Prepared for the Australian Renewable Energy Agency

In the spotlight:

Australian solar energy R&D outcomes and achievements in a global context

A review of ARENA's portfolio of solar research and development

July 2018

About this report

The research was commissioned by the Australian Renewable Energy Agency, (ARENA).

This document presents the findings of reviews carried out by ITP Renewables in 2016 and 2018 of ARENA's portfolio of solar research, development and pilot-scale demonstration projects, as well as associated PhD and Post-Doc Fellowship programs.

Cover images

From left to right:

Solar Hybrid Fuels, CSIRO

CloudCAM PV Generation Forecasting, Fulcrum 3D

Forecasting Distributed Solar Energy, ANU

About ITP Renewables

The IT Power Group, formed in 1981, is a specialist renewable energy, energy efficiency and carbon markets consulting company. The Group has offices and projects throughout the world.

ITP Renewables was established in 2003 and has undertaken a wide range of projects, including providing advice for government policy, feasibility studies for large renewable energy power systems, designing renewable energy power systems, developing micro-finance models for community-owned power systems in developing countries and modelling large-scale power systems for industrial use.

The staff at ITP have backgrounds in research, renewable energy and energy efficiency, development and implementation, managing and reviewing government programs, high level policy analysis and research, including carbon markets, engineering design and project management.

Report Control Record

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Document Control					
Report Title	In the spotlight: Australian solar energy R&D outcomes and achievements in a global context				
Client Contract No.	PO1381		ITP Project No.	A0271	
Filepath	Work/0Projects/A0271 ARENA Solar R&D Review Update/1Deliverables/Solar R&D Synthesis June_2018.pdf				
Client	ARENA		Client Contact	Damir Ivkovic	
Rev	Date	Status	Authors	Project Manager	Approved
	May 2018	Draft	M. Watt, K. Lovegrove, D. Jordan, J. Wyder, R. Bader.	M. Watt	J. Wyder
	June 2018	Final	M. Watt, K. Lovegrove, D. Jordan, J. Wyder, R. Bader.	M. Watt	J. Wyder
1	July 2018	Final (Rev)	M. Watt, K. Lovegrove, D. Jordan, J. Wyder, R. Bader.	M. Watt	D. Jordan

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TERMS OF REFERENCE

This report consolidates the results of reviews undertaken in 2016 (for projects up to end 2015) and 2018 (for projects up to end 2017) which aimed to collate, synthesise and document the rationale and outcomes associated with ARENA's current and past portfolio of solar photovoltaic and solar thermal research and development projects.

A synopsis is to be provided of the rationale, activities undertaken, knowledge generated, lessons learnt and overall contribution of ARENA's solar R&D projects and Fellowship program, in order to:

- Better communicate activities and achievements; and
- Better articulate significance and implications.

The report is to include:

- a summary of the key issues and trends in global solar R&D;
- summary of significant project outcomes and lessons learned;
- a selection of important project Case Studies;
- a specific assessment of the Fellowship program and how it has contributed to ARENA's purpose.

ABBREVIATIONS

ACAP	Australian Centre for Advanced Photovoltaics
AEMO	Australian Energy Market Operator
ANU	Australian National University
ARENA	Australian Renewable Energy Agency
AREMI	Australian Renewable Energy Mapping Infrastructure
ARP	Advancing Renewables Program
ASEFS	Australian Solar Energy Forecasting System
ASI	Australian Solar Institute
ASTRI	Australian Solar Thermal Research Initiative
AUSIAPV	Australian US Institute for Advanced Photovoltaics
BoM	Bureau of Meteorology
BREE	Bureau of Resources and Energy Economics
CdTe	Cadmium Telluride
CER	Clean Energy Regulator
CIGS	Copper Indium Gallium Selenide
CPV	Concentrating Photovoltaics
CRC	Cooperative Research Centre
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSP	Concentrating Solar Power
CST	Concentrating Solar Thermal
ERP	Emerging Renewables Program
GMS	Grants Management System
IEA	International Energy Agency
ITP	ITP Renewables
mc-Si	Multi-crystalline Silicon
NA	Not applicable
NEM	National Electricity Market
OPV	Organic Photovoltaics
OIPV	Organic-Inorganic PV
PDF	Post-Doctoral Fellowships and PhD Scholarships
PET	Polyethylene terephthalate
PGA	Post Graduate Award
PV	Photovoltaic
PVT	Photovoltaic and Thermal Energy hybrid
Si	Silicon
SIRF	Solar Industrial Research Facility

R&D	Research and Development
RD&D	Research and Development as well as pilot-scale Demonstration
RE	Renewable Energy
RET	Renewable Energy Target
RMIT	Royal Melbourne Institute of Technology
SHARE	Supporting High-value Australian Renewable Energy (SHARE) Knowledge
TRL	Technology Readiness Level
UNSW	University of New South Wales

EXECUTIVE SUMMARY

Solar energy is set to be one of the dominant sources of electricity generation globally. Solar PV in particular has emerged as one of the key technologies that will underpin the electricity grid of the future. This will mean a massive investment in solar PV over the coming decades, with credible estimates of over 15 fold increases in installed capacity by 2050 and over USD 5 trillion of investment.

One of the main reasons for solar PV's emergence as a core electricity generation technology is the rapid price decrease which has occurred as uptake has increased, thanks to the characteristic "learning rate" that it shares with another well-known silicon-based technology - computers.

Just like computer chips, solar PV has reduced in cost for every doubling of installed capacity. Since the mid 1970's the cost of solar PV has consistently fallen by 28% every time the amount of solar PV installed has doubled. As a result, the cost of crystalline silicon solar PV modules has dropped from US$79 per Watt in 1976 to US$0.37 per Watt in 2017.

This means that today, Australian families can, without subsidy, install a significantly bigger and more efficient solar PV system on their roofs than was possible 5 years ago with a subsidy. Utility scale solar PV plants are also getting cheaper to build - plants that 5 years ago could only be built with a significant government grant are now being built entirely on commercial terms.

The declining cost of solar PV modules is an important contributor to the decreasing cost of installations and one of the main drivers of this in turn has been technology innovation driven by cutting edge research. Australian solar researchers have played a leading role in the global research effort for the past 4 decades and Australian technology is expected to dominate the PV market over the next decade, with the PERC cell developed by the University of NSW expected to be used in over 60% of commercial cells.

The improvements in efficiency and performance of solar PV enabled by Australian research translates directly into savings for Australian consumers and greater uptake of solar PV in Australia and globally. However, the solar PV market is still relatively new, having only reached widespread commercial success in the last decade. There is therefore much innovation still to come.

Concentrating solar thermal technology holds out great promise as another form of solar power with a built-in storage capability. While CST uptake has not advanced nearly as quickly as solar PV, as the requirement for flexible and dispatchable electricity grows there is renewed impetus to overcome the technical and commercial hurdles facing the technology.

Australia has, over the past decade, developed its research capability in the CST field and is now producing world-leading results. With appropriate support, Australia can continue to play a world-leading role in the new solar energy frontier.

Key Findings of this report

This report, based on a systematic review of over 300 solar and associated enabling research projects supported by ARENA, provides a critical assessment of the outcomes of Australian solar research and places those outcomes in a global context. It also includes a survey of early career researchers who received PhD and Post-doctoral awards from ARENA. The evidence presented shows that ARENA's support for solar R&D is helping accelerate the shift to an affordable and reliable renewable energy future and is training the next generation of solar specialists who will enable this to happen.

Figure E1 shows the breakdown of ARENA funding contributed to the three focus areas: PV, CST and Enabling research projects, as well as the significant leverage of funding achieved from industry and research institution contributions.

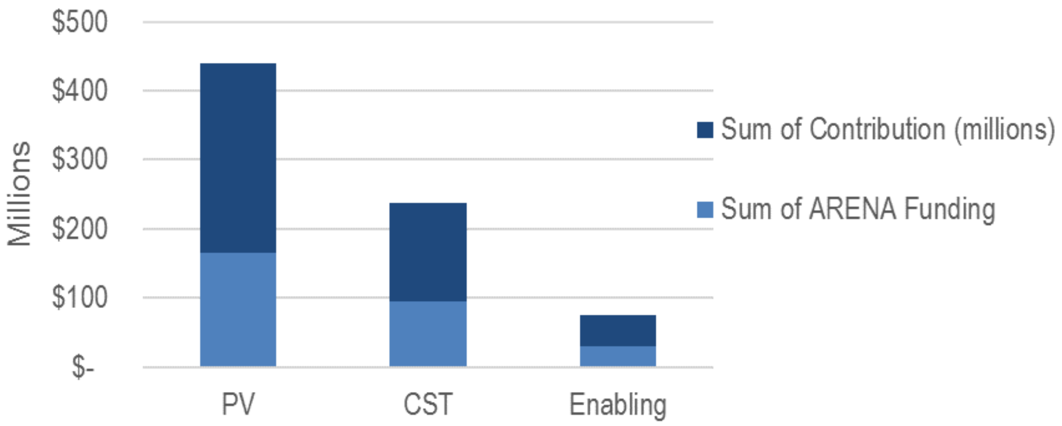


Figure E1: ARENA funding and leverage by research type 2008-2017.

Research Aims

The predominant research goal across all Solar R&D projects was efficiency improvement, followed by manufacturing cost reduction, as shown in Figure E2 below. This reflects the immediate relevance to industry of much of the Australian Solar R&D effort.

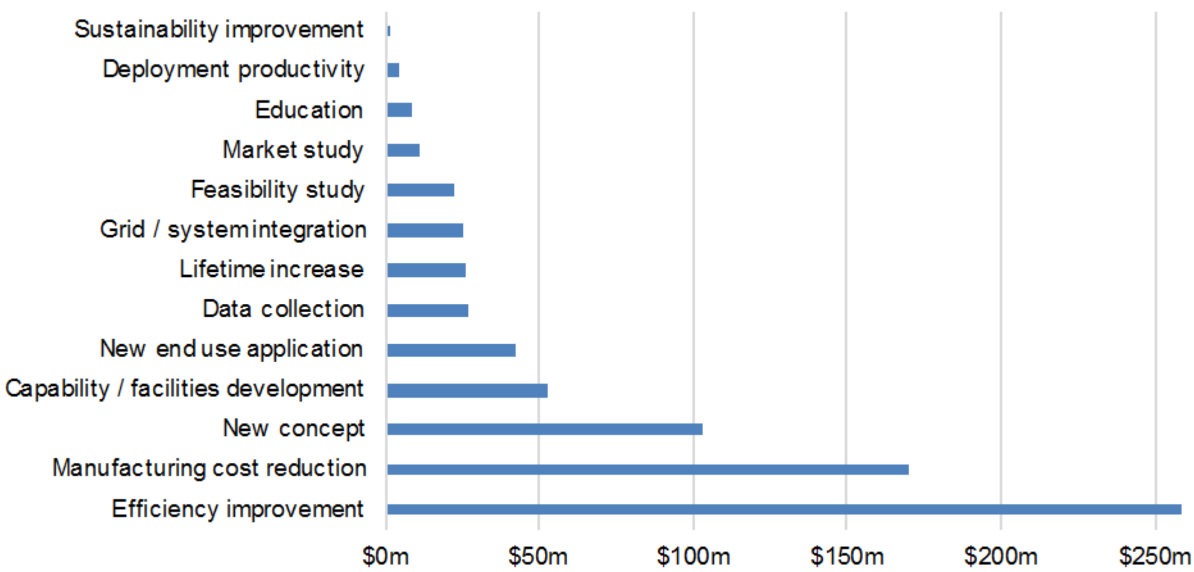


Figure E2: Solar R&D Total Project Expenditure ($752m) by primary goal.

Technology Development Progression

Technology Readiness Level (TRL) at the start and finish of all R&D projects was assessed. The largest portion (39%) of projects started at a TRL of 2 (basic concepts validated) and, though the spread of TRL was larger, the highest number of projects (26%) finished, or expected to finish, at TRL 5 (prototype feasibility demonstrated). This reflects the R&D calls made by ARENA, which specified TRLs between 2 and 6. The projects at higher TRLs are those in the early stage demonstration category.

Project Outputs

Project outputs assessed for this analysis are summarised in Table E1. Although this is likely to be a portion only of the total project outputs, it is clear that the R&D funding has resulted in significant knowledge creation and extensive knowledge sharing, as well as important skills development, and will contribute to Australia's continued contribution to future commercial solar technology developments.

Table E1: Summary of Solar R&D reported project outputs

	Number of						
Project Outputs	**Patents filed**	**Licences entered into**	**Journal publications**	**Other publications**	**Presentations**	**PhDs**	**Postdocs and other researchers**
PV	139	19	1,183	163	890	183	158
Enabling	3	0	31	54	97	11	51
CST	6	2	167	95	248	26	132
TOTAL	**148**	**21**	**1,381**	**312**	**1,235**	**220**	**341**

The PhD and Post-doctoral award recipients surveyed reported a total of 406 publications, with 91% reporting journal papers and 82% international conference presentations. Nine patents resulting from their work were reported as filed and four granted. 75% of the respondents indicated that they had collaborated with international research groups since or during their ARENA award while a total of $12m in grants received following their awards were reported. This high level of achievement reflects the calibre of the students receiving ARENA awards, as well as the success of this R&D support program.

Conclusions

ARENA funding has significantly boosted Australia's solar R&D effort, and in turn the research outcomes and capability which has kept Australia in the forefront of this burgeoning new international solar industry. Key achievements typically build on a long-term research commitment, with funding spanning many years and the establishment of well-functioning research teams. Solar research funding provided by ARENA over the past decade has significantly improved Australian solar research facilities, maintaining Australia's world leading role and bringing research and pre-commercial industrial demonstration facilities up to world class. This has facilitated a wider range of research projects and assisted in enhancing research-industry collaboration. Funding for early career researchers has been critical in keeping high achievers in Australia, which has further enhanced research outcomes. Commercialisation will be facilitated by the value stream from research through development and demonstration, and the strong links to the market and the key industry players, which have now been established.

While there are many new PV materials and processes being developed in research laboratories around the world, Australia maintains the lead in developments most relevant to the mainstream commercial PV industry. This means that many Australian developments are able to have a rapid and a large impact on mainstream PV products, with higher efficiencies and lower costs being passed through to consumers relatively rapidly. With crystalline silicon remaining the dominant technology in use worldwide (>90%) and with Australia's research dominance in this field, as well as the strong education and research ties which have been established between Australian research institutions and the key world manufacturers, Australia is in a good position to maintain this lead through strategic research funding.

For CST, the past decade of research funding has facilitated the establishment of a number of key research and demonstration facilities. Despite a lack of a commercial CST deployment in Australia, these facilities are now being used to develop a range of related technologies and components for use in new value streams, including solar fuels and industrial energy systems. Key development in high temperature processes have also improved the cost effectiveness of CST systems, including the increasingly valuable storage component.

As Australia moves towards higher levels of renewable energy deployment, in response to the climate change imperative and, increasingly, because renewable energy provides the lowest cost electricity, enabling R&D is becoming critical. Forecasting systems, energy storage and control technologies are now providing the elements necessary to integrate renewables into electricity systems which were designed for fossil fuels. New methods, both technical and regulatory, to manage both supply and demand will minimise the cost of deploying increasing amounts of renewable energy while maintaining system reliability and responsiveness.

Given that solar technologies are still only in their early phases of deployment, research remains crucial. Research priorities may change over time as the market environments evolve. Nevertheless, key efforts on technology improvement, such as higher efficiencies, lower costs, use of less toxic or more abundant materials and environmentally sustainable manufacturing processes, remain key drivers.

Research and industry hubs have played a key role internationally in focusing research and moving it through to market, as have long term commitments to research institutions. ARENA funding has been critical in supporting and developing research infrastructure which is now facilitating large-scale industry collaboration in PV (ACAP, SIRF), CST (ASTRI), storage, data and forecasting (ASEFS, AREMI) and other associated research areas (such as nano-fabrication, quantum computing). Such institutions and hubs:

- reduce the volatility of research funding,
- ensure continued high level educational outcomes,
- secure employment for our leading graduates and top researchers,
- enhance the prospects for local industries, and
- provide links into the global industry.

