2 power cycle, including turbine technology and dynamic modelling. 2. Development of hybrid cooling technologies to minimise the water consumption while maintaining efficient power generation, particularly in arid areas. 3. 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. Nobody manufactures sCO_2 turbines commercially, although some commercial companies are involved in the development of compressor-expander turbines for CST applications.

Natural Draft Test Tower and the heat exchangers being installed at UQ Gatton campus

Project P31A	Supercritical CO_2 Power Block
Supercritical CO_2 power cycle:	The closed-loop Brayton cycle sCO_2 power block has some complexity and some simplifications compared with a conventional superheated steam Rankine cycle. The complexity arises due to the need to increase the cycle efficiency for a design temperature limited by the molten salt of 565 °C. This involves the use of additional partial recompression (RC) and recuperation units. The simplification arises because the compressor, recompressor and expander are normally on a common drive shaft. In combination, these parts constitute a compact turbine unit that is smaller than conventional turbines. The project scope does not need to include the development of either a sCO_2 compressor or the heat exchangers, such as recuperators, because the project team has identified existing commercial equipment to build the 30-MWe power block. The efficiency of such equipment can be addressed in future systems improvements.
Turbine design:	From the published literature, the project team has identified the most significant challenges facing the development of sCO_2 turbines. These include issues with corrosion, the bearings and seals, and aerodynamic design. A laboratory-scale subcritical radial turbine has been designed and is being manufactured. In 2015, it will be tested to validate the design and simulation tools, which is a crucial step towards the development of the high-temperature supercritical turbine. Design of a second, supercritical refrigerant turbine has also started. Other progress in the design of supercritical CO_2 turbines includes the identification of stainless steel as a cost-effective candidate. Different materials will be needed in the future if the temperature is to be increased further.
Dynamic modelling of sCO_2 power block:	A CST plant is subject to transient environmental conditions, which may result in oscillations within a sCO_2 power block. CO_2 exhibits large fluid property variations in the vicinity of its critical point, noting it has a near ambient critical temperature of 31.1 °C. While a sCO_2 CST plant with thermal storage will be buffered from variations in solar irradiance, a preliminary analysis has been completed for a hypothetical system without thermal storage, in which sCO_2 is both the heat transfer fluid and working fluid. Variations in thermal energy input and ambient air temperatures results in movement of CO_2 mass between the hot and cold-sides of the system. This causes dynamic changes in CO_2 mass-flow rate, pressures, temperatures, and net power output. The volume of the receiver influences the extent to which CO_2 mass movement occurs. An addition of a relatively large volume on the hot-side, such as extra receiver sections, thermal storage, or intermediate heat-exchangers, increases the system's stability.

Project P31A	Supercritical CO_2 Power Block
Hybrid cooling:	A natural draft hybrid cooling tower has been designed and will be commissioned and tested as part of the ASTRI program. The tower design, construction and commissioning is funded by an additional grant of $1.5 m obtained from the Queensland State Government. Construction of the tower, heat exchangers, site works and associated instrumentation is expected to cost $1.2 m. The test tower is a unique asset and will be extremely useful to develop and demonstrate hybrid cooling technologies for CST power generators built in arid regions. No similar such test facility exists anywhere in the world. Because it will be near full-scale, it will be possible to undertake research that cannot be conducted elsewhere. Such research is necessary because the existing natural draft dry cooling tower design is optimised for large steam power plants, and is not optimal for a CST plant. However manufacturers have been reluctant to invest in building test facilities to undertake new research necessary to apply this technology to CST power plants.
sCO_2 power block techno-economic model:	ASTRI has defined the need for the sCO_2 power block system concept to be at a molten salt heat transfer temperature of 560 °C, with potential temperatures of up to 750 °C later. The largest power block, based on a radial turbine, is 30-MW net. To be equivalent to the ASTRI reference case of 100-MW, the sCO_2 power block system concept will be based on four 30-MWe radial turbines. The 30-MWe sCO_2 power block has a modelled efficiency of 44% and a predicted cost of $1134/MWe. In comparison, the 100-MWe superheated steam Rankine cycle has an efficiency of 37.7% and a cost of $1000/MWe.
Key findings	Detailed design of the laboratory-scale subcritical radial turbine resulted in new questions about and insights into the practicality of planned experiments and future commercial supercritical CO_2 turbines. Factor to consider include bearings, seals, corrosion, loop control, performance evaluation and maintenance. Design of the cooling tower raised a number of practical issues that have been resolved internally and through discussions with the industry. The design modifications by the suppliers of the heat exchangers and the tower identified the need for research into air flow dynamics. The findings will be of significant value to the commercial cooling tower for the ASTRI CST plant.
Future directions	An immediate activity is the further development of the sCO_2 power cycle, including the turbine technology based on a radial expander. This will involve the aerodynamic design, loss models and bearing and seal component models. Testing of the turbine will be completed in 2015. The

Project P31A	Supercritical CO_2 Power Block
	development of hybrid cooling technologies will move from design and construction into testing and evaluation. The techno-economic optimisation of power cycles for future sCO_2 plants will focus on optimising the 25–30 MWe sCO_2 power block for both 100-MWe and 25-30 MWe CST power plants. This will involve part-load and off-design performance of the power block as well as better cost estimation.

ARENA visit to The University of Queensland High Pressure Turbine Test Rig

Project P32	Alternative Power Block
Project Leader: Andrew Beath (CSIRO **Collaborating & Contributing Institutions:** CSIRO Queensland University of Technology **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.
Future direction	Immediate activities include: • Review and selection modelling tools with assessment of software for power block simulation and various open source tools for thermodynamic simulation and process optimisation • Reviews of working fluid selection, turbine design and optimisation methods for power blocks • Initial scope of systems analysis of a variety of organic Rankine cycle (ORC) configurations that could be used in combination with high temperature cycles. We expect that this to expand as additional modelling tools are implemented for other systems.

Node 4: Add Product Value

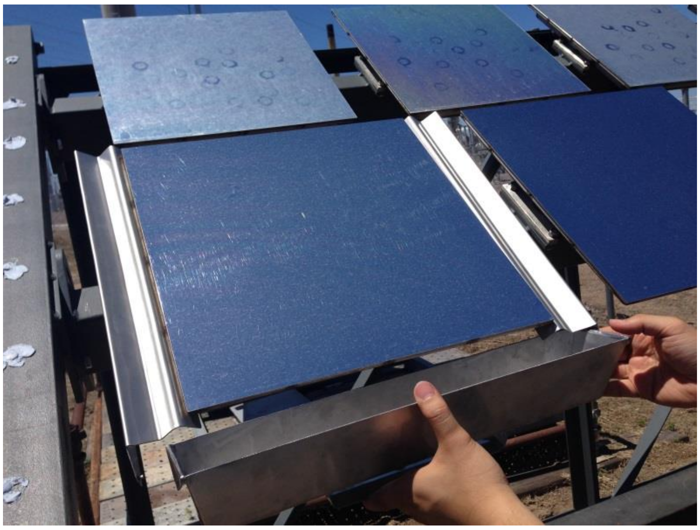
Node 4 Leader:	Prof Gus Nathan (Adelaide)	Node 4 Co-Leader:	Professor John Barry (QUT)

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.

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.

Queensland University of Technology Mirror Washing and Exposure, Collinsville, Queensland



Project P41	Cost-Effective Operations and Maintenance
Project Leader: John Barry (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 through three main activities: • efficient mirror cleaning • condition monitoring • reliability modelling. We will examine how to reduce these costs through design improvements based upon operational data from existing CST plants and, in areas where data is lacking, design improvements will be based upon experience and know-how derived from CST plant operation. For mirror cleaning, automatically controlled, high-pressure jet washing methods are considered most cost-effective and suitable for CSP plants. The effectiveness of mirror cleaning is measured as a function of water pressure, water spray volume, nozzle type and nozzle distance to the solar mirror surface. In addition, hydrophobic surfaces are being synthesised to measure the dust–surface interaction and influence on cleaning effectiveness. The mirror soiling rate is dependent upon dust type and weather conditions. Dust type and reflector weathering are therefore being monitored at two Queensland sites to estimate the type and frequency of mirror cleaning required for the O&M model. Condition monitoring requires monitoring plant performance and setting trigger points for specified actions for the part of the plant at fault. Condition monitoring of CST plants will use weather data and operational data to calibrate plant performance. Reliability modelling estimates maintenance schedules and length of life of plant components. The reliability model will define actions required to avoid catastrophic failure of critical components, and actions required to maintain the entire plant in optimum operational order. The mirror-cleaning activities have now been underway for one year, with the condition monitoring and reliability modelling being added late in 2014. To date, the mirror-cleaning activities have achieved good progress in: • dust monitoring collection and characterisation • acquisition of various reflector (mirror) types and weathering of reflector surfaces • development of CFD models.

Project P41	Cost-Effective Operations and Maintenance
O&M costs:	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 obtain. Conversations with industry representatives and researchers reveal some willingness to review O&M costs data and collaborate, if funding is available.
Dust monitoring:	Dust monitoring stations have been installed at three Queensland locations: 90 km west, 300 km west and 1250 km north of Brisbane. The dust monitoring equipment measures particle size and weight, and collect samples on filter paper for scanning electron microscopy. Test frames involving different types of reflectors have been installed to study the dust soiling mechanisms, weathering behaviour and monitor reflectivity. We have found that polymer reflector surfaces attract dust more readily than glass surfaces. The reflector weathering results have shown that not all polymer reflectors are alike; some, but not all, of the tested reflectors degraded substantially after three months' exposure to the elements.
Mirror cleaning test frames with 400x400mm reflectors	
Spray cleaning experimentation:	A spray cleaning system has been constructed in a wind tunnel at UQ. The system includes a particle image velocimetry analyser and phase Doppler particle anemometry to measure water droplet spray characteristics. We have developed preliminary cleaning protocols, based on testing effectiveness, to restore the reflector reflectivity. A motorised linear drive for moving the reflector in front of the various commercial spray nozzles is being finalised. A protocol for preparing soiled reflectors for mirror-cleaning tests is being developed using 'Arizona road dust' as a 'standard dust', and by exposing the reflector to ambient sunlight and humidity.