1. CASE STUDIES

Selected projects from each area of research are highlighted below, to provide an indication of the sorts of projects carried out under the R&D Program, the staff and organisations involved and the key outcomes.

1.1. Improving the Efficiency of Low Quality Low Cost Silicon Wafers

ARENA Funding Support

2010/ASI 1008 / 1-A082, ACAP PP1.1 Solar Silicon 2014-17,
ARENA RND 2017 / 003 – 009 – 015 – 016

Participant Institutions

ANU, UNSW, Apollon, Jinko, Trina, Sunpower, ECN

Key Researchers

ANU: Prof Daniel Macdonald, Dr Fiacre Rougieux, Dr Nick Grant, Dr Ryan Sun, Dr Hang Cheong Sio

UNSW: Prof Stuart Wenham, Assoc. Prof CheeMun Chong, Dr Brett Hallam and others.

Aims and Objectives

- To achieve, for the first time, cell efficiencies significantly above 20% using wafers grown from 100% solar grade (such as UMG, Upgraded Metallurgical Grade) silicon wafers supplied by industry partners, with a near term aim of efficiencies above 23%.
- To further develop novel pre-processing passivation methods (Tabula Rasa anneal / phosphorous gettering) for improving the electronic quality and high temperature tolerance of solar grade wafers, and to develop new cell processes that maintain the electronic quality of the pre-processed solar-grade wafers.
- To optimise charge-state controlled hydrogen deactivation of Boron - Oxygen defects in these devices, to ensure their stability under normal operating conditions.

Benefits

This technology has been demonstrated to increase the performance of low quality / low cost solar grade silicon wafers to levels similar to those currently being achieved with high purity / high cost wafers. Using wafers appropriately pre-processed, this technology can be incorporated into current standard cell manufacturing lines, with minimal equipment change.

The technology delivers significant cost benefits at the PV module level. Using current projections of approximate annual PV manufacturing levels (say 100 GW pa in 2018), a conservative module cost / sell price of US $0.50/W, and assuming wafer costs are one third of module costs and solar grade wafers are 50% cheaper than CZ electronic grade, a global saving of some US $7.5b pa is possible. In Australia, at 1 GW pa deployment rate, the equivalent savings are US $75m pa, or US $750m over the 2018 to 2028 period.

Commercial Interest

Considerable commercial interest has been shown in this technology, including with a significant silicon wafer manufacturing partner. In addition, a large consortium of top tier wafer, cell and tool manufacturing companies are involved in the advanced hydrogenation program. A number of patents have been filed in support of various aspects of this work.

Outcomes and Current Research

It has been shown that the boron-oxygen defect in solar-grade silicon can be permanently deactivated by utilising a range of pre-processing and charge-state controlled hydrogen passivation.

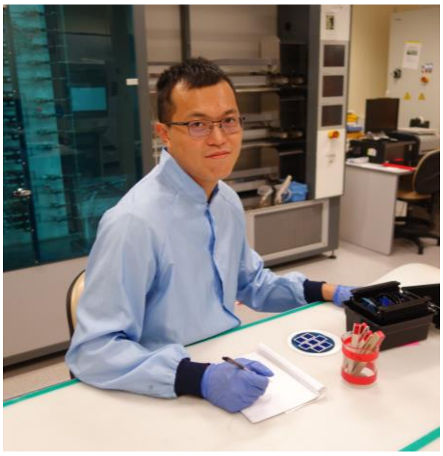
Results in 2016 include an independently verified cell efficiency of 21.1% on commercial n-type solar grade wafers, compared with 21.9% on co-processed electronic grade material. During 2017, an in-house efficiency of 21.2% was recorded for an n-type UMG heterojunction solar cell pre-processed at ANU and fabricated at Arizona State University.

Charge-state controlled advanced hydrogenation via illuminated annealing has been shown to almost completely deactivate the boron-oxygen defect in solar grade silicon wafers, making the final devices stable under normal operating conditions.

The overall program has contributed significantly to the establishment and operation of the Solar Industrial Research Facility (SIRF) at UNSW, and the award in 2014 of the UK IET AF Harvey Engineering Research prize in London to the late Professor Stuart Wenham.

Early Career Researcher Profiles

Dr Hang Cheong (Kelvin) Sio, ANU



Hang Cheong Sio (Kelvin) is a research fellow at the Australian National University. Born and raised in Macau, Kelvin came to Australia to undertake an Engineering degree for the challenge, practicality and contribution to society. After completing his undergraduate studies at ANU, Kelvin was offered the opportunity to undertake his PhD in PV application of novel photoluminescence spectroscopy, a project funded by The Australian Solar Institute (ASI, a precursor to ARENA) in conjunction with BT Imaging, a UNSW technology spin-off company.

The study has strengthened Kelvin’s strong belief in the importance of renewable energy to the future of humankind. Since starting his PhD in 2011, Kelvin has authored and co-authored more than 20 papers. His research interests include semiconductor defects characterisation, defect mitigation, and modelling of solar cells.

Kelvin is currently an ACAP research fellow, working on multi-crystalline and mono-like silicon for high efficiency solar cells, with a career vision to bridge the gap between academic research and industrial applications.

Dr Brett Hallam, UNSW

After schooling in Victoria, Brett chose undergraduate study at UNSW in 2004, supported by a Rural Engineering Scholarship and based on UNSW's position as a world-leader in solar cell research, gaining a First Class Honours degree, the University Medal and the Faculty of Engineering Dean's Award.

Brett continued with a UNSW Research Excellence Scholarship for his PhD in the School of Photovoltaic & Renewable Energy Engineering after becoming "hooked on PV", conducting research on an ARENA funded project to develop the Advanced Hydrogenation Technology.

The world-class facilities, the great minds and passion for PV of pioneers like Prof. Martin Green and the late Prof. Stuart Wenham, not to mention the Sydney beaches, have kept Brett at UNSW, being awarded an ACAP postdoctoral fellowship and receiving ARENA-ACAP pilot-project funding to develop a low-cost p-type heterojunction technology. Last year, this project transitioned into a large ARENA funded project led by Brett, to further develop and commercialise a next-generation p-type solar cell technology featuring heterojunctions; Brett is also continuing ARENA funded work to commercialise the Advanced Hydrogenation Technology.

In the future, Brett intends continuing with industry-focused research, capitalising on the capabilities of UNSW's Solar Industrial Research Facility and continued ARENA funding support to develop next-generation silicon solar cell technologies.

1.2. Low Cost, High Efficiency Kesterite Solar Cells on Silicon and BIPV Substrates

ARENA Funding Support

2011/PFD001, 2013/ASI 029, ACAP Projects PP1.3a / 2.2a / b / c, RND 3-2017/RND006

Participant Institutions

UNSW, Baosteel, NREL, Guodian, Colorado School of Mines, IBM, NTU Singapore, Corning Research & Development, China Electronics Technology Group (CETC), Open Instruments P/L, China Lucky Group Corp, General Research Group or Nonferrous Metals, Catalonia Institute for Energy Research (IREC)

Key Researchers

UNSW: Dr Xiaojing Hao, Professor Martin Green and others

Aims and Objectives

- To develop low cost, high throughput manufacturing processes for high efficiency stand alone or silicon tandem solar cells utilising non-toxic, earth abundant kesterite materials (copper-tin-zinc-sulphur selenium), CZTS/CZTSSe.

Benefits

Cheap, non-toxic, high performance, thin film solar cells deposited onto glass and steel supporting substrates offer great potential as building materials.

CZTS based solar cells utilise abundant, non-toxic materials and can be deposited in a flexible, thin film layer onto architectural building materials, potentially with a relatively high solar conversion efficiency.

Commercial Interest

Significant interest has been shown from glass and steel building component manufacturers, as evidenced by the industry partners.

Outcomes and Current Research

Results to date include four independently verified (NREL) world record CZTS solar cells. The highlighted current two world records are large area solar cells with 10% efficiency from a 1cm^2 CZTS thin film solar cell on molybdenum coated soda lime glass and 11% for a smaller (<1cm^2) device.

In addition, UNSW has demonstrated 22.7% tandem CZTS/Si PERL and 19% CZTS/Si PERC cells by an in-house spectrum splitting method, comparable to the performance of Solar Frontier commercial high bandgap tandem CIGS/S cells. The researchers are confident of achieving efficiencies over 20%.

Utilising a Zinc Tin Oxide (ZTO) buffer layer, UNSW has also developed an in-house measured 9.3% efficient Cd free CZTS cell, the highest ever reported for cells of this type.

UNSW is also working on strategies for transferring the CZTS technology to steel substrates for building integrated applications and has demonstrated efficiencies of around 8% on flexible stainless steel.

Early Career Researcher Profile

Dr Xiaojing Hao

Dr Xiaojing (Jeana) Hao, inaugural UNSW Scientia Fellow, ARC DECRA and Senior Lecturer at UNSW.

Xiaojing obtained her PhD in 2010 at the School of Photovoltaic and Renewable Energy Engineering at UNSW and was awarded an inaugural ARENA research fellowship in 2011. With the support of this fellowship, she initiated a new line of research, CZTS solar cells, at UNSW from scratch.

She leads the UNSW CZTS solar cells research group, achieving four NREL-certified world records since 2016 and establishing the forefront leadership position internationally.

Recently, she extended her research work into other abundant and environmentally-friendly green PV materials and devices. She has also been contributing to addressing the PV challenges by improving the performance of low temperature processed perovskite solar cells and lowering the manufacturing cost of III-V/Si tandem cells. She has extensive project management experience as lead or Principal Investigator or Chief Investigator on seven ARC and five ARENA grants, with a total funding of >$16 million, and has published 96 journal papers.

Xiaojing was selected as one of UNSW's "20 rising stars who will change our world" and also selected as a finalist in the UNSW Women in Engineering awards for the "Professor Judy Raper Award for Leadership in Engineering".

1.3. Printed Solar Cells - Perovskites

ARENA Funding Support

2011/ASI 043, ACAP PP2.5 / 4.1 / 4.2 / 6.12 / 6.17, 2017/RND 012 / 013

Participant Institutes

CSIRO, Monash University, University of Melbourne, Cambridge University UK, CSR Viridian, Greatcell Solar

Key researchers

CSIRO: Dr Gerry Wilson, Dr Fiona Scholes, Dr Mei Gao, Dr Doojin Vak & Others

Monash University: Prof Udo Bach, Prof Yi-Bing Cheng, Dr Feng Li & Others.

University of Melbourne: Prof Ken Ghiggino, Dr David Jones

Aims and Objectives

- To investigate a range of perovskite materials & device structures, including Pb-free, suited to high volume manufacture.
- To understand and address stability and durability issues in these materials and devices, and develop suitable synthesis and encapsulation approaches to address them.
- To investigate scaling to commercially relevant device size in roll-to-roll (R2R) processing on flexible substrates, translating high efficiency laboratory cell performance to large area devices, and modelling / analysing the manufacturing costs.

Benefits

The continuous roll-to-roll printing of perovskites builds on significant prior work done by the group on organic semiconductor (OPV) materials and processing, offering potentially higher efficiency perovskite thin film solar cells on rigid or flexible substrates which are stable and durable. Success presents the potential of significant module cost reduction and new opportunities for incorporation into a range of portable, appliance integrated and building integrated PV systems.

Commercial Interest

Significant manufacturing and commercial activity already exists in the PV industry in flexible thin film R2R manufactured products using different semiconductor material formulations (a:Si, CIGS, OPV) and the potential for higher efficiency perovskite based processing attracts great interest from building integrated industrial companies like CSR Viridian and Greatcell Solar.

Outcomes and Current Research

Laboratory scale devices have already been achieved using industry relevant process techniques, with newly developed “blowing-assisted drop-casting” methods demonstrating small area efficiencies in the range of over 15% for batch processed slot-die coating on glass substrates, and over 11.0% for R2R air ambient one-step printing on flexible PET film.

Continuing work is focussed on CSIRO's "lab-to-fab" approach, translating the high efficiencies achieved in laboratory-scale devices to R2R produced PV modules with efficiencies >10%. Considering estimated manufacturing costs and the merits of the flexible form factor, products using these modules are projected to be producible in 2 to 3 years after the current ARENA project concludes in 2021.

Early Career Researcher Profile

Dr Hasitha Weerasinghe

Dr Hasitha Weerasinghe is an early career researcher in the field of Emerging PV technologies, most recently working on the development of printable photovoltaic technologies in Australia. He has been the project leader for an ACAP collaboration grant between CSIRO and Stanford over the past two years, and was recently appointed as a Research Scientist in CSIRO as a key researcher in the ARENA R&D project on Printed Perovskite Solar Cells.

Following his Master's degree in Physics at the University of South Florida in 2007, Hasitha commenced his PhD at Monash University supported by a Monash International Postgraduate Research Scholarship, working on developing new inks and low-temperature deposition methods to prepare electrodes for efficient flexible dye sensitised solar cells (DSCs), fabricating the first Australian made working flexible DSC device.

In 2013, Hasitha was awarded an ARENA 3-year fellowship with the major objective of developing encapsulation techniques for flexible devices, improving and analysing the stability of printed organic (OPV) and, more recently, perovskite, solar cell modules.

Hasitha's current research has further been recognised as a recipient of the 'Australia-India Early and Mid-Career Fellowships' 2018-2019, working on 'Investigation of Degradation Mechanisms and Long-Term Stability of Highly Efficient Perovskite Solar Cells' with the Indian Institute of Technology (IIT) Kanpur and building collaborations with printed photovoltaic teams at IIT Kanpur and other institutes in India.

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1.4. Concentrating Solar Fuels

ARENA Funding Support

2012/ASI054, 2012/PFD011, 2013/ASI033, ASTRI (P42)

Institutions

CSIRO, UoA, ANU, UNSW, Flinders University

Key Researchers

Wes Stein, Jim Hinkley, Robbie McNaughton, Graham Nathan, Philip van Eyk, Wojciech Lipinski, John Pye, Evatt Hawkes, David Lewis and others.

Aims and Objectives

Concentrated Solar Fuels research aims to develop processes and technologies for the efficient conversion of concentrated solar energy into chemical energy carriers, such as hydrogen, ammonia, diesel, methanol and petroleum synfuels. These fuels can be used either as transport fuels, long-term domestic solar energy storage or to export renewable energy overseas.

Outcomes and Current Research

The solar fuels roadmap study, published in 2016, carried out the most complete literature review on concentrating solar fuels to date. It produced a detailed roadmap and recommendations for concentrating solar fuel technology options and market opportunities for Australia, examining factors such as levelised cost of fuel, key operating parameters, technology readiness level (TRL), limits to conversion efficiencies and more. The technologies reviewed range from hybrid solar plus gas, biomass or coal options, with TRLs in the range 1 to 6, to advanced, multistep water-splitting processes with TRLs in the range 1 to 5.

The highest ranked process was steam reforming of natural gas. This was due to its good economics ($10–15/GJ for solar syngas), current high TRL and relatively low score for unsolved hurdles. Water splitting with redox cycles also scored well in the screening. Despite its much higher syngas production cost (~$30/GJ), it has a reasonable TRL score and appears to offer a potential cost of hydrogen production that is half that of PV electrolysis. Overall, the study showed strong potential for solar thermal fuel production to be cost effective in a low carbon world and identified a potential future market for production of hydrogen rich fuels for export to traditional energy customers such as Japan.

Within the Australian Solar Thermal Research Initiative (ASTRI), ongoing research on solar fuels production includes processes for the gasification of different sources of biomass, thermochemical water and CO_2 splitting and processes coupling methane partial oxidation with water splitting. The work encompasses material development and optimisation, reactor and process development and modelling, and techno-economic modelling and assessment. Outside ASTRI, CSIRO continues to explore solar driven methane reforming and UNSW has developed numerical and experimental design tools for the design of solar thermochemical reactors.

Benefits

Concentrating Solar Fuels technologies are a longer-term prospect but could be of enormous future importance. They could lead to energy exports that could move to replace coal in a carbon constrained world. This may prove to be the most important CST application in the future for Australia. This has been a major driver in ARENA adopting solar energy for export as a funding priority and, following a request for information in 2017, a 2018 R&D funding round focussed on hydrogen for energy export has been held.

Commercial Interest

So far there are no direct industrial partnerships for Concentrating Solar Fuels and no established market mechanisms for them. However, solar fuels could leverage Australia's existing fuel export infrastructure and partnerships with large overseas energy customers and enable large-scale renewable energy exports.

Australia's solar fuels research has generated considerable interest in Japan and has set the scene for future commercial steps. It is expected that further Concentrating Solar Fuels projects will follow from the 2018 R&D funding round and these will have increasing levels of industry involvement.

Earlier Career Researcher Profile

Dr Philip van Eyk

Dr Philip van Eyk is a Research Fellow and Lecturer in the School of Chemical Engineering at the University of Adelaide with a background in combustion, gasification and sustainable fuel technologies. He has performed research in a range of areas, mostly focusing on alternative methods to produce sustainable replacements for fossil fuels.

Philip obtained his PhD in 2011 from the University of Adelaide in the area of solid fuel combustion. In 2012, he was awarded a fellowship from the Australian Solar Institute to assess the potential of introducing solar thermal energy into gasification of low grade solid feedstocks to produce syngas for solar fuels synthesis (such as diesel and kerosene). From his work both at the University of Adelaide and at ETH Zürich, he was able to show that such technologies have large potential for Australia to produce cleaner, more sustainable fuels. One of the key achievements of this research was the successful development of reactors to demonstrate the solar gasification of wet feedstocks.

Most recently, Philip has extended his research into hydrothermal processes to convert by-products from agricultural industries and wastewater treatment, as well as new crops (such as hemp and macroalgae) into biofuels to replace coal and crude oil. Additionally, Philip is performing ARENA funded research as part of a team led by University of Adelaide, and including UNSW, CSIRO, Hatch, Alcoa and IT Power, to look at incorporating solar thermal energy into a very large industrial process: the Bayer process for alumina production. Philip is leading the process modelling and kinetics aspects of the gibbsite calcination part of the program.

1.5. Solar-driven Supercritical CO_2 Brayton Cycle

Projects

2012/ASI020, 2014/RND040, ASTRI

Institutions

CSIRO, Queensland University of Technology, University of Queensland, University of Sydney, Sandia NL, NREL, Toshiba, Abengoa, 8 Rivers, Chinese Academy of Science

Key Researchers

Robbie McNaughton, Wes Stein, Hal Gurgenci, Kamel Hooman, Ted Steinberg, Emilie Sauret, Ali Abbas

Aims and Objectives

The supercritical CO_2 (sCO_2) Brayton cycle is a new power cycle technology currently under development. The technology promises a step change in energy conversion efficiency compared to conventional steam turbine power cycles, while operating at significantly lower temperatures than air Brayton and combined air/steam power cycles. In addition, the sCO_2 cycle promises a strongly reduced footprint due to the compactness of the turbine. These features render it potentially highly suitable for integration with concentrated solar thermal energy and thermal energy storage.

Outcomes and Current Research

Project 2012/ASI020 "Solar-driven Supercritical CO_2 Brayton Cycle" aimed at advancing the solar-driven sCO_2 power technology by integrating advanced power cycle components into a closed solar-heated sCO_2 test loop.

On-sun operation of sCO_2 solar receiver at CSIRO's tower facility, Newcastle, NSW (image: CSIRO).

A major achievement of the project was the successful completion and on-sun operation of the sCO_2 flow loop at CSIRO's concentrating solar tower test facility. The main system components included a new solar receiver to heat sCO_2 to 650°C, a sCO_2 pump operating at 20 MPa, high-pressure heat recuperators and a thermal storage system.

A major finding from the project was that the conditions under which sCO_2 is required to operate within the power cycle result in short life spans for traditional seal materials. This was identified within the reciprocating pump seals and valve seats, which were observed to deteriorate at an advanced rate. CSIRO continues to experiment with the sCO_2 system and is working with manufacturers of pumps and developers of seal materials to better understand the behaviour and mechanisms of attack for sCO_2 in the presence of carbon-based seals materials.

This project built on CSIRO's previous experience with solar-driven Brayton (gas) turbine power cycles, for example through the Solar Air Turbine Systems project (2010/ASI044). Ongoing R&D on advanced power cycles is underway within the High Efficiency Solar Allam Cycle project (ARENA 2014/RND040).

Strong synergies also exist with the ASTRI program which is designed around the sCO_2 power cycle. The ASTRI program encompasses complementary R&D on a sCO_2 power system, including development of a new radial turbine and a hybrid (dry/wet) cooling system and techno-economic power plant modelling and optimisation (UQ). The sCO_2 flow loop developed at CSIRO's solar tower facility provides a framework for further on-sun testing of new sCO_2 technologies.

Benefits

SCO_2 power cycles have potential cycle efficiencies of over 50%, compared to around 42% with current sub-critical steam turbine power cycles, at temperatures of around 700–800°C. This step change in efficiency allows the solar field (heliostat field, receiver, tower) and balance of plant to be reduced accordingly, resulting in significant reductions in capital and O&M costs and hence in levelised cost of electricity. SCO_2 cycles further promise to be compatible with next-generation thermal energy storage technologies based on solid particles, phase-change materials or high-temperature molten salts.

Commercial Interest

The sCO_2 power cycle technology is currently still in the R&D phase. CSIRO and others have a track record of successful commercialisation of proprietary CST technology, such as solar field technology. Research collaborations with large industrial partners have been established, which may be leveraged for future commercialisation of new sCO_2 power cycle technologies. This work is very much a part of international efforts and the Australian researchers are joining with US colleagues under the DOE funded Gen 3 CSP program.

1.6. Vast Solar Grid-Connected CSP R&D Facility with Thermal Energy Storage

ARENA Projects

2011/PFD007, 2012/ASI046, 2013/ERP070

Institutions

Vast Solar with Twynam Agricultural Group, Doosan-Skoda Power, Essential Energy, MACCSol, University of New South Wales, Royal Melbourne Institute of Technology

Key researchers

James Fisher, Nicholas Boerema and others

Vast Solar's CST demonstration power station in Jemalong, New South Wales (Source: Vast Solar)

Aims and Objectives

The 6 MW_{th} demonstration aims to provide vital information and learnings about the integration of sub-systems to form a safe and reliable operating CST generation plant (1.1 MW_e) with integrated thermal energy storage.

Outcomes and Current Research

Vast Solar has developed innovative designs for components of a CST power plant based on multiple modular field and small towers. These high efficiency/low cost components offer the potential for reductions in the cost of electricity from CST power plants.

The project involves 3,500 heliostats (mirrors) in five solar arrays, a thermal energy storage system comprising a 'hot tank' (565°C) and a 'cold tank' (over 200°C), a steam turbine electrical generation system, and a novel, modular air-cooled condenser technology.

The CST pilot power plant was commissioned and connected to the main-grid in 2017 and has since undergone performance and operational testing and optimisation.

Benefits

This demonstration project is the next phase of Vast Solar's commercialisation program. The project provides data to further validate system costs and performance. This allows for a progress assessment against Vast Solar's aim of achieving $100 per megawatt hour of electricity for utility-scale CST power plants.

This project is one of the first demonstrations globally of the use of sodium as a heat transfer fluid in a fully functioning pilot power generation facility.

Commercial Interest

This project is the most high profile CST effort driven by a private company. When the 1.1 MW_e pilot plant has been fully debugged and has demonstrated sufficient reliable continuous operation, it will allow Vast Solar to move on to its plans for a scale up to a 30MW_e plant. It will be a necessary prerequisite for raising the capital for such a next stage project.

Early Career Researcher Profile

Dr Nicholas Boerema – Industry Collaboration PhD Scholar

Nick Boerema has a BE in Renewable Energy Engineering from UNSW.

From 2011 to 2015, as a PhD student, he worked at Vast Solar's demonstration facility in Jemalong, NSW, where he worked on technology development including new sodium receiver designs. In addition, he developed operational procedures for the operation of the plant. He has published 3 journal papers on receiver design.

Currently, Nick works in Cambodia on financial services for environmental and renewable energy projects.

"ARENA's support allowed me to gain sector knowledge on the state-of-the-art for research, development and commercialisation of solar thermal technology, and to connect with researchers and industry leaders."

1.7. Integrated Solar Radiation Data Sources over Australia

Institutions

CSIRO, BoM and NREL

ARENA Project

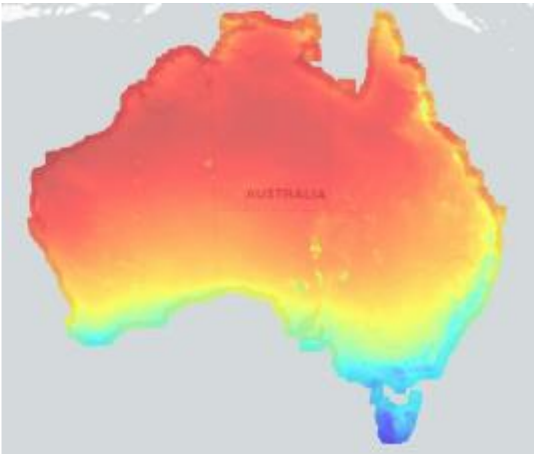
2013/ERP047

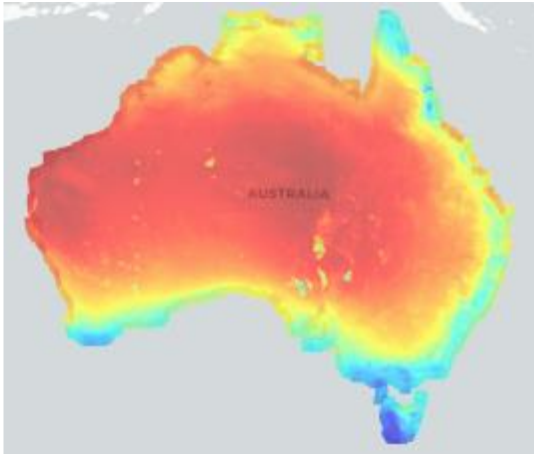
Funding

ARENA:	$712,000
Total project:	$1,437,000
Duration:	November 2012 to August 2015

Key Researcher

Dr Alberto Troccoli





Annual average daily Global Horizontal Irradiance (11 to 23.5 MJ/m2/day) and Direct Normal Irradiance (9.5 to 27.5 MJ/m2/day) maps of Australia, from AREMI.

Aims and Objectives

High quality information about historical solar radiation assists investors assess the forecast output of solar technologies and the seasonal and yearly variability. Detailed information is critical to securing finance, estimating power production and negotiating Power Purchase Agreements.

Outcomes

This project built upon the outcomes of Geoscience Australia and BoM's Solar Resource Mapping Project that involved developing better satellite models and deploying eight solar monitoring stations at selected sites.

Solar data was collated to provide definitive information for solar developers. Project developed an integrated solar radiation data set at 30 minute and 10 km resolution. High resolution (1 min) solar data has also been produced for several sites.

Benefits

This project led to a significant improvement in the availability of published solar data.

It also led to several follow on projects including:

- APVI's *Development of an Australian PV output map* project which tracks distributed PV capacity and performance and won a National Energy Globe Australia award.
- ANU's *PV output forecasts for DNSPs which provides real-time PV output forecasts for network operators.*

It also was a key component of developing:

- AEMO's Australian Solar Energy Forecasting System, and
- AREMI's solar data layers, see: http://nationalmap.gov.au/renewables/

Commercial Interest

The solar data sets that are now publicly available allow for feasibility studies and improved confidence in solar output forecasting by correlating solar data gathered on site with observed measurements and historical data.

Comments

This research has been an essential component of planning and facilitating investments in large PV systems around Australia. It also assists with the development of Concentrating Solar Power and solar thermal industrial heat projects.

1.8. CloudCam - Cloud Detection and Prediction for Maximising Solar PV Utilisation in Off-grid Hybrid Power Systems

Institutions

Fulcrum3D and Epuron Solar

ARENA Project

2013/ERP047

Funding

ARENA:	$452,000
Total project:	$1,110,000
Duration:	April 2014 to December 2016

Key Researchers

Martin Poole

CloudCam system and sample sky image.

Aims and Objectives

This project involved the development and demonstration of a sophisticated cloud tracking technology. The aim was to develop a real time and short term PV output forecasting solution that performed better than existing optical sky cameras, particularly in identifying cloud height and separating out layered clouds.

Outcomes

Fulcrum3D have developed a commercial product and an associated suite of tools that allows for accurately predicting near-term changes in PV output using cloud characteristics and velocities. The software allows for various sampling frequencies, predictions for the next 15 minutes and statistical analysis that allows for accuracy assessments based on current conditions.

Benefits

Effectively tracking clouds and predicting near-term PV output allows for higher penetration of PV in diesel mini-grids by optimising the use of diesel generators. It also has benefits for control systems and design options for incorporating batteries in hybrid diesel mini-grids.

The sky camera technology has been significantly improved and customized for PV applications, so that now it can be used for large, grid-connected PV systems.

Commercial Interest

A patent application has been prepared.

Comments

This world leading research has increased the amount of PV that can be incorporated into diesel mini-grids and assisted with increasing the forecast life of any batteries. Epuron's trials across three sites in the NT provided valuable learnings, including the need to consider insect activity on the camera lens.

CSIRO is also working on cloud prediction technology but with the aim of releasing a lower cost product. Other private companies are also developing competing sky camera products and software tools.

Due to the significant financial benefits, this technology is expected to become standard, particularly for large PV systems in diesel mini-grids. It is also likely to be deployed in some, grid-connected PV applications.

1.9. Consumer energy systems providing cost-effective grid support (CONSORT)

Institutions

ANU, TasNetworks, Uni of Sydney, Uni of Tasmania, Reposit Power

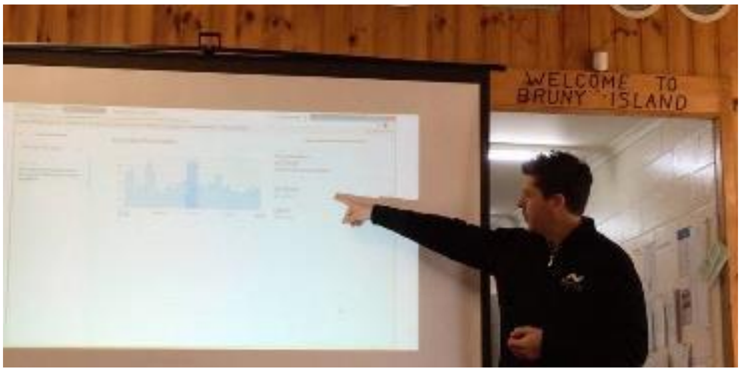
ARENA Funding

Ref No:	2015/RND006
ARENA:	$2.896m
Total project:	$7.992m
Duration:	April 2016 to June 2019

Key Researchers

Professor Sylvie Thiebaux, Dr Evan Franklin

Home of Bruny Island battery trial participant (photo credit: Jonathon Jones)



TasNetworks' Andrew Fraser speaking at a community event (photo credit TasNetworks).

Aims and Objectives

The CONSORT project aims to develop an automated control platform and new payment structures to enable distributed batteries to provide, and be rewarded for, providing support services for constrained networks.

Battery control system providers (such as Reposit Power) enable customers to participate in markets by managing the individual batteries on the customer's behalf. The Network-Aware Coordination (NAC) software being developed allows for each battery controller to receive forward pricing and demand signals that are continuously optimised according to network conditions.

Outcomes

This project is ongoing so the results discussed below are preliminary.

Consultations have revealed that some participants' understanding of how the Reposit optimisation system works is lacking. This has led to participants modifying their electricity consumption patterns based on battery behaviour. However, as the Reposit system optimises battery behaviour on the basis of previous consumption patterns, among other inputs, this may cause sub-optimal economic outcomes.

For many participants, backup power is a critical feature of their system. However, use of batteries as backup is not currently taken into account by Reposit Power's optimising controllers.

Benefits

This project is likely to lead to new ways of controlling and optimising the benefits of distributed batteries.

Commercial Interest

This project is due to be completed in June 2019, so it is too early to assess the commercial opportunities that may arise from Network Aware Coordination software.