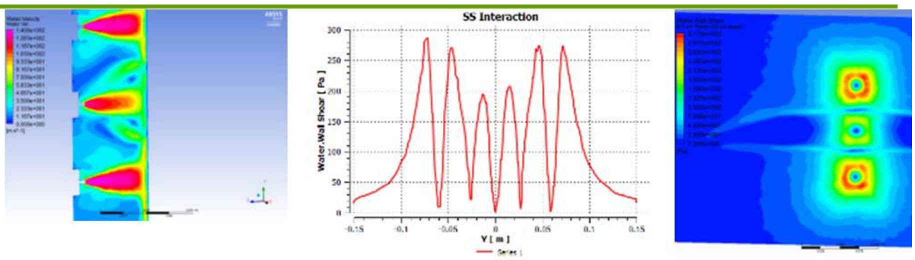
Project P41 — **Cost-Effective Operations and Maintenance**

CFD spray modelling:

Modelling spray dynamics has advanced using ANSYS CFX CFD software. Preliminary tests and CFD modelling spray dynamics show that spray droplets can have velocities of up to 100 m/s, but that these vary over the solid surface. This has important implications for the accuracy of measurement of spray droplet size and velocity.

Our simulations show that some nozzle types create turbulence on the cleaning surface, which can impede cleaning effectiveness. Water temperature and pressure, additives, and distance from the mirror surface also affect cleaning.

Visualisation of turbulence and flow



Turbulence and flow that occurs on a surface at 25x nozzle diameter with inlet pressure 70 Pa

Measurement of properties for surfaces and surface coatings:

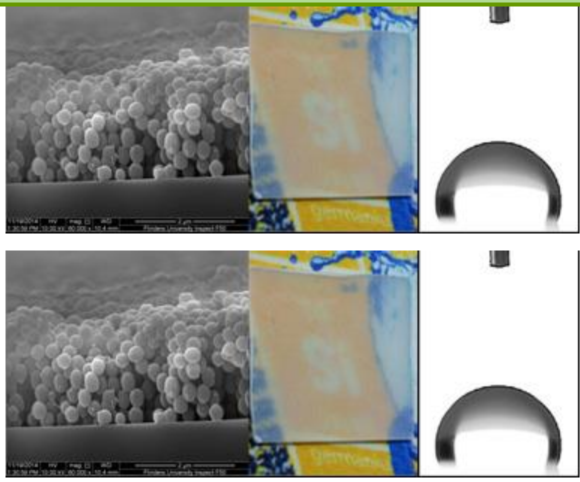
Our work on creating self-cleaning mirror surfaces has developed a silica particle synthesis method to be used as the filler material in the matrix, and to add surface roughness to improve hydrophobicity/hydrophilicity. These particles have been incorporated into initial coatings in an attempt to optimise the required concentration for consistency.

Highly loaded coating formulations are necessary to achieve durable films with consistent and robust surface topography. However, these formulations have resulted in significant challenges in film quality, including discontinuity, with cracking and agglomeration of particles. An understanding of the interaction of functionalised silica nanoparticles with polymers on glass substrates has been a crucial development.

We measured the water contact angle on films with varying polyelectrolyte concentrations to identify the concentration at which the matrix material becomes dominant. Our results show that vinyl silica particles on their own have hydrophobic properties, and the hydrophilic nature of the polymer begins to take effect at concentrations higher than 0.3%.

Project P41	**Cost-Effective Operations and Maintenance**

Structure, impact and water contact angle of hydrophobic coatings



The coating with a higher thiol silica content (top) is shown to have a much higher water contact angle (125^{o}) than the other coating (91^{o})

Key findings

The last year has been very productive with the following key findings:

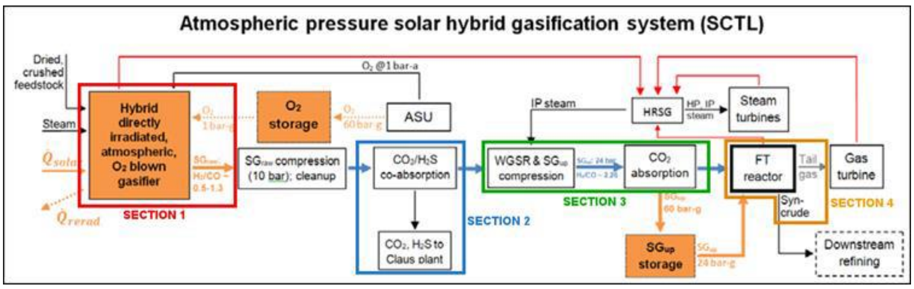
- Large differences were found for different types of polymer reflectors in their response to weathering. Polymer surfaces accumulate more dust than glass surfaces.
- Preliminary tests and CFD modelling show how vortices generated on cleaning surfaces can create dead zones in surface spray shear velocity, which diminish cleaning effectiveness. Future experimental tests will validate the CFD findings.
- Highly loaded coating formulations are needed to produce durable hydrophobic films with consistent and robust surface topography. However, high loading reduces film quality, causing discontinuity, cracking and agglomeration of particles.

Future direction

Mirror-cleaning activities will involve finalising the protocol for preparing soiled reflectors to allow controlled testing of the effectiveness of cleaning of prepared and real soiled reflectors.

CFD modelling will focus on the challenging task of developing realistic models for spray nozzles, as well as validation of the CFD simulations using results from the laser phase Doppler particle analysis experimental study of sprays. The coating developed to date will be tested for response to dust exposure and exposure to weathering. The next step in coating will focus on the roughness required for superhydrophobic behaviour.

Condition monitoring will identify operational constraints in CST plants, while reliability modelling will focus on collection and pre-processing of historical data and identification of critical components.