Comments

This research is assisting Reposit Power further develop their battery control software. The project may lead to new ways to manage peak demand events on Bruny Island and other constrained, fringe-of-grid locations.

2. SOLAR TECHNOLOGIES – BRIEF TECHNOLOGY OVERVIEW

2.1. Photovoltaics

Photovoltaic (PV) technology converts the energy in sunlight to direct current (DC) electrical energy within an absorbing material, such as silicon. Incident sunlight energy liberates electrons normally bound within the atomic structure of the absorbing material, and these electrons are collected via an electric field intentionally introduced into the material to form a *solar cell*. Cells are interconnected in series to boost the voltage to usable levels, typically by metal conductors between cells.

Many cells types (crystalline silicon, for instance) are brittle and prone to mechanical breakage, while most of the thin film materials are prone to degradation by exposure to moisture or air, as are the metal interconnections. It is thus important to protect the interconnected cells in a process called "encapsulation", where cells are mounted behind or onto a supporting platform (typically highly transparent glass) and encased in an optically transparent soft plastic. Electrical outputs are protected in a junction box and the completed assembly is called a *solar panel* or *solar module*. Modules in turn can be interconnected to form *solar arrays*.

The electrical current produced from PV cells, modules or arrays can be connected through an external circuit and used to perform electrical work with no noise or other emissions and no mechanical movement, as illustrated in Figure 1.

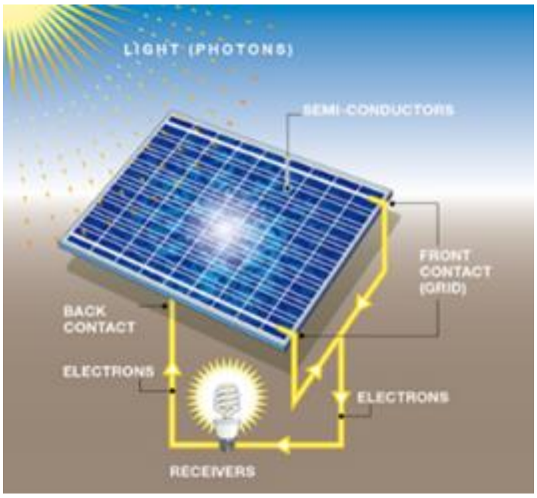


Figure 1: Schematic of a solar module connected to an electrical circuit (Source: Total.com).

2.1.1. PV efficiencies

PV cell or module efficiencies describe the amount of incident light energy which is converted to electricity. Higher solar cell efficiencies mean that the same electricity output can be achieved from a smaller module. This in turn means reduced areas needed for deployment and hence also reduced material requirements for "balance of system" components, such as support frames and cables. The latter flows through as per kW cost savings from cells to modules, to distribution and final system costs. Not surprisingly, increasing efficiency while not increasing costs is often a key aim in PV research. Efficiencies of commercial solar modules are currently typically 17 to 22%, with the higher efficiency modules tending to be more expensive.

2.1.2. PV Materials

There are several classes of PV relevant semiconductors, and many suitable materials or material combinations. The first and major type distinction is between inorganic and organic PV materials. *Inorganic semiconductor* materials include a range of elements and are typified by silicon (Si) which currently dominates the PV industry. Other important inorganic PV materials are silicon-like compound alloys, most notably gallium arsenide (GaAs), cadmium telluride (CdTe), the chalcogenide copper-indium-gallium-selenide (CIGS) and kesterite copper-zinc-tin-sulphide (CZTS).

PV cells from these materials can be fabricated into either relatively thick, discrete crystalline building blocks (silicon wafers, for instance, which are used for the majority of commercial PV products) or quasi-continuous thin film layers, typically deposited onto supporting substrates which can be rigid or flexible (plastic or thin metal foil). Such thin film materials include amorphous silicon (a:Si), and the compound alloys noted earlier (CdTe, CIGS and CZTS).

The other major PV material type is *organic PV*, or OPV, where the active components are carbon-based organic semiconductors. At present, these materials are significantly less efficient in the conversion of sunlight into electricity than the inorganic semiconductors and require the use of very thin, often mixed, polymer compounds. They are, however, flexible and potentially very cheap to manufacture.

A newly emerging and highly promising third type of material is a combined *inorganic-organic class of materials* currently broadly denoted as “perovskites” based on their crystal structure. These are metal-organic halide materials, such as methyl ammonium lead tri-iodide ($CH_3NH_3PbI_3$), which promise simple and cheap fabrication with conversion efficiencies approaching those of established inorganic PV materials. They currently, however, have the disadvantages of incorporating toxic lead (Pb) and suffering extreme sensitivity to environmental exposure (including moisture-based dissolution).

2.2. Concentrated Solar Thermal Systems

Solar thermal technologies convert sunlight to useful heat. Most people are familiar with the solar hot water systems for household rooftop use. Concentrating Solar Thermal (CST) systems, however, use systems of mirrors to focus the direct beam solar radiation to smaller areas and achieve higher temperatures. CST systems are suitable for industrial process heat, large thermal power stations as well as thermochemical processes.

CST power systems almost exclusively use steam turbines to generate electricity in a similar manner to coal fired power stations. There are other power cycles that are the subject of R&D activities and may offer advantages over steam turbines.

To obtain high temperatures for electricity generation, there are four main CST technologies – linear Fresnel, trough, tower and dish, as described in Table 1. While trough plants have the longest track record of operation and account for the bulk of systems deployed, tower plants are emerging as a more favoured option, due to the higher temperatures and efficiencies as well as cost-effective energy storage that has been achieved. Linear Fresnel and dishes have their own advantages and are also being actively pursued.

There are also smaller concentrator systems for industrial process heat. These can be installed on commercial rooftops. Troughs, linear Fresnel and systems with non-tracking compound mirrors are all applied for this purpose.

Table 1: The main CST technology types[1]

Parabolic trough **100 - 450ºC**		The tubular receiver is fixed to the focal line of the array of parabolic mirrors, which track the sun along one axis throughout the day. Trough systems can heat a heat transfer fluid such as synthetic oil, or generate steam directly for process heat or power generation.
Linear Fresnel **100- 450ºC**		Removing the need for a moving receiver and flexible couplings, the Linear Fresnel system is similar to a trough concentrator in that it provides heat over the same temperature range. Long, semi flat mirror strips in parallel rows track the sun independently, to focus direct beam radiation on a linear focus that is fixed on a non-moving tower.
Heliostats and tower **300 - 2000ºC**		For higher temperatures, the heliostat field plus tower arrangement is available. Many Individual mirrors on double-axis tracking devices are all simultaneously moved to reflect sunlight to a single receiver on a tower, which typically reach temperatures of around 600°C. In principle, much higher temperatures can be obtained.
Dish **300 – 2000ºC**		A mirrored paraboloidal dish system can also offer high temperatures and with a higher efficiency than tower systems. However, this approach is less commercially mature than tower systems.

2.2.1. Key CST subsystems

CST plants are complex, integrated systems made up of a series of subsystems as illustrated for the particular case of a molten salt tower plant in Figure 2. The key subsystems roles are:

- The mirror field gathers solar radiation and directs it to a focal point by tracking the sun during the day.
- The receiver intercepts the reflected radiation and converts it to high temperatures.
- The heat transfer fluid system takes heat from the receiver and transports it to storage and/ or the power block.

[1] ITP, 2012, Realising the Potential for Concentrating Solar Power in Australia, for the Australian Solar Institute.

- The thermal storage subsystem, that is typically based on two tanks of liquid salt but can use other processes.
- The power block and associated equipment for generating electricity, typically a steam turbine.

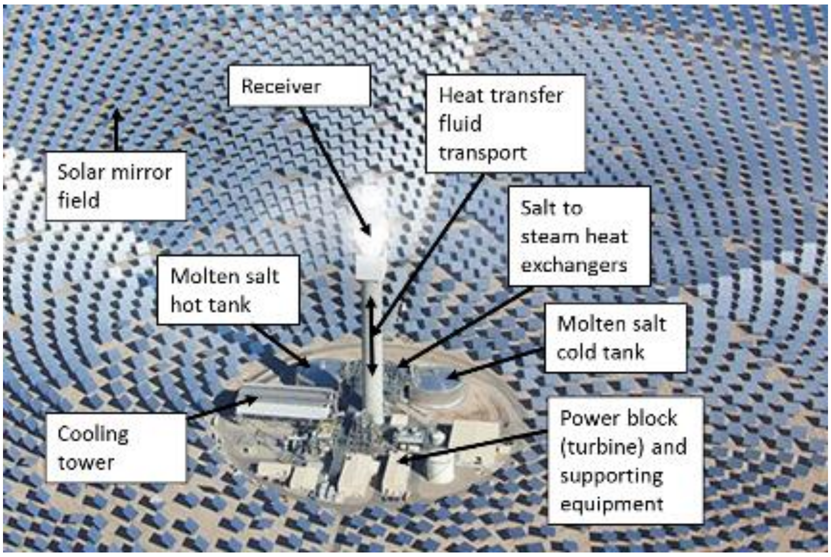


Figure 2: Subsystems in a molten salt tower plant.

CST power plants are attracting increasing interest due to their ability to store large amounts of energy and provide dispatchable electricity supply. The current industry standard approach is to use a use a mix of molten nitrate and potassium salts as a heat storage medium that is moved between a ‘cold’ tank at around 250ºC to a ‘hot’ tank at 400ºC or 600ºC, depending on the concentrator type. Many other thermal storage approaches are the subject of investigation.

At scale, thermal storage such as molten salt heat storage has significant cost advantages over many other storage technologies for electricity, such as batteries. This is now increasingly important as levels of variable generation increase in electricity markets.

2.3. Enabling

This report also classifies some research as enabling. This includes research into activities such as solar resource mapping, forecasting and monitoring tools which can benefit both PV and CST. There are also enabling research projects examining regulatory and network issues, community acceptance and ownership models.

In addition, there are enabling projects that are specific to PV or CST. For example, a project researching and developing cloud prediction and tracking technologies for the diesel mini-grid market could be classified as PV. However, as the predominant research is about cloud tracking and prediction, it has been classified as enabling. Similarly, a research project developing drones for inspecting large PV arrays is an enabling project as the predominant research is on the camera and drone software.

Another example is a project researching and developing advanced control systems for distributed batteries, which could be classified as PV. However, for this report it has been classified as enabling. To be consistent with this approach for batteries, a project researching sodium as a thermal energy storage technology has also been classified as enabling.

3. GOVERNMENT SOLAR R&D SUPPORT

Government support for early stage R&D is critical in all sectors and has been significant in the growth of many new industries and products worldwide.

The Australian Government supports research and development in a variety of ways, including through the Australian Research Council, industry research and development tax incentives and specific purpose allocations. This report examines solar R&D projects supported by:

- the Australian Solar Institute (ASI), August 2009 to December 2012, and
- the Australian Renewable Energy Agency (ARENA), July 2012 to December 2017.

3.1. ARENA Objectives

ARENA was established on 1 July 2012 by the Australian Renewable Energy Agency Act 2011. ARENA has two objectives:

- To improve the competitiveness of renewable energy
- To increase the supply of renewable energy in Australia

How ARENA plans to achieve these objectives is illustrated in Figure 3.

Figure 3: Accelerating Australia's shift to secure, affordable and reliable renewable energy (Source: Innovating Energy – ARENA's Investment Plan 2017).

ARENA funds projects across the innovation chain - from research to pre-commercial deployment. This funding is focused on finding and demonstrating first-of-a-kind renewable energy solutions, which reduce technical and commercial risks and grow Australia's renewable energy knowledge and expertise. Renewable energy solutions include hybrid, related or enabling technologies. This means ARENA may fund solutions, such as storage, demand response, energy efficiency, electrification and fuel switching, where they could help grow the supply of renewable energy in Australia.

Research support is available through the Research and Development (R&D) Program funding rounds and strategic research initiatives. The scope of the ARENA's funding streams are illustrated in Figure 4. ARENA also manages legacy projects from the ASI, the Australian Centre for Renewable Energy (ACRE) and the Department of Resources Energy and Tourism (including the Solar Flagships program).

Figure 4: Current ARENA programs and their scope across the technology development pipeline (Source: Innovating Energy – ARENA's Investment Plan 2017)[2].

ARENA'S approach to investment is set out in detail in the investment plan published by ARENA from time to time. The investment plan describes ARENA's funding programs and initiatives and the priority areas for investment. A review of ARENA's investment priorities was undertaken in 2016-17 and the following priority areas were identified:

- Delivering secure and reliable electricity
- Accelerating solar PV innovation
- Improving energy productivity
- Exporting renewable energy.

ARENA projects funded from 2017 will build on the investments made in the earlier priority area "Building next generation solar".

[2] https://arena.gov.au/assets/2017/05/AU21397_ARENA_IP_Document_FA_Single_Pages_LORES.pdf

3.2. ARENA Program Funding

ARENA was established with funding of $2.522b until 2019-20.[3]. The budget has been amended several times and is now less than $2b over the period to 2021-22.

As of December 2017, more than $1.1b had been spent or committed for projects. This funding supports a range of activities and an indication of the investment types is shown below.

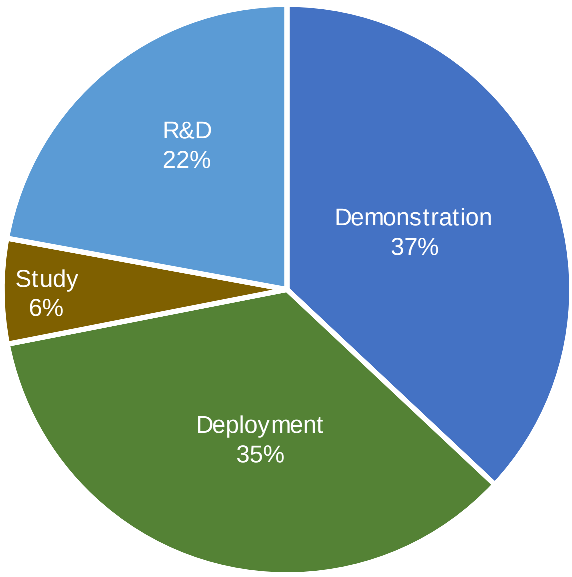


Figure 5: ARENA Project funding spent or committed to December 2017 by category, ITP analysis[4].

The solar R&D investment examined in this report is the majority of the R&D segment above, with some relevant studies and pilot demonstration projects. It is important to note that demonstration and deployment projects may also include R&D components, but the projects are usually classified according to the predominant project activity. Bioenergy, marine and hydro energy R&D projects are not included in this report's analysis.

3.3. Background to ARENA's Solar R&D Activities

The current portfolio of ARENA solar R&D projects has its origins in the formation of the ASI in 2009. The ASI was initially set up to deliver:

- $50m for photovoltaic R&D, and
- $50m for concentrating solar thermal R&D.

[3] https://www.legislation.gov.au/Details/C2012C00629

[4] ARENA inherited financial commitments from a range of sources including the Australian Solar Institute and the Department of Resources, Energy and Tourism.

Central to the subsequent evolution of ASI and ARENA's R&D activities was the role of three core institutions:

- the Commonwealth Scientific and Industrial Research Organisation (CSIRO),
- University of New South Wales (UNSW), and
- Australian National University (ANU).

CSIRO had most of its activities in the concentrating solar thermal (CST) area, with a smaller effort in PV. UNSW was almost exclusively PV and remains the largest PV R&D effort in Australia. ANU had a split of activity, with its PV group being about four times larger than its small but well known CST group.

The rationale for the two separate $50m commitments to PV and CST was different:

PV research at UNSW and ANU has a long history and the groups were relatively well resourced, large and with extensive laboratory facilities. The $50m commitment was about maintaining this position of excellence and building upon it.

CST research activities were an order of magnitude smaller in terms of resourcing and numbers of personnel involved. The $50m commitment represented a major strategic decision to substantially grow an area in which the country had a well-recognised expertise but not a large base of facilities and staff to take it forward. Without such facilities, leading Australian researchers needed to go overseas to further develop their technologies, which reduced the long-term benefits for Australia.

Using the $100m, ASI provided funding for:

i) Foundation projects aimed at establishing research infrastructure ($10m).

ii) Enabling projects examining socio-economic and market issues ($1.9m).

iii) Three solar R&D calls focussed on:

   - Improved cost effectiveness ($27m),
   - Pre-commercial technologies ($20m), and
   - CST hybrid and storage systems ($12m).

iv) International collaborative solar research projects with:

   - Germany ($3.76m), and
   - USA.

The Australia - US Institute for Advanced Photovoltaics (AUSIAPV) was established and is now coordinated via the Australian Centre for Advanced Photovoltaics (ACAP), with ARENA funding of $33.1m, which was increased to $46m in 2017. A parallel Australian Solar Thermal Research Institute (ASTRI) was established for CST research, with funding from ASI and ARENA of $35m.

3.4. ARENA's R&D Program

Three specific calls have been made for R&D projects, targeting the Technology Readiness Levels 2 to 6: basic principles through to prototype development (See Appendix A for TRL definitions). R&D rounds have been two stage processes – Expressions of Interest (EOIs) and then full applications for those short-listed at the EOI stage.

3.4.1. R&D Round 1: Solar Excellence – announced 13 December 2013

Round 1 grants were aimed at providing support for excellent R&D projects in priority renewable energy technologies that:

- Maintain or build on Australia's world class research
- Show commercial viability
- Address conditions specific to Australia
- Support growth of skills, capacity and knowledge for Australian RE technology R&D.

This was a very competitive round with 110 EOIs and 25 full applications received. Funding recipients were announced in August 2014[5].

The projects funded ranged from enhancing existing technologies to advancing emerging technologies in solar photovoltaics, solar thermal and solar storage. The projects' total value was $70.5 million. ANU was the lead for 5 projects, CSIRO 3 projects, UNSW 3 projects and UTS 1 project. The 12 successful projects were allocated total funding of $21.5m.

R&D Round 1 grant funding and total project value by research area is shown in Figure 6.

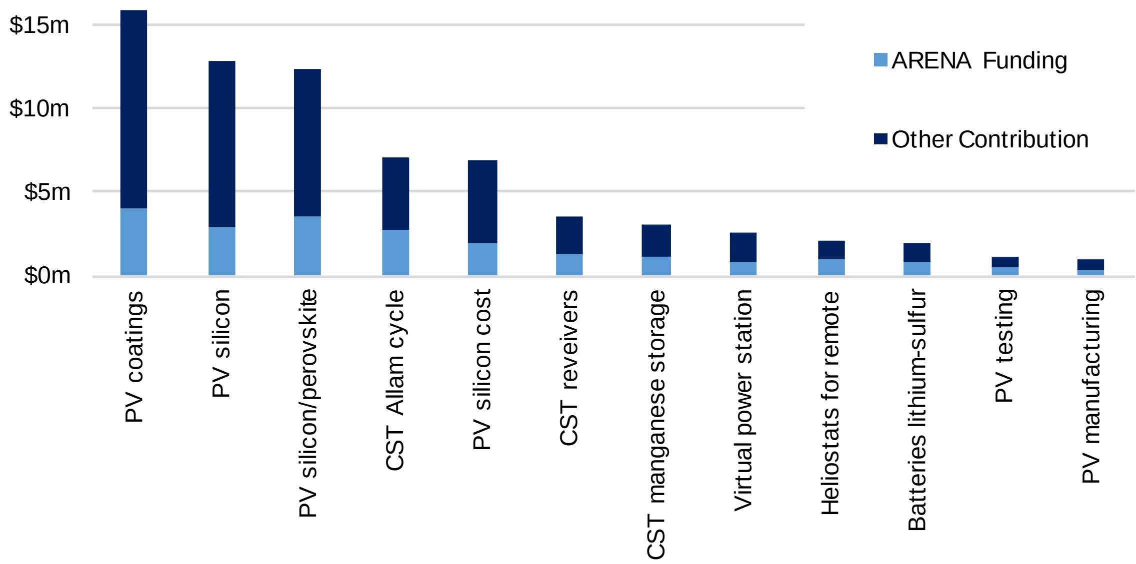


Figure 6: R&D Round 1 Funding and Total Project Value ($70.5m) by research area.

[5] https://arena.gov.au/assets/2017/02/140826-MEDIA-RELEASE-ARENA-supporting-brights-ideas-in-solar-RD.pdf

Allocation of grant funding by lead organisation is shown in Figure 7.

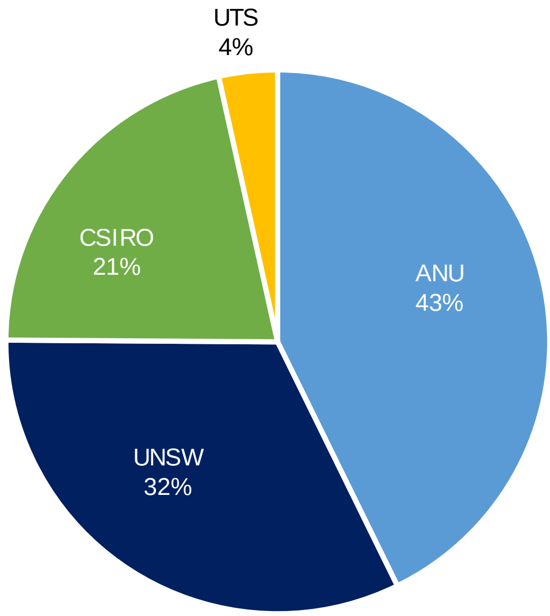


Figure 7: R&D Round 1 Grant funding allocation ($21.5m) by lead organisation.

3.4.2. R&D Round 2: Industry-Researcher Collaboration – announced 13 April 2015

The second round of the R&D Program promoted industry and research partnerships to develop and commercialise renewable energy technologies and to provide a broader range of energy options to reduce future energy costs. Key technology focus areas were:

- Balance of System (BoS) cost reduction (either on-grid or off-grid)
- Integration and high penetration of renewables into networks (either on-grid, off-grid or mini-grids)
- Integration of renewable energy for industrial process (excluding electricity generation)
- Integration of renewable energy into buildings or building materials.

Eighty-nine EOIs and 23 full applications were received. Nine successful projects were announced in April 2016[6]. A total of $17m in grants was allocated, with grants in the range $0.875m to $4.5m. The total project value of the successful projects was $54.1m. Removing the bioenergy and wave research projects, the total solar R&D grant was $13.9m with total solar R&D project value of $44.8m.

[6] https://arena.gov.au/assets/2017/02/160413_MEDIA-RELEASE-ARENA_RD-industry-collaboration-bringing-ideas-to-the-market.pdf

The solar research areas funded and lead organisations are shown in Figure 8 and Figure 9.

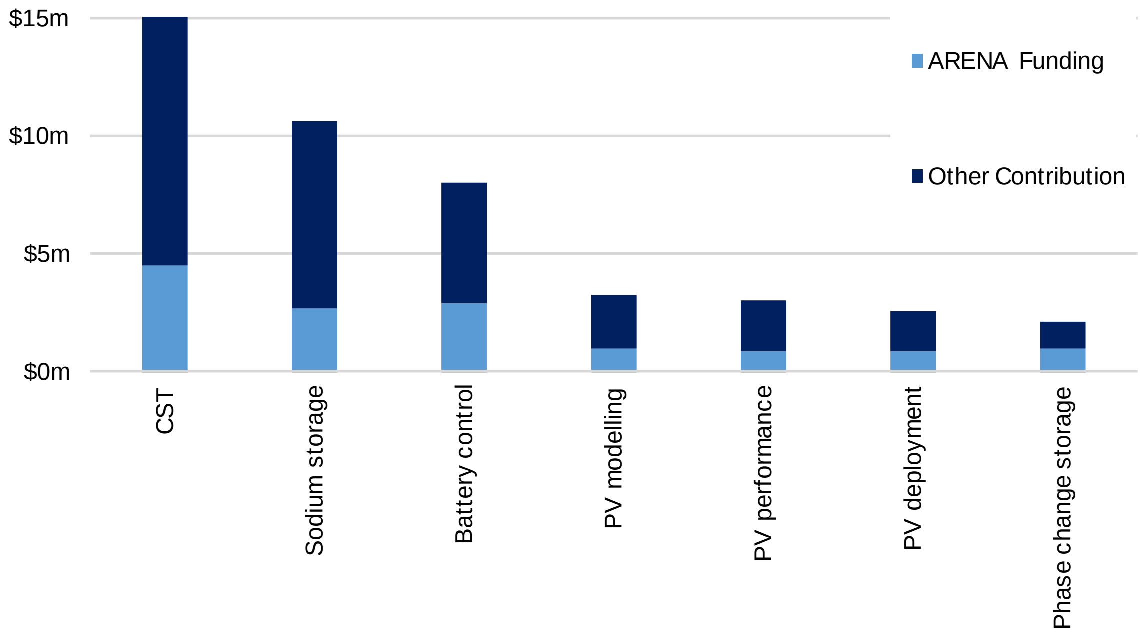


Figure 8: R&D Round 2 Solar Funding and Total Project Value ($44.8m) by research area.

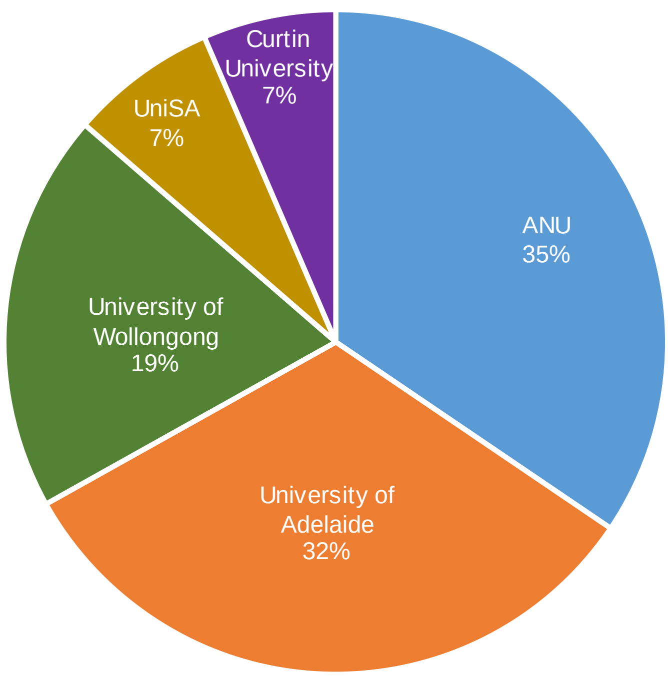


Figure 9: R&D Round 2 Funding Allocation ($13.9m) by lead organisation, (excluding biomass and wave projects).

3.4.3. R&D Round 3: Accelerating Solar PV Innovation – announced 23 May 2017

The third R&D round focussed on one of the new ARENA priority areas: accelerating solar PV innovation, with applications called for under the following criteria:

- Have TRL between 2 and 4 at the project start, and
- Reduce the future cost of solar PV deployment through R&D on:
  - established and emerging solar cell technologies, including lower cost materials, and/or improved efficiency and/or stability and/or reliability and/or scalability,
  - established and emerging solar module technologies, including lower cost materials, and/or improved efficiency and/or reliability and/or durability.

Sixty EOIs and 32 full applications were received. On 13 December 2017, the 20 successful projects were announced[7]. A total of $29.2m in funding was allocated with grants in the range $0.5m to $3.2m. The total project value was approximately $102m though the breakdown wasn't included in the media release.

The total project value by research aim and lead organisation are shown in Figure 10 and Figure 11.

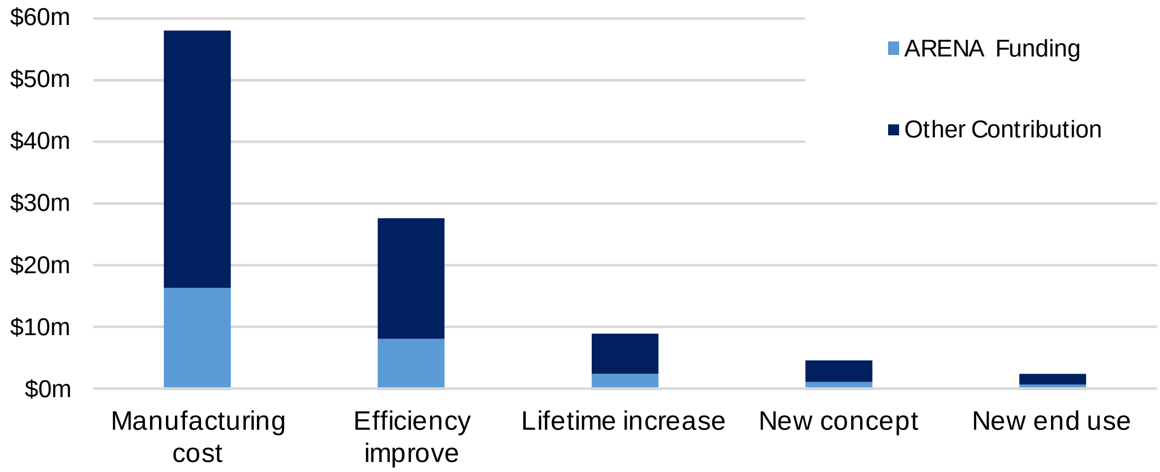


Figure 10: R&D Round 3 Funding and Total Project Value ($102m) by PV research aim.

[7] https://arena.gov.au/assets/2017/12/20171312_SOLAR-RD-ARENA-MEDIA-RELEASE-FINAL-1.pdf

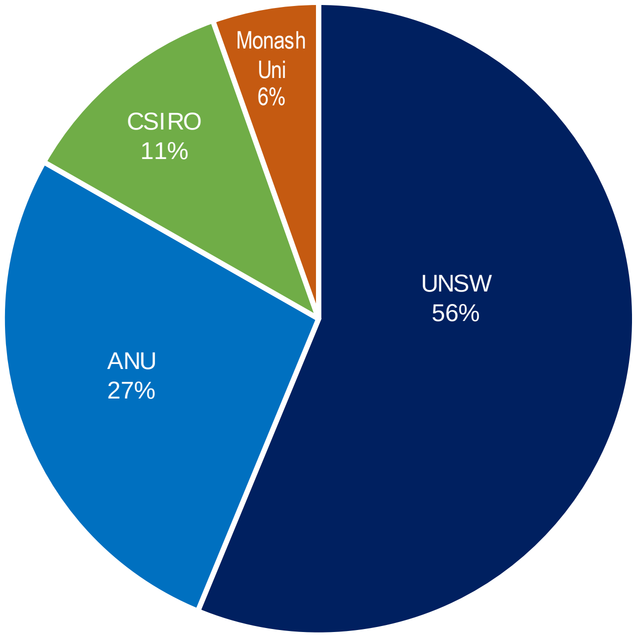


Figure 11: R&D Round 3 Funding Allocation ($29.2m) by lead organisation.

ASI and then ARENA have directly funded 35 PhD scholarships and 48 Postdoctoral Fellowships. Others have been funded indirectly via ACAP and ASTRI. The 86 PhD and Post-Doc grants analysed in this report received total funding of $18.1m. Further information on scholarships and fellowships is available from ARENA's website[8].

For many R&D projects, the ARENA awards have provided the key labour source for the research undertaken. They have therefore been crucial to the success of the initial projects and to maintaining high achieving students and early carrier researchers in Australia. The skilled research base created now comprise many of the lead researchers for new or extension projects subsequently funded.

PhD scholarships fell into two categories: top-up awards ranging from $20,000 to $50,000 for students in receipt of ARC or university scholarships; full scholarships ranging from $50,000 to $120,000 over 3 to 4 years.

For the Post-doctoral awards, funding provided ranged from $7,000 for short visits to international renewable energy institutions to over $400,000 for four year research projects.