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 of less than $1.5/L. An LCOF for solarised production of diesel-grade liquid via synthesis gas (syngas) and Fischer–Tropsch (FT) liquids pathway was estimated in the range of $0.9–1.5/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 • supercritical water gasification of micro-algae • 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 CO2 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.
Solar fuels process modelling	

Project P42	Solar Fuels
Techno-economic model for solar to liquids fuels:	The project has established a common framework for techno-economic modelling of different processes, with reference conditions and methodology. Development of the techno-economic model for the solar-to-liquids processes has involved standardisation of the key input parameters. The key reference conditions are as follows: • Reference year: 2020 chosen as a realistic time-frame for which the technology could be developed • Reference scale: 50 MW_{th} for each receiver, chosen as the largest realistic scale for a cavity receiver in the time-frame to 2020 • Reference site: Geraldton, WA chosen because it is well suited to all feedstocks and processes being considered • Reference FT reactor: micro-channel technology, chosen because the development of micro-channel and micro-tubular FT reactor technologies has rapidly advanced in recent years, enabling much greater cost effectiveness at smaller scale than is possible with the existing commercial FT reactor • Reference methodology for economic analysis: the formula used to calculate the LCOF for all the solar-to-liquids technologies has been standardised. The costing for the solar components has also been standardised (i.e. heliostats, receiver(s), tower(s), balance of plant).
Qualitative assessment methodology for solar to liquids fuels:	We have established a qualitative assessment method to compare different combinations of solar fuels technology and feedstock. The broad assessment matrix includes technical feasibility, solar share, economic feasibility, sustainability, stage of development/technology readiness, and the calculated LCOF. A simple method was developed to account for the solar share, which is the influence of solar variability on the relative capacities of the system components to maintain a constant output. Our assessment revealed that nearly all technologies offer significant merit, with no one combination of technology and feedstock scoring a superior priority. Only one process was eliminated from further development within ASTRI: the solar hybridised gasification of black coal with a vortex flow reactor.

Project P42	Solar Fuels
Key findings:	The LCOF evaluation highlighted the importance of pursuing a range of processes suited for both fossil fuel and biomass feedstocks, owing to their different costs, availability and sustainability. The LCOF from CST is estimated to be around \$0.9–1.0/L via the two processes of solar mixed reforming of natural gas and solar hybridised dual-fluidised bed gasification of brown coal (lignite), and \$1.4/L for the gasification of wood. These are both within the ASTRI target of \$1.5/L. The cost of the solar-to-liquids fuels is strongly influenced by the cost of the feedstock, which is an important contributor to the higher estimated cost of the supercritical gasification of micro-algae (>\$10/GJ) than of coal (\$1–2/GJ) or biomass (\$4–12/GJ). However, this metric does not account for the net carbon emissions in the fuel, which are expected to fall significantly when an algal feedstock becomes commercially available. We believe that our direct comparison of the costs of solar fuels is the first to assess different feedstocks using a common method that accounts for the full process.
Future direction:	The subsequent project aims to achieve a LCOF target of \$1.2/L for current feedstocks and \$2.5/L for future feedstocks. This will be achieved through the following activities: 1. Establishing a comprehensive framework to assess the production of liquid transport fuels via CST together with FT liquid processing on a common basis. This will incorporate technical feasibility, solar share, LCOF, environmental sustainability and status of development. 2. Identifying combinations of feedstock and CST processing technologies through the FT liquid process. This will consider both solar-only and hybrid concepts with short and/or long-term potential for future development. It will be based on the relative performance of these concepts considering all of the above metrics, from both commercially available feedstock and feedstocks that are anticipated to be of longer-term significance. 3. Developing two more reactor technologies through the proof-of-concept stage, noting that solar reforming of natural gas is already developed beyond this stage. 4. Supporting the advancement of solar thermal production of high-value fuels from syngas by adding value through the targeted development of downstream processing.

Education Program Project

Project P02	Project to develop a CST education program
Program Leader: Professor Bassam Dally **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	 

Project P02	Project to develop a CST education program
Platform for distributing education modules:	The proposed course required a platform in which modules could be shared and that is ultimately accessible to all, including the general public. The software we identified as a suitable platform accepts and integrates a variety of file formats that are commonly used to produce teaching material. The output is in HTML5 format, which is accessible by any web browser running on computers, laptops and hand-held devices such as tablets. The ASTRI university partners now all own a licence for this software.
Recording of modules:	Three demonstration modules have been recorded and are now undergoing peer review within ASTRI. The files contain slides with a voice-over recording by the academic who developed the module. Modules will also be distributed to ASTRI students as part of their training. Feedback will be collected from students to continue improving the modules and keep them up to date.
CST training courses:	Researchers within ASTRI were contracted to deliver a 10-day intensive training course to a multinational company. The course content was negotiated to increase their knowledge and understanding of feasibility studies of CST systems. The attendees were highly motivated and punctual, asked pertinent and challenging questions, and rated the course highly. Although the course included several design exercises, attendees indicated they would like to see more exercises in future courses. The ASTRI Director was invited to make a follow-up visit. A CST training course was organised and run over two days at CSIRO, Newcastle. Two of the modules were tested during the course. The feedback received will be used to continue developing these modules to benefit the students and ASTRI in general.
Key findings	The project is progressing well. Three modules have been recorded, while others are being finalised or peered within ASTRI. The ‘core’ and ‘enriching’ modules of the ASTRI CST course make it adaptable to different needs. The modules will therefore serve the needs of ASTRI as well as potentially become the reference course for anyone around the world who wants to learn about CST. If this were to happen, ASTRI CST activities will become known worldwide, which will increase our international reach and the pool of talent we can recruit from to establish Australia as the leading hub of CST research and development.

Project P02	Project to develop a CST education program
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 • liaise with universities to seek permission for the new course • organise peer review of produced modules • resolve outstanding technical issues related to software, platforms and integration of content • analyse feedback to ensure future modules incorporate tools such as animation and graphics to engage students and help explain CST. At least one of the modules will be trialled at the researcher development day of the 2015 Annual Workshop.
ASTRI training and networking	 

Knowledge Sharing Activities

Knowledge sharing plays a crucial role in ASTRI. With such an extensive collaboration providing a step-change in CST research opportunities, internal and external communication will increase the effectiveness of ASTRI. Therefore, ASTRI is placing an emphasis on communication activities and distribution of research to stimulate interest among prospective researchers, industry collaborators and the wider community.

A variety of communication activities within ASTRI in 2014 have used innovative approaches and novel technologies to improve ASTRI's collaborative spirit, community reach and effectiveness of its systems-based research.

ASTRI is now in a position to build on our current communication resources and practices, and expand our collaboration to involve more young researchers. We are also ready to cement our position as a go-to point for CST within Australia by bringing together researchers, policy makers and industry players interested in CST.

Communication Activities

The communication tools and strategy that ASTRI put in place throughout 2013 have been adopted by our members, who have created consistent, clear messages that demonstrate ASTRI's work in the field of CST. Our website has been the main means of general external communications in 2014. Specific dissemination of research has taken place through events such as conferences.

WEBSITE

The ASTRI website went live at the beginning of 2014, and is proving to be a valuable resource to spark interest in solar thermal research in Australia. Sharing knowledge via our website is vital to raising awareness of CST among the general public, potential researchers and investors, by showing how it can be a practical part of Australia's energy future.

Throughout the year, the website has expanded its purpose and content to provide:

- more information on current CST research
- useful information about CST power for the general public
- details on how industry, researchers and the public can get involved
- news updates to bring the public's attention to initiatives and advances in CST research.

The website has been an opening for a number of exchanges with researchers and other interested groups. This includes some researchers who have joined ASTRI projects in the latter part of 2014, along with a group helping to develop the report '*Pathways to deep decarbonisation in 2050*' (Denis et al., 2014[5]). This report, which is also supported by ARENA and other partners, aims to demonstrate how countries such as Australia can move to low-carbon economies.

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[5] Denis, A., Jotzo, F., Ferraro, S., Jones, A., Kautto, N., Kelly, R., Skarbek, A., Thwaites, J. (2014) "Pathways to deep decarbonisation in 2050 - How Australia can prosper in a low carbon world" Melbourne, Victoria, ClimateWorks, ISBN 978-0-9941725-0-1

Dissemination of Public Research

PAPERS AND PRESENTATIONS

ASTRI is presenting its research outcomes in a range of science disciplines and to a variety of industry forums. The rate of publishing refereed journal publications and conference presentations has substantially increased. The variety of conference and journals in which our work is being presented has also expanded.

WORKSHOPS

ASTRI held five internal workshops in 2014. Themes varied from specialised topics to providing the general context of CST systems to ASTRI researchers.

ASTRI Annual Workshop

The two-day ASTRI Annual Workshop was run at the University of South Australia, City West Campus in February 2014. This was the first ASTRI workshop for many researchers, providing them with an opportunity to learn about the status of CST internationally and obtain a general introduction to CST. Highlights of the first year of research were presented, and new projects were planned. It was a fruitful event, with ARENA commenting on ASTRI's focus on achieving the KPIs through strong collaboration under the direction of senior members of ASTRI, including the director, Manuel Blanco.

Modelling Tools Workshop

A Modelling Tools Workshop was held on in February 2014 to ensure methods and tools used across ASTRI are consistent and can interact seamlessly. The workshop examined a range of modelling techniques used in ASTRI projects, including, optical, thermofluid, chemical, system, annual performance and economic modelling. Discussion centred around the level of integration, complexity and flexibility of the models and modelling tools.

CST Training Workshop

A training workshop provided all young ASTRI researchers (postdoctoral fellows and students) with a holistic understanding of CST research. This gave them a better context for their research, and enabled them to grasp the concepts involving parts of the CST system beyond their area of expertise. It was the first course of its kind held in Australia specifically for researchers interested in CST, and it was great that ASTRI researchers could benefit from it.

The course included a tour of the heliostat field and receiver towers in the CSIRO National Solar Energy Centre, which gave the researchers first-hand experience with tangible components of a CST system. Such experiences help bring to life the research they are conducting through models and experimental work. The course proved successful, with even senior researchers noting that they had gained valuable insights, and was a valuable opportunity for young researchers to network.

Systems Workshop

An ASTRI Systems Workshop was held in October 2014 to discuss integrating several projects. This was a pivotal point to ensure the projects would interact to contribute to the ASTRI high-temperature CST systems approach and ultimately achieve the agreed LCOE cost reduction(s). Common objectives with respect to boundary conditions between the subsystems in the ASTRI configurations would ensure that technical KPIs could be met through a co-ordinated effort. Since the workshop, levels of discussion between projects have increased, with a focus on identifying and modelling short-term and long-term configurations for the ASTRI plant.