[8] https://arena.gov.au/scholarships-fellowships/

4. ANALYSIS FRAMEWORK

The work undertaken for this study aimed to assess the inputs and the outcomes of ASI and ARENA support for solar R&D over the past decade. The methodology developed to do this is as follows:

a) provide consistent summaries of all projects,

b) survey recipients and assess the research and capability outcomes of the Scholarship and Fellowship program,

c) provide an analytical framework by which to assess:

  i) knowledge generated, disseminated, and lessons learnt,

  ii) increased industry awareness, understanding, commercialisation, and uptake,

  iii) improved application of solar energy solutions for end-users,

  iv) increased industry and research collaboration,

  v) overall value in enhancing the awareness, understanding and commercial uptake of related renewable energy solutions, and

d) prepare a synopsis of the solar R&D program outcomes as a whole, its contribution to ARENA's objectives and implications for future ARENA programs.

For project assessment, the approach taken was to develop a system of standard metrics by which each project could be documented and sorted, thus allowing overall program coverage and outcomes to be readily assessed.

Solar R&D projects to be included were selected from the ARENA Grants Management System, (GMS) database and the available information entered into a database. Additional information on ASI funded projects was added to the spreadsheet from analysis undertaken in 2012 by the Wyld Group[9].

The broad technology categories used for this review were:

Photovoltaics (PV)

Research into PV cells, modules and systems.

Concentrating Solar Thermal (CST)

Research into components or systems using mirrors to focus sunlight onto a receiver producing heat, which can be used for power generation, heat or fuels.

Enabling

Research into solar enabling projects such as resource mapping, forecasting and monitoring tools, regulatory analysis, grid integration, storage and ownership models.

[9] Summary report available at: https://arena.gov.au/funding/programs/australian-solar-institute-initiatives-asi/

The ACAP and ASTRI projects, each of which is a major, multi-participant program of work, were separated into their sub-components to also be added to the database. This led to a listing of 314 projects, with ACAP and ASTRI comprising 80 and 20 sub-projects respectively (note that the current ACAP project count is around 50, as projects have been terminated or consolidated). Table 2 shows the technology types and the programs under which they received funding.

Table 2: Numbers of Solar R&D Projects Included in Analysis by Technology and Program.

Program	CST	Enabling	PV	Total
ASI	20	17	31	**68**
PDF	15	4	67	**86**
ASTRI	20			**20**
ACAP			80	**80**
SHARE		1		**1**
R&D 1	4	2	6	**12**
R&D 2	1	6		**7**
R&D 3			20	**20**
ERP	6	8	5	**19**
ARP	1			**1**
Totals	**67**	**38**	**209**	**314**

New column headings were added to those from the GMS database and a range of keywords developed to facilitate standardisation and sorting. This led to 44 columns for each project where information could be entered.

Where available, project summaries, the latest milestone reports, Public Dissemination Reports or Final reports were obtained from ARENA. Information from these documents was entered into the spreadsheet, with any previous entries being updated if necessary.

Thus the metrics included in the project database are a combination of those in ARENA's GMS database, headings used in typical summary sheets and public dissemination reports, metrics used in the 2016 assessment and extra ones that were developed in order to undertake this assessment. The metrics included in the database are summarised in Appendix A.

4.1. Assessment of the Scholarship and Fellowship Program

To assess the Scholarship and Fellowship program, a comprehensive web-based survey was undertaken of all ASI and ARENA PhD and Post-Doc Fellowship recipients. Demographic and institutional information was sought, as well as information on research focus, research outcomes and outputs, and post-Fellowship activities. The Survey is reproduced in Appendix E.

Contact details were available for 34 Scholarship and 47 Fellowship recipients. Key institutions were contacted for further information on recipients who did not initially respond. A total of 33 responses were received.

5. OVERALL PROGRAM ASSESSMENT

Between 2009 and 2017, a total of $291m in funding was allocated to the 314 solar R&D projects assessed in this report. ARENA expenditure across the broad technology categories is shown in Figure 12. More detailed analysis follows.

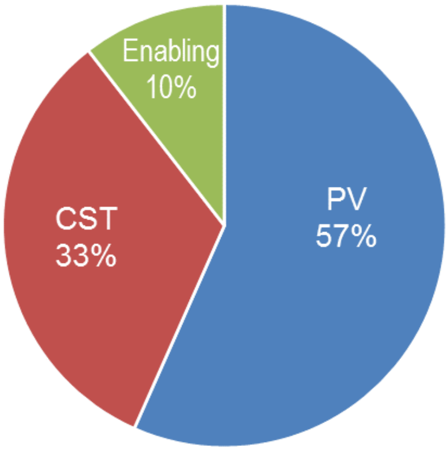


Figure 12: Allocation of $291 million ARENA R&D expenditure by technology area.

5.1. Contribution to ARENA's Purpose

ARENA's purpose is to accelerate Australia's shift to an affordable and reliable renewable energy future.

For this synthesis report, research projects were classified according to the following categories derived from ARENA's Investment Plan 2017:

- Improved affordability,
- Security and reliability,
- Innovation,
- Skills,
- Markets and regulation,
- Accelerating uptake,
- Improved energy productivity, and
- Exports.

The aim is to show how R&D project outcomes contribute to the broader outcomes that ARENA seeks to achieve by pursuing its investment priorities. These investment outcomes ultimately contribute to ARENA achieving its purpose.

Total R&D project investment by category is shown in Figure 13.

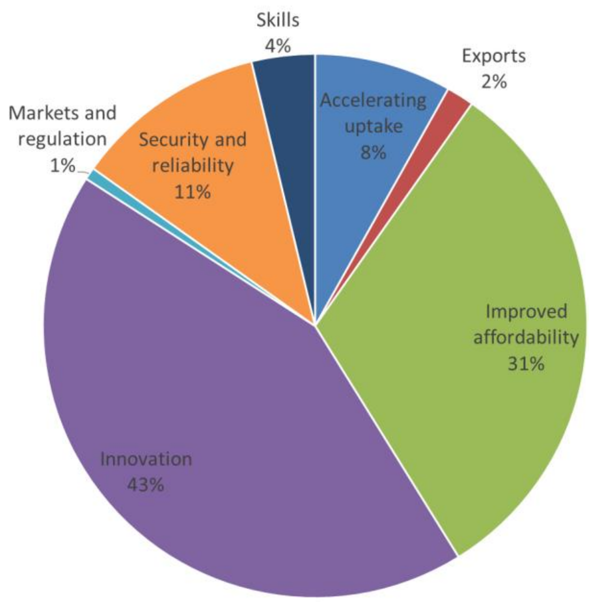


Figure 13: Total project expenditure ($752m) by category.

5.2. Key Achievements

5.2.1. Photovoltaics

While there are many new PV materials being developed in research laboratories around the world, as illustrated in Figure 13, Australian developments (highlighted) have focussed on the mainstream commercial PV industry, with the UNSW developed PERC cell expected to dominate the market over the next decade, as shown in Figure 14.

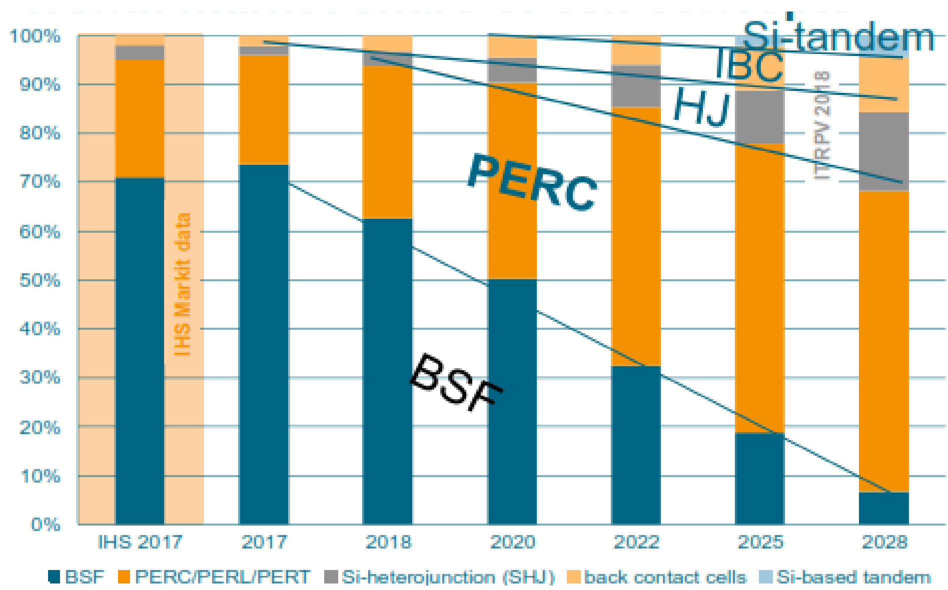


Figure 14: Trends in market share of cell processing concepts[10]

[10] International Technology Roadmap for PV (ITRPV), Ninth Edition 2018, http://itrpv.net/Reports/Downloads/.

Key achievements typically build on a long-term research commitment, with funding spanning many years and the establishment of well-functioning research teams. PV funding provided over the past decade has significantly improved Australian PV research facilities, maintaining UNSW's world leading role and bringing ANU and CSIRO facilities up to world class. This has facilitated a wider range of research projects and assisted in enhancing research-industry collaboration. Funding for PhD scholarships and Post-Doc fellowships has been critical in keeping top students and early stage researchers in Australia, which has further enhanced research outcomes.

The significance of achievements from early-stage research may not be evident for many years, nevertheless, some world-leading developments have been reported, including:

- A silicon defect hydrogenation process developed at UNSW which can be retrofitted into existing PV cell manufacturing lines to significantly increase the efficiencies of low cost upgraded metallurgical (solar grade) silicon wafers. In 2015, 20.9% PV cells were achieved from 'solar grade' silicon, compared to 21.9% for more expensive, co-processed electronic-grade silicon material.
- A concentrating PV system developed by UNSW and industry partners Raygen, AZUR Space, Spectrolab and Trina Solar, using a unique beam splitting device called the *Power Cube* which facilitates use of the wider spectral range covered by Silicon and III-V PV cells. In 2016, world record efficiencies of 34.5% with a flat plate, non-concentrating (one-sun) cell and 40.6% under concentration (nominally 365 suns[11]) were recorded on 4-terminal devices, and a near-term target has been set of 42% concentrating and well over 30% one-sun for larger area (800cm^2) devices utilising a newly introduced optical band-pass filter in the design architecture.
- Researchers at ANU have since fabricated commercial upgraded metallurgical grade (UMG or solar) silicon solar cells with demonstrated world-first solar cell efficiencies above 21% utilising the UNSW hydrogenation process. Further development of novel thermal pre-processing (Tabula Rasa anneal) and phosphorus gettering is expected to raise efficiencies to above 22%.
- The achievement at UNSW of independently verified world record performance of 10% conversion efficiency on 1cm^2 thin film CZTS (copper-zinc-tin-sulphide, kesterite) solar cells on soda lime glass and 11% efficiency on smaller area (<1cm2) devices, with promising results on coated flexible steel. In addition, CZTS/silicon tandem solar cells have demonstrated efficiencies of 22.7% on PERL and 19% on PERC silicon sub-cells, as well as an in-house measured 9.3% Cd-free device structure.
- Perovskite organic-inorganic solar cells are a very promising new technology, at the moment demonstrating poor stability and incorporating some high cost and/or toxic materials. ACAP has now combined the considerable and varied expertise of all of its nodes (two laboratories accredited for PV performance measurement (CSIRO Energy and NREL) and eight PV research laboratories, including the key nodes within ACAP (UNSW, UoM, Monash, UQ, ANU, CSIRO Manufacturing Flagship) and introduced a new program dedicated to perovskite research, specifically addressing basic material

[11] ACAP 2014 Annual Report p96

and device properties, utilisation of non-toxic, Pb-free material variants, understanding material stability and developing advanced encapsulation techniques, developing tandem device structures and scaling up device sizes in concert with manufacturing cost analysis. Progress to date has been very promising, with the demonstration of larger area (>1cm^2) devices of certified efficiency 19.6% on a 1.02cm2 cell, development of a low-cost glass-glass encapsulation technique capable of protecting formadinium lead halide (FAPbI) cells to IEC6122016 thermal cycling standard, and demonstration of small area flexible, roll-to-roll (R2R) printed cells of 11.6% efficiency.

- High efficiency tandem or multi-junction cells on a silicon sub-cell developed at UNSW using a variety of top-cell layers include perovskites, the previously noted kesterites (CTZS), III-V materials, such as GaAs, and organic semiconductor (OPV) top cells. Results to date include a triple junction 2-terminal InGaP/GaAs top cell bonded to Si with efficiency 23.2%, with recently developed external surface texturing boosting Jsc by nearly 1mA/cm^2 and absolute efficiency by more than 2%. Other results include a 22.67% CZTS tandem on PERL silicon sub-cell and 19.04% on Si PERC by the spectrum splitting method, small area 4-terminal stacked perovskite on silicon tandem of efficiency 26.9% and 1cm^2 2-terminal monolithic device of efficiency 26.9%. Promising work is also underway with concatenated organic-perovskite and organic-organic tandem cell structures.
- Progress on organic semiconductor based (OPV) solar cells continues with a range of promising new materials under development at the University of Melbourne, University of Queensland and University of NSW, and successful translation at CSIRO of reported high efficiency PPDT2FBT to R2R slot-die coated devices of 7.1% efficiency on PET film and non-fullerene-based polymer cells batch slot-die coated on glass of 10% efficiency, with all print processing at industrially relevant ambient conditions.

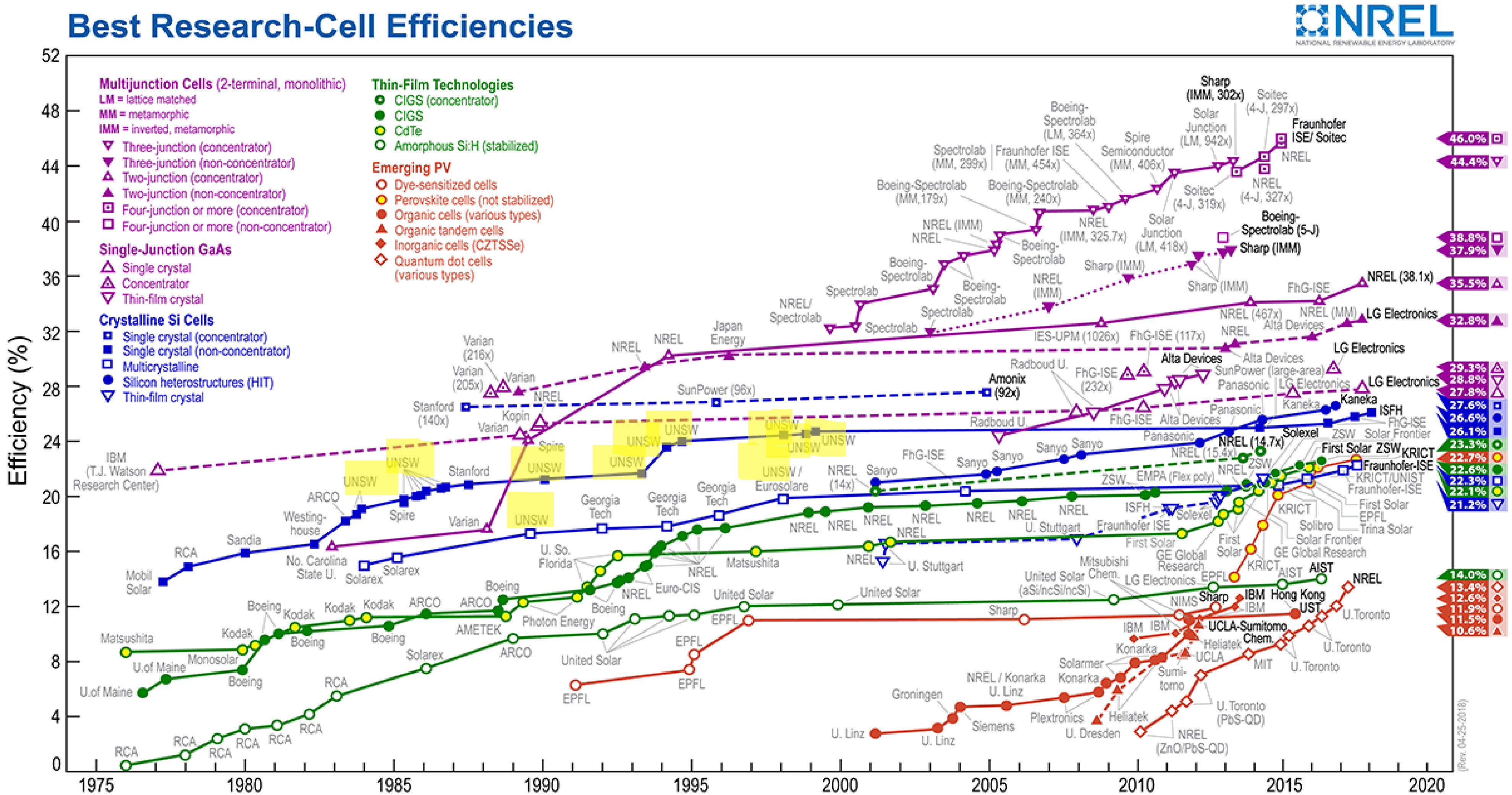


Figure 15: PV Cell types and efficiencies over time (NREL, 2018)[12]

[12] From: www.nrel.gov/pv/assets/images/efficiency-chart.png

5.2.2. *Concentrating Solar Thermal*

Overall, the major impact of the ARENA-administered investment in CST R&D in Australia has been a significant increase in capability in the area. The activity is certainly world competitive and, for some projects, world leading.