Webcast on Learnings from SolarPACES 2014

To facilitate the sharing of knowledge gained by the attendees of the SolarPACES 2014 conference, a webcast was made available to everyone from each of ASTRI's partner institutions, not just ASTRI researchers. Attendees at SolarPACES were given five minutes to quickly provide an impression of what was interesting at the conference, particularly with respect to its implications for ASTRI. This productive exercise brought ASTRI researchers together to network and to learn. We expect that many more opportunities will arise for knowledge sharing within ASTRI as we explore more tools to facilitate communication and networking between researchers.

SolarPACES 2014 Conference Topics

Topic	Total
Thermal/Thermochemical Energy Storage	57
Thermal Receiver	56
CSP Systems	54
Solar Collectors	51
Measurement and Control	22
General Topics in CSP	20
Power Cycles	20
Solar Fuels	18
Commercial and Demonstration Projects	16
Heat Transfer Fluids	16
Solar Resource Assessment	16
Reliability and Service Life Prediction	10
Policy and Markets	9
Water Desalination ad Detoxification	1
TOTAL	366

Publications and Presentations

Publications

1. Coventry, J. and J. Pye (2014). "Heliostat Cost Reduction – Where to Now?" Energy Procedia 49: 60-70
2. Gurgenci, H. (2014). "Supercritical CO2 Cycles Offer Experience Curve Opportunity to CST in Remote Area Markets." Energy Procedia 49: 1157-1164
3. He, S., Z. Guan, H. Gurgenci, K. Hooman, Y. Lu and A. M. Alkhedhair (2014). "Experimental study of film media used for evaporative pre-cooling of air." Energy Conversion and Management 87: 874-884
4. He, S., Z. Guan, H. Gurgenci, I. Jahn, Y. Lu and A. M. Alkhedhair (2014). "Influence of ambient conditions and water flow on the performance of pre-cooled natural draft dry cooling towers." Applied Thermal Engineering 66(1–2): 621-631
5. Liu, M., M. Belusko, N. H. Steven Tay and F. Bruno (2014). "Impact of the heat transfer fluid in a flat plate phase change thermal storage unit for concentrated solar tower plants." Solar Energy 101: 220-231
6. Lu, Y., H. Gurgenci, Z. Guan and S. He (2014). "The influence of windbreak wall orientation on the cooling performance of small natural draft dry cooling towers." International Journal of Heat and Mass Transfer 79: 1059-1069
7. Sadafi, M. H., I. Jahn, A. B. Stilgoe and K. Hooman (2014). "Theoretical and experimental studies on a solid containing water droplet." International Journal of Heat and Mass Transfer 78: 25-33
8. Singh, R., S. A. Miller, A. S. Rowlands and P. A. Jacobs (2013). "Dynamic characteristics of a direct-heated supercritical carbon-dioxide Brayton cycle in a solar thermal power plant." Energy 50: 194-204.
9. Singh, R., A. S. Rowlands and S. A. Miller (2013). "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: 1025-1032

Presentations

10. Aghaeimeybodi, M. (2014). Variability in the estimated LCOE for CSP technologies arising from uncertainty in cost and solar data inputs. 2014 Asia-Pacific Solar Research Conference. UNSW, Sydney
11. Ashman, P. (2014). Solar hybridized coal-to-liquids via gasification in Australia: techno-economic assessment. SolarPACES 2014. Beijing, China
12. Beath, A. (2014). Improving the financial performance of concentrating solar thermal power. ASME 2014 8th International Conference on Energy Sustainability. Boston, U.S.A.
13. Blanco, M. (2013). ASTRI Overview. SolarPACES executive committee meeting. Newcastle, NSW
14. Blanco, M. (2013). Current status of CST. First Australian Workshop on Solar Thermal Chemical and Industrial Processes. Adelaide, SA
15. Blanco, M. (2013). Overview of CSIRO & ASTRI. EUROTHERM Seminar No. 98 - Concentrating Solar Energy Systems. Vienna, Austria.