As well as a major strengthening of the CST research groups at CSIRO and ANU, there are now strong groups at UniSA, UQ, UoA and RMIT. The results of this work are projects that end at a range of TRLs. The research groups publish widely and are well linked in with all the key international groups.

It is hard to predict the exact trajectory of the technology from individual projects as few have strongly engaged industry partners with clear commercialisation strategies. Nonetheless, a simple probabilistic analysis indicates that considerable value, well in excess of the initial investments, will be generated globally in the coming years. Just how much of that accrues to Australia will be very much dependant on future policy settings that will determine how much CST deployment eventuates here, and how conducive the business environment is to local companies. It should be noted that there does not appear to be a very large portfolio of patents from the institutional work.

Support for projects by business organisations has had less encouraging results. A number of supported companies have run into financial difficulties. Other companies, with other core business interests, have looked at CST opportunities, studied them and concluded that, in the current environment, they are unlikely to generate the commercial returns they would expect.

Specific achievements of note include:

- A major new solar tower test system with associated laboratories, instrumentation and infrastructure at the CSIRO National Solar Energy Centre at Newcastle.
- The largest pilot scale solar driven air turbine (200 kW_e) system designed and constructed by CSIRO working in partnership with Mitsubishi Heavy Industries.
- Support for an Australian start-up company (Vast Solar) through a series of projects that has led to an innovative system of modular small tower plus heliostat systems with sodium-based receivers and thermal energy storage. A 6 MW_{th} / 1 MW_e pilot system is in the final stages of commissioning near Forbes in NSW.
- Work with steam receivers at ANU and CSIRO has established respectively a cavity receiver design that claims the record for highest ever thermal efficiency and at CSIRO the first test of a solar driven receiver producing steam at ‘supercritical conditions’.
- On-sun demonstration of a supercritical CO_2 flow loop for next-generation solar-driven power cycles.
- A new test facility for high-temperature thermal energy storage materials and testing of new phase-change materials at UniSA.
- Investigation of new routes to solar thermal production of fuels and the analysis of the potential for these to form a major new export industry specifically targeted at existing energy customers, such as Japan.

5.2.3. Enabling Projects

A wide range of enabling technologies is used to facilitate the generation, storage and use of solar energy.

The 38 enabling R&D projects examined for this report are across a diverse range of areas. Enabling projects often involve both software and hardware. When examining the main focus of the research, the projects can be summarised as 26 software and 12 hardware.

Some key achievements are highlighted below.

- The largest performance prediction project was for the Australian Solar Energy Forecasting System (ASEFS) which involved CSIRO, in conjunction with AEMO, BoM, UNSW, University of SA and NREL developing a solar forecasting system for the NEM. ASEFS has been incorporated with the existing Australian Wind Energy Forecasting System and is designed to project expected generation from solar power generators in the short, medium, and long term. This tool will become increasingly important as the amount of PV generation in the NEM increases.
- Another performance prediction project involved the development and demonstration of sky camera technology to enable cloud detection and prediction for maximising solar PV utilisation in diesel mini-grids. This project has significantly advanced the technology and brought costs down to the point that cloud detection technologies are likely to become widely deployed in PV and diesel mini-grids and for large PV plants connected to main-grids.
- In the resource information category, BoM has improved the availability and access to one minute resolution solar data. It has also led to work by CSIRO's Data 61 to develop the Australian Renewable Energy Mapping Infrastructure (AREMI)[13] which is hosted by Geoscience Australia.
- In the policy and regulations category, models for community owned solar have been developed, issues associated with strata titles and PV ownership examined and international collaborations strengthened.
- In the systems category, the Re-deployable Hybrid Power system, cloud tracking and prediction technologies as well as the UltraBattery have been developed into commercially available products. Significant advancements have also been made in developing hardware and software for controlling distributed battery systems.

5.3. Contribution to Solar Development

5.3.1. Photovoltaics

Photovoltaic technologies have progressed rapidly from niche market to mainstream application over the last decade and are now benefitting from mass production economies of scale and significant advances in technology-based device performance improvement. PV is the largest source of new generation capacity worldwide, accounting for two thirds of all new capacity added in 2016[14]. Nevertheless, PV is still a relatively new technology, with only a decade of

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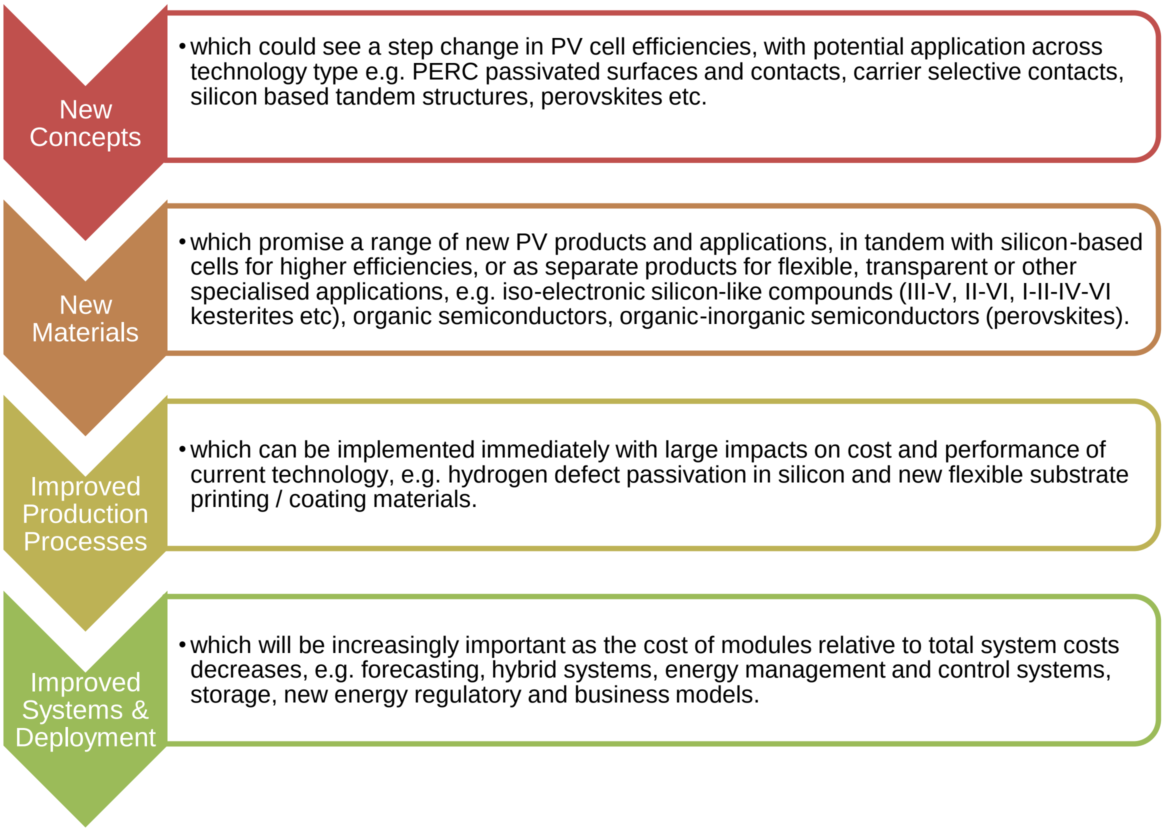
[13] http://nationalmap.gov.au/renewables/.

[14] https://www.iea.org/publications/renewables2017/

mass market deployment, indicating that many opportunities are available for improving PV device performance, production processes, materials use, cost and functionality along the PV technology research and development pipeline, as illustrated below:



Researchers around the world compete strongly for developments in the field, which has been one of the fastest growing energy technologies and is seen as one of the most promising for taking over large portions of energy supply in coming decades[15]. Australian researchers at UNSW and ANU in particular have played a key role in development of the industry over the past four decades and continue to dominate developments in the commercial industry, most noticeably in silicon-based technologies[16]. With the support of ASI and ARENA funding, an increasing number of other Australian research organisations have entered the PV space, with many of the new entrants focusing on new materials and concepts (in particular the Victorian based CSIRO/Monash/Melbourne University consortium), as well as system components, including inverters, controllers, monitoring, storage and applications.

While there are many new PV materials being developed in research laboratories around the world, Australia maintains the lead in developments most relevant to the mainstream commercial PV industry. This means that many Australian developments are able to have a rapid and a large impact on mainstream PV products, with higher efficiencies and lower costs being passed through to consumers relatively rapidly. With crystalline silicon remaining the

[15] See for instance International Renewable Energy Agency, 2016, Letting in the Light, how solar photovoltaics will revolutionise the electricity system, http://www.irena.org/DocumentDownloads/Publications/IRENA_Letting_in_the_Light_2016.pdf, or https://about.bnef.com/blog/clean-energy-10-predictions-2018/

[16] See for instance Green, M. A., 2016, "Estimate of Economic Benefits to Australia of Past Australian PV Research", *UNSW Information Paper MAG/UNSW1603, Release 2*, 17 May 2016.

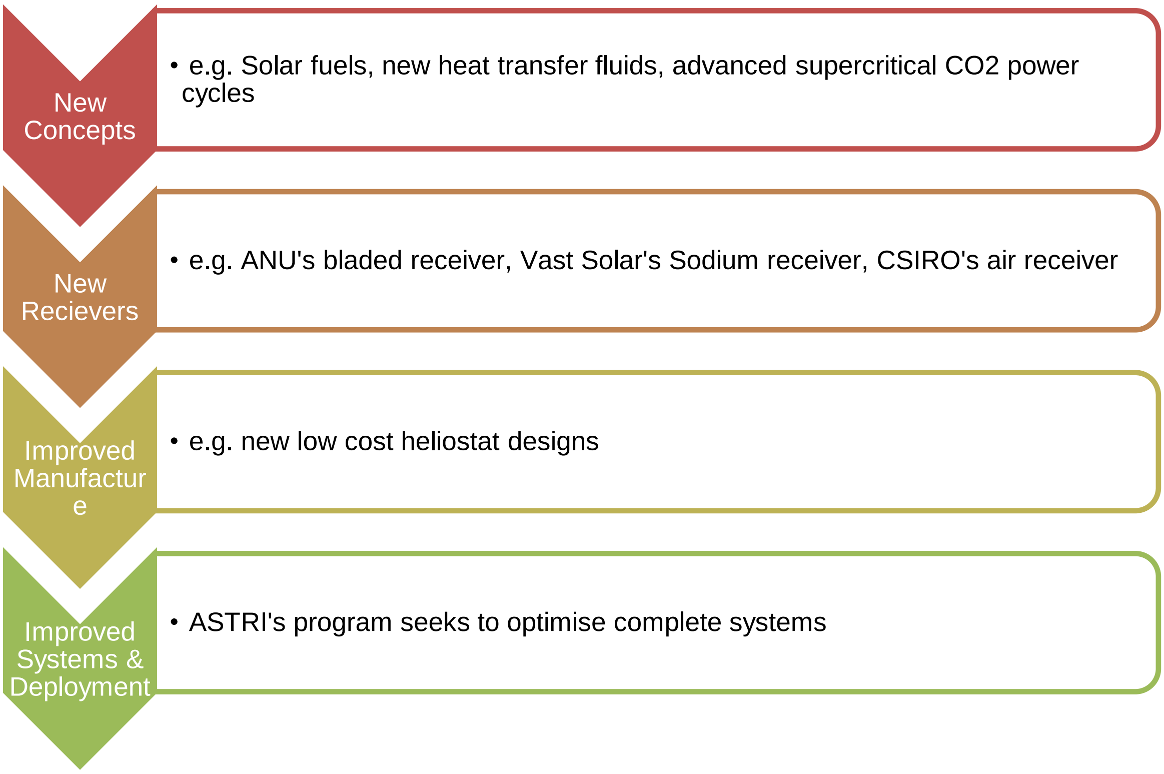
dominant technology in use worldwide (>90%) and with Australia's research dominance in this field, as well as the strong education and research ties which have been established between Australian research institutions and the key world manufacturers, Australia is in a good position to maintain this lead through strategic research funding. Nevertheless, Australian researchers are also systematically exploring new materials which can be used independently of, or in tandem with, silicon for higher efficiency PV cells.

5.3.2. Concentrated Solar Thermal

Major CST power generation deployment began in the USA in the 1980s but was followed by a long hiatus. Deployment activities restarted in 2006, following policy initiatives in Spain and the south-western states of the USA. CST power plants are attracting increasing interest due to their ability to store large amounts of energy at low cost and provide dispatchable renewable electricity generation. At scale, molten salt heat storage has significant cost advantages over many storage technologies. This is increasingly important as levels of variable generation increase in electricity markets.

By the end of 2017, installed CST power generation capacity had increased to around 5.1 GW, with average compound growth over the period 2007-2017 of 27.5%/year. Spain and USA (California, Arizona and Nevada) have dominated installed capacity but slowed in their efforts in recent years. At present there is considerable activity in Morocco, South Africa, China and Chile, plus various individual projects in other countries in North Africa and the Middle East.

Besides concentrated solar power production (CSP), there is also the growing research area of CST fuel production which offers large potential for value adding to fossil fuels as well as developing new, renewable fuel export industries. In addition, there is growing interest in the area of CST technologies displacing gas in industrial processes. CST R&D ranges from new, advanced concepts through to whole of system improvements under all of these configurations.



Research efforts are focused on reducing costs to accelerate widespread deployment. Internationally, significant CST research is being undertaken with industry partners examining ways to improve existing technologies already in commercial operation. The coverage of research topics spans all aspects of CST systems including:

- solar concentrators,
- receivers,
- heat transfer fluids,
- thermal energy storage, and
- electricity generation systems.

Australian research effort is mainly focussed on examining new concepts and technologies. These include advanced receivers, new energy storage processes, new power cycles and solar fuels. Future effort is more strongly coordinated through ASTRI which is planning to shift its emphasis away from new concepts / technologies (TRL 3/4) to demonstration / pilot testing of key system components at the TRL 5/6 level. This also coincides with close cooperation with key US institutions and participation in the US DOE ‘Gen3’ program that focuses on the development of subsystems specifically targeted at the use of supercritical CO_2 cycles.

5.3.3. Enabling

The portfolio of enabling R&D projects has supported the development of solar energy in a diverse range of ways.

The performance prediction tools and freely available, solar resource information data have contributed to the significant reduction of the cost of financing for large-scale PV plants. This has assisted in accelerating the deployment of ground-mount PV plants around Australia.

The cloud camera technologies developed allow for new ways of optimising design and performance of PV-battery-diesel mini-grid systems, leading to greater deployment opportunities. The higher, instantaneous PV penetrations able to be achieved without compromising power reliability have assisted in increasing interest in PV deployments in the off-grid mining sector.

Developments in energy storage have also been facilitated which increases options in a range of sectors. For example, distributed battery control systems assist with PV deployment by increasing the value and increasing the potential income for distributed PV with batteries.