16. Blanco, M. (2013). Plenary: Global CSP initiative. SolarPACES 2013. Las Vegas, U.S.A.
17. Blanco, M. (2013). Solar Thermal's Potential. Solar 2013 Conference and Expo. Melbourne, Victoria.
18. Blanco, M. (2014). Overview of R&D activities in Solar Thermal Electricity technologies worldwide. Solar 2014. Melbourne
19. Coventry, J. (2013). Heliostat Cost Reduction - Where to Now? SolarPACES 2013. Las Vegas, U.S.A.
20. Coventry, J. (2014). Sodium receivers for solar power towers: a review. SolarPACES 2014. Beijing, China
21. Guan, Z. (2014). Design options of solar enhance natural draft cooling tower for solar thermal power plants. International symposium on Industrial Chimneys and Cooling Towers. Prague, Czech Republic
22. Guan, Z. (2014). Performance analysis of natural draft cooling tower with inlet air precooling. International symposium on Industrial Chimneys and Cooling Towers. Prague, Czech Republic
23. Guo, P. (2014). Fischer-Tropsch liquid fuel production by cogasification of coal and biomass in a solar hybrid dual fluidized bed gasifier. SolarPACES 2014. Beijing, China
24. Gurgenci, H. (2013). Supercritical CO2 Cycles Offer Experience Curve Opportunity to CST in Remote Area Markets. SolarPACES 2013. Las Vegas, U.S.A.
25. Gurgenci, H. (2014). Supercritical CO2 Systems for Concentrating Solar Thermal Power. Solar 2014. Melbourne
26. Jacob, R. (2014). Techno-Economic Analysis of Phase Change Material Thermal Energy Storage Systems in High Temperature Concentrated Solar Power Plants. 2014 Asia-Pacific Solar Research Conference. UNSW, Sydney
27. Kan, Q. (2014). Validation of a Three-dimensional CFD Analysis of Foil Bearings with Supercritical CO2. 19th Australasian Fluid Mechanics Conference. RMIT
28. Liu, M. (2014). Investigation of cascaded shell and tube latent heat storage systems for solar tower power plants. SolarPACES 2014. Beijing, China
29. Miller, S. A. (2013). CSP challenges and opportunities. SOLAR SOLUTIONS: The future of concentrating solar power in Australia : transitions and benefits. UTS, Sydney
30. Obadaee, M. (2014). Validation of a Three-dimensional CFD Analysis of Foil Bearings with Supercritical CO2. 19th Australasian Fluid Mechanics Conference. RMIT
31. Pye, J. (2014). An exergy analysis of tubular solar-thermal receivers with different working fluids. SolarPACES 2014. Beijing, China
32. Sadafi, M. H. (2014). An Investigation of Evaporation from Single Saline Water Droplets: Experimental and Theoretical Approaches. 19th Australasian Fluid Mechanics Conference. RMIT
33. Saw, W. (2014). Techno-economic evaluation of solar hybridised and non-solar gasification poly-generation plants. 4th International Symposium on Gasification and its Application. Vienna, Austria
34. Singh, R. (2014). Impacts of collector receiver volume on dynamic performance of a direct-heated supercritical-CO2 closed Brayton cycle in a solar thermal power plant. Solar 2014. Melbourne
35. Sun, Y. (2014). Cost analysis of high temperature thermal energy storage for solar power plant. Solar 2014. Melbourne
36. Tay, S. (2014). Thermal performance of phase change thermal storage systems for concentrated solar power applications with different heat transfer fluids. Solar 2014. Melbourne

ASTRI People

ASTRI OFFICE

NAME	ROLE
Dr Manuel Blanco	Director
Ms Sarah Miller	Chief Operating Officer
Ms Jane Sherman	Administration
Dr Jacqueline Hicks	Research Co-ordinator

CSIRO BUSINESS SUPPORT

NAME	ROLE
Ms Brooke Horton	Finance
Mr Andrew Lake	Legal
Mr Stephen O'Dowd	Business Development
Mr Simon Hunter	Communications
Ms Kacey Chambers	Project Support

POSTGRADUATE STUDENTS

NAME	ASTRI PARTNER	NAME	ASTRI PARTNER
Abbasi, Ehsan	Australian National University	Li, Xiao Xiao	University of Queensland
Aljawi, Raad	Queensland University of Technology	Modirshanechi, Mohsen	University of Queensland
Anglani, Francesco	Queensland University of Technology	Odabaee, Mostafa	University of Queensland
Asselineau, Charles-Alexis	Australian National University	Omaraa, Ehsan	University of South Australia
Corsi, Clotilde	CSIRO	Persky, Rodney	Queensland University of Technology
Czapla, Jason	University of Queensland	Qi, Jianhui	University of Queensland
Emes, Matthew	University of Adelaide	Raud, Ralf	Queensland University of Technology
Fairuz, Zakariya Mohd	University of Queensland	Riahi, Soheila	University of South Australia
Guo, Peijun	University of Adelaide	Sadafi, Hosein	University of Queensland
Jacob, Rhys	University of South Australia	Smith, Christine	CSIRO
Jiang, Yifeng	CSIRO	Ventura, Carlos	University of Queensland
Kan, Qin(Jason)	University of Queensland	Yu, Jeremy	University of Adelaide
Karunagaran, Ramesh	University of Adelaide	Yu, Shengzhe	University of Queensland
Keep, Josh	University of Queensland	Zou, Aihong	Queensland University of Technology
Lee, Ka Lok	University of Adelaide		

POSTDOCTORAL FELLOWS

NAME	ASTRI PARTNER	NAME	ASTRI PARTNER
Aghaeimeybodi, Mehdi	CSIRO	Saw, Woei	University of Adelaide
Bayon Sandoval, Alicia	CSIRO	Singh, Rajinesh*	University of Queensland
Bell, Stuart	Queensland University of Technology	Toster, Jeremiah	Flinders University
Gentleman, Alexander	University of Adelaide	Veeraragavan, Anand	University of Queensland
Grigoriev, Victor	CSIRO	Venkataraman, Mahesh	Australian National University
Kumar, Apurv	CSIRO	Xu, Yun Peng	University of Adelaide
Rakshit, Dibakar*	CSIRO		

*resigned

RESEARCHERS

NAME	ASTRI PARTNER	NAME	ASTRI PARTNER
Andersson, Gunther	Flinders University	Kim, Jin-Soo	CSIRO
Arjomandi, Maziar	University of Adelaide	Knight, Chris	CSIRO
Ashman, Peter	University of Adelaide	Lewis, David	Flinders University
Barry, John	Queensland University of Technology	Lim, Seng	CSIRO
Beath, Andrew	CSIRO	Lipinski, Wojciech	Australian National University
Belusko, Martin	University of South Australia	Liu, Ming	University of South Australia
Borghesani, Pietro	Queensland University of Technology	Losic, Dusan	University of Adelaide
Bruno, Frank	University of South Australia	Ma, Lin	Queensland University of Technology
Burgess, Greg	Australian National University	Meredith, Paul	University of Queensland
Campbell, Jon	Flinders University	Metha, Greg	University of Adelaide
Cholette, Michael	Queensland University of Technology	Murphy, Peter	University of South Australia
Coventry, Joe	Australian National University	Nann, Thomas	University of Adelaide
Cumptston, Jeff	Australian National University	Nathan, Gus	University of Adelaide
Dally, Bassam	University of Adelaide	Pratt, Rodney	University of South Australia
Dennis, Mike	Australian National University	Pye, John	Australian National University
Di Pasquale, Berto	University of Queensland	Rowlands, Andrew	University of Queensland
Doonan, Christian	University of Adelaide	Russell, Hugh	University of Queensland
Guan, Zhiqiang	University of Queensland	Saman, Wasim	University of South Australia

NAME	ASTRI PARTNER	NAME	ASTRI PARTNER
Gurgenci, Hal	University of Queensland	Sauret, Emilie	Queensland University of Technology
Gwynn-Jones, Stephen	University of Queensland	Stein, Wesley	CSIRO
Hall, Colin	University of South Australia	Sun, Yanping	CSIRO
Hinkley, Jim	CSIRO	Tang, Youhong	Flinders University
Hooman, Kamel	University of Queensland	Tay, Steven	University of South Australia
Hughes, Graham	Australian National University	Tian, Zhao Feng	University of Adelaide
Jacobs, Peter	University of Queensland	Venn, Felix	Australian National University
Jahn, Ingo	University of Queensland	Webby, Brian	University of South Australia
Kaniyal, Ashok	University of Adelaide	Will, Geoffrey	Queensland University of Technology
Kaufer, Martin	Australian National University	Zanatta, Ivan	University of South Australia
Khare, Sameer	CSIRO		

Financial Summary

The following is a financial summary for the relevant reporting period (1-Nov-2013 to 31-Oct-2014) 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-2013 TO 31-OCT-2014	PROGRAM OVERALL
Grant funding (ARENA)	$3,987,500	$4,737,500
Collaborator contributions	$3,570,729	$4,899,244
TOTAL CONTRIBUTIONS	$7,558,229	$9,636,724

Total expenditure with breakdown by heads of expenditure

HEADS OF EXPENDITURE	1-NOV-2013 TO 31-OCT-2014	PROGRAM OVERALL
Salaries	$5,061,862	$7,154,365
Equipment	$230,576	$265,363
Materials	$167,594	$236,865
Sub-contract	$0	$0
Travel	$172,433	$249,697
Other	$199,463	$248,079
TOTAL EXPENDITURE	$5,831,928	$8,154,369

Statement of financial performance

FINANCIAL SUMMARY	1-NOV-2013 TO 31-OCT-2014	PROGRAM OVERALL
Total contributions	$7,558,229	$9,636,724
Total expenditure	$5,831,928	$8,154,369
OPERATING PROFIT (LOSS)	$1,726,302	$1,482,355

Declaration:

I hereby certify that the above statement covering the period from commencement to 31 October 2014 represents the financial transactions fairly and is based on proper accounts and records.

Signature:

Cindy Digby BCom MAcc CPA
Finance Manager, Energy Flagship
Date: 26th March 2015

Shortened forms

ABL	atmospheric boundary layer
ANU	Australian National University
ARENA	Australian Renewable Energy Agency
ASTRI	Australian Solar Thermal Research Initiative
CapEX	capital expenditure
CFD	computational fluid dynamics
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CST	concentrating solar thermal technologies
CSP	concentrating solar power
FT	Fischer-Tropsch
GJ	gigajoule
GW	gigawatt
IEA	International Energy Agency
KPI	key performance indicator
kW	kilowatt
kWh	kilowatt-hour
LCOE	levelised cost of electricity
LCOF	levelised cost of fuel
MW	megawatt
MWe	megawatt electrical
NREL	National Renewable Energy Laboratory
O&M	operation and maintenance
PCM	phase change material
QUT	Queensland University of Technology
RD&D	research, development and demonstration
SAM	System Advisor Model developed by NREL
sCO_2	supercritical carbon dioxide
SRI	strategic research initiative
UniSA	The University of South Australia
UQ	The University of Queensland
USASEC	USA Solar Energy Collaboration

Glossary

Capacity factor – the fraction of a period, normally a year, in 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

Direct normal irradiance – 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

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. A heliostat includes a reflective surface, usually a planar mirror, with a mechanically controlled range of motion used to reflect sunlight in a constant direction towards a predetermined target

Heat transfer fluid – 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 1 000 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, with 1 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 one 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. Thermal energy is absorbed or released when the material changes from solid to liquid and vice versa. Also referred to as latent heat storage units

Poly-generation – generation of more than one useful energy product

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

Solar energy – electromagnetic energy transmitted from the sun (solar radiation). The amount of solar energy that reaches 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, parabolic troughs and linear Fresnels

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

Supercritical CO_2 (sCO_2) – carbon dioxide operating above its critical point, such that it behaves as a fluid in a single phase that has some gas-like and some liquid-like properties

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, refers to the United States-Australia Solar Energy Collaboration as a funding mechanism to support collaborative research between the United States 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)

FOR FURTHER INFORMATION

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