5.4. Allocation of Funding by Project Objectives

Allocation of funding by primary research goal is shown in Figure 16. Efficiency improvement is the single largest aim, followed by manufacturing cost reduction and development of new concepts. This reflects the high level of industry relevance of Australian R&D.

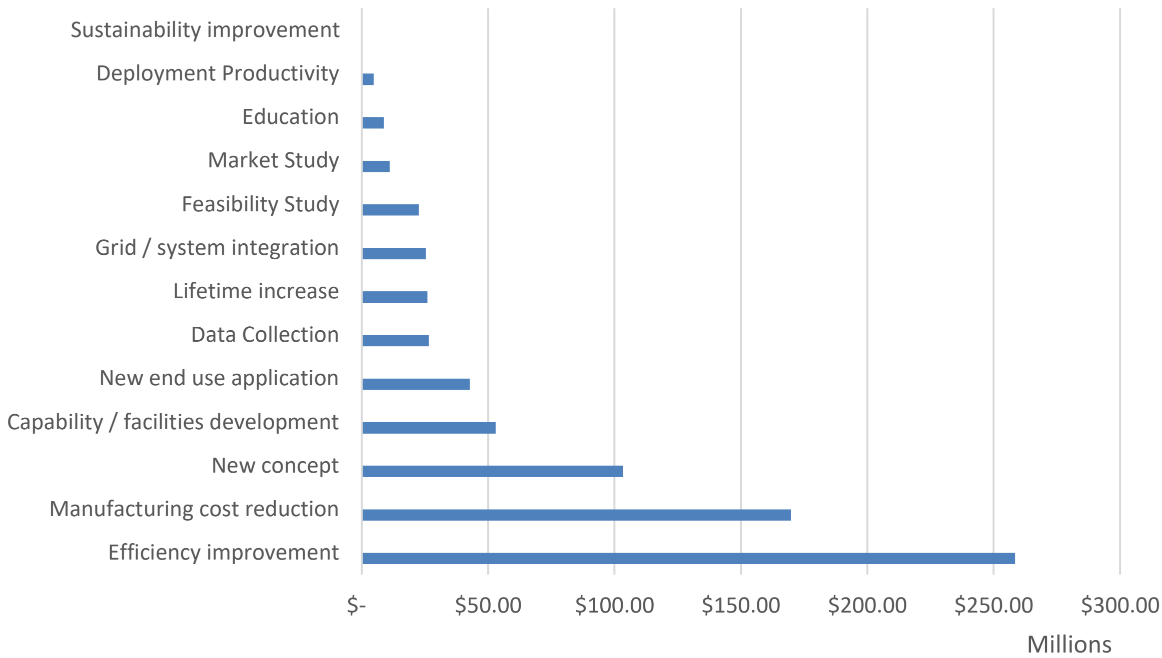


Figure 16: Solar R&D Total Project Value ($752m) by primary goal

5.5. Allocation of funding by Lead Organisation

Funding has been allocated to 54 different organisations. While the majority of funding has gone to University and CSIRO-led projects, as would be expected, 28 projects are industry-led, including a range of new companies developing products and applications for the burgeoning international solar market.

CSIRO, UNSW and ANU in particular have received significant funding. In order to illustrate the funding allocations more clearly, we have classified private companies as large, (eg private utilities, large international solar and engineering companies, Bluescope Steel) or small. Universities, other than ANU and UNSW, were categorised as either belonging to the Group of Eight large research-intensive universities (G8) or as ‘other university’. It should be noted that many projects involve several partners and while the lead organisation receives all the funding, significant proportions are often passed on to other research partners. Overall allocation by organisation is shown in Figure 17.

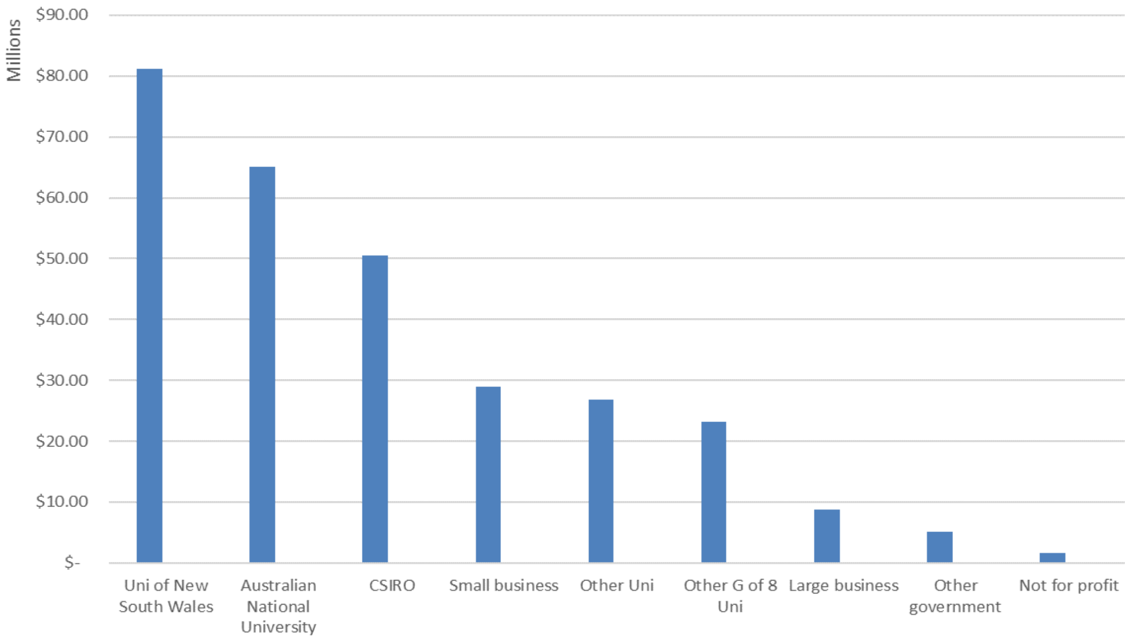


Figure 17: Allocation of R&D funding ($291m) by lead organisation.

5.6. Regional allocation of funding

Breakdown of funding by States and Territories has been estimated using the home base of the research leader and is shown in Figure 18. However, it should be noted that many projects, particularly those undertaken via ACAP and ASTRI, have several participants, so that actual expenditure is likely to be much more widely spread. NSW dominates as it has significant CSIRO and UNSW activities, while ACT funding reflects the significant funding of ANU activities.

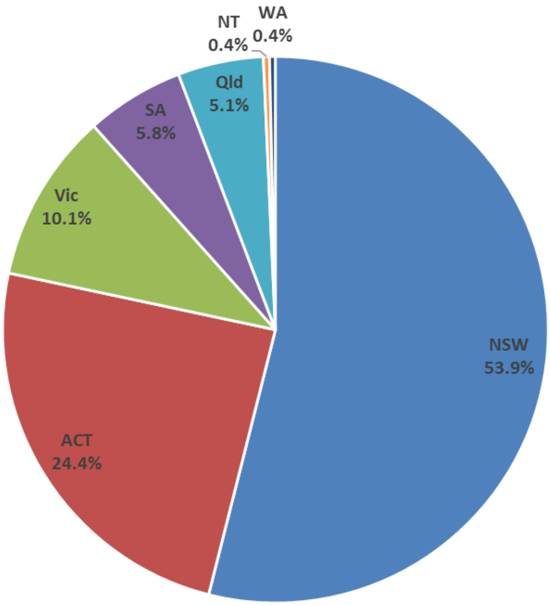


Figure 18: R&D funding ($291m) by location of lead organisation.

5.7. Technology Development Progression

An assessment was made of technology development during the research projects using the US Department of Energy Technology Readiness Level classifications, as defined in Appendix A.1. A summary is shown in Table 3. Scholarship and fellowship projects have been removed since their TRLs were generally low (70% started at 1 and stayed at 1 or moved to 2 or 3) while for some projects, such as studies, TRL is not applicable (NA). TRLs specific to the CST, PV and Enabling streams are shown in Table 3.

It can be seen that the largest portion (39%) of projects started at TRL 2 (basic concepts validated) and, though the spread of TRL was larger, the highest number of projects (26%) finished, or expected to finish at TRL 5 (prototype feasibility demonstrated). The TRLs reflect the R&D calls made by ARENA, which focussed on the range 2-4 or 2-6. The projects at higher TRLs are those in the early stage demonstration category.

Table 3: Estimated TRL at start and finish of R&D projects (excluding scholarships, fellowships & NA)

TRL Start	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Total**
TRL Finish										
CST	**3**	**8**	**13**	**7**	**7**	**3**	**1**	**1**		**43**
2	3									3
3		3								3
4		5	4							9
5			7	4						11
6			2	3	7	1				13
7						2	1			3
8								1		1
Enabling	**2**	**1**	**3**	**2**	**1**	**3**	**2**			**14**
2	1									1
3	1									1
4		1	1							2
5			1	1						2
6				1	1	1				3
7			1			2				3
9							2			2
PV	**26**	**68**	**19**	**12**	**6**	**3**	**2**	**1**	**1**	**138**
2	7									7
3	16	16								32
4		14	4							18
5	2	28	4	3						37
6	1	7	4	6	2					20
7		1	7	2		2				12
8		2		1	3		2			8
9					1	1		1	1	4
Total	**31**	**77**	**35**	**21**	**14**	**9**	**5**	**2**	**1**	**195**

5.8. Leverage of ARENA Funding

The average project leverage (Total project budget/ARENA contribution) was 1.58. The highest was for PV projects at 1.67 and the lowest for Enabling projects at 1.43, as shown in Figure 19 and Figure 20. This compares to an average leverage ratio for all ARENA projects of 2.4 and ratios of 1.5 for ARENA funded studies, 1.8 for demonstration projects and 3.6 for deployment projects.

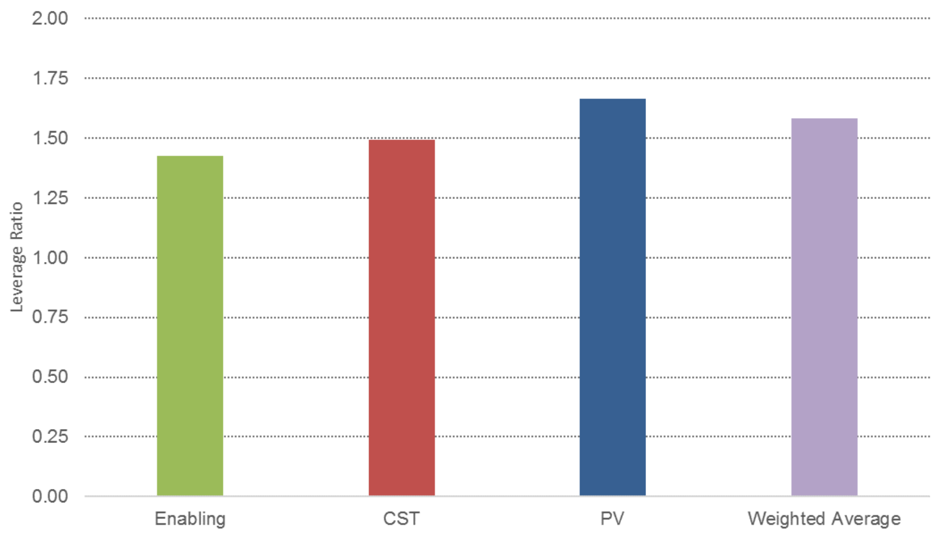


Figure 19: Leverage of ARENA funding by project type and total Solar R&D projects

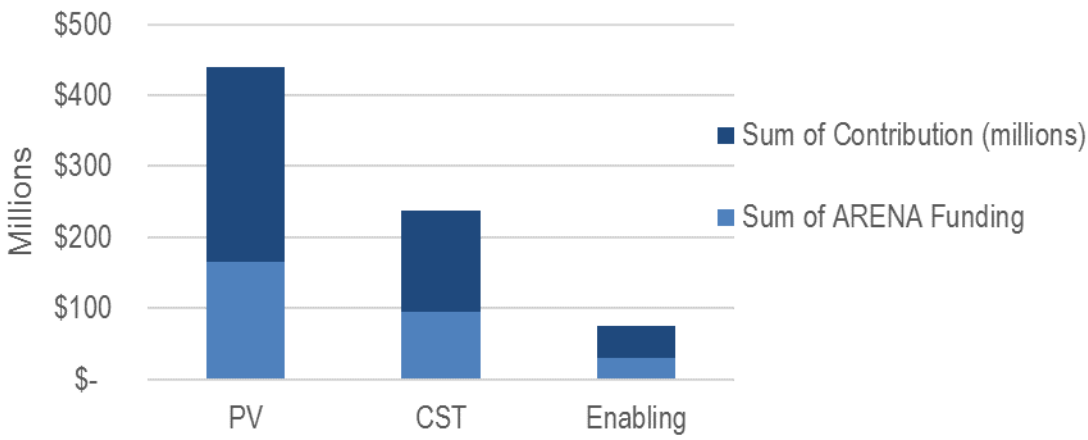


Figure 20: Leverage of ARENA funding by project type 2008-2017.

5.9. Project Outputs

Project outputs reported in the project documents assessed for this analysis are summarised in Table B1. It is likely that this is an underestimate of outputs since many of the final project reports examined listed final milestone outputs only, not total outputs. However, there may also be some double counting of outputs across ASI and R&D projects which were later merged into ASTRI and ACAP.

Benchmarking of R&D outputs is difficult, since different criteria are used across disciplines and little assessment of energy agency funding has been undertaken. However, as an indicator, the average ARENA funding is about $172,000 per publication for the projects assessed and the publications reported here. This is very close, for instance, to scientific research expenditure in Australia of USD 90,000 per publication reported in a 2010 analysis[17] (in Year 2000$), which is equivalent to AUD 167,000 in 2018$.

Table 4: Summary of Solar R&D reported project outputs

	Number of						
Project Outputs	**Patents filed**	**Licences entered into**	**Journal publications**	**Other publications**	**Presentations**	**PhDs**	**Postdocs and other researchers**
PV	139	19	1,183	163	890	183	158
Enabling	3	0	31	54	97	11	51
CST	6	2	167	95	248	26	132
TOTAL	**148**	**21**	**1,381**	**312**	**1,235**	**220**	**341**

It is clear that the R&D funding has resulted in significant knowledge creation and extensive knowledge sharing, as well as valuable skills development. This will ensure that Australia continues to make significant contributions to future commercial solar developments.

[17] Auranen, O. and Nieminen, M., 2010, 'University research funding and publication performance – an international comparison', *Research Policy* 39(2010) 822-834.

6. ASSESSMENT OF PHD AND POST-DOC FELLOWSHIP PROGRAM

6.1. Background

ASI and then ARENA have directly funded 34 PhD scholarships and 46 Postdoctoral Fellowships. Others have been funded indirectly via ACAP and ASTRI. A survey was sent to the 80 directly funded scholarship and fellowship recipients. 33 responses were received. For many R&D projects, these awards have provided the key labour source for the research undertaken and have therefore been crucial to the success of the initial projects. The awards have also encouraged high achieving students and early career researchers to remain in Australia. The skilled research base created now comprise many of the lead researchers for new or extension projects subsequently funded.

PhD scholarships fell into two categories: top-up awards ranging from $20,000 to $50,000 for students in receipt of ARC or university scholarships; full scholarships ranging from $50,000 to $120,000 over 3 to 4 years. 13 of the 34 award recipients responded to the survey.

For the Postdoctoral awards, funding provided ranged from $7,000 for short visits to international renewable energy institutions to over $400,000 for 4 year research projects. 23 of the 46 recipients responded to the survey.

6.2. Survey Results

6.2.1. Recipient backgrounds

There were 12 females in the initial list of 80 award recipients (15%). This was in line with general university student intakes for engineering reported by Engineers Australia[18]. Four females responded to the survey, out of a total 33 respondents (12%).

The average age of respondents at the start of their scholarship or fellowship was 28, with ages ranging from 23 to 34 years, indicative of the post graduate / early career focus of this program.

Awards had been granted for research at 15 Institutions. 12 of these were represented in the survey responses, as shown in Figure 21.

[18] Engineers Australia, 2017, Public Affairs Note “Applications for, Offers of and acceptances of places in university entry level engineering courses: Annual monitoring report 2017”.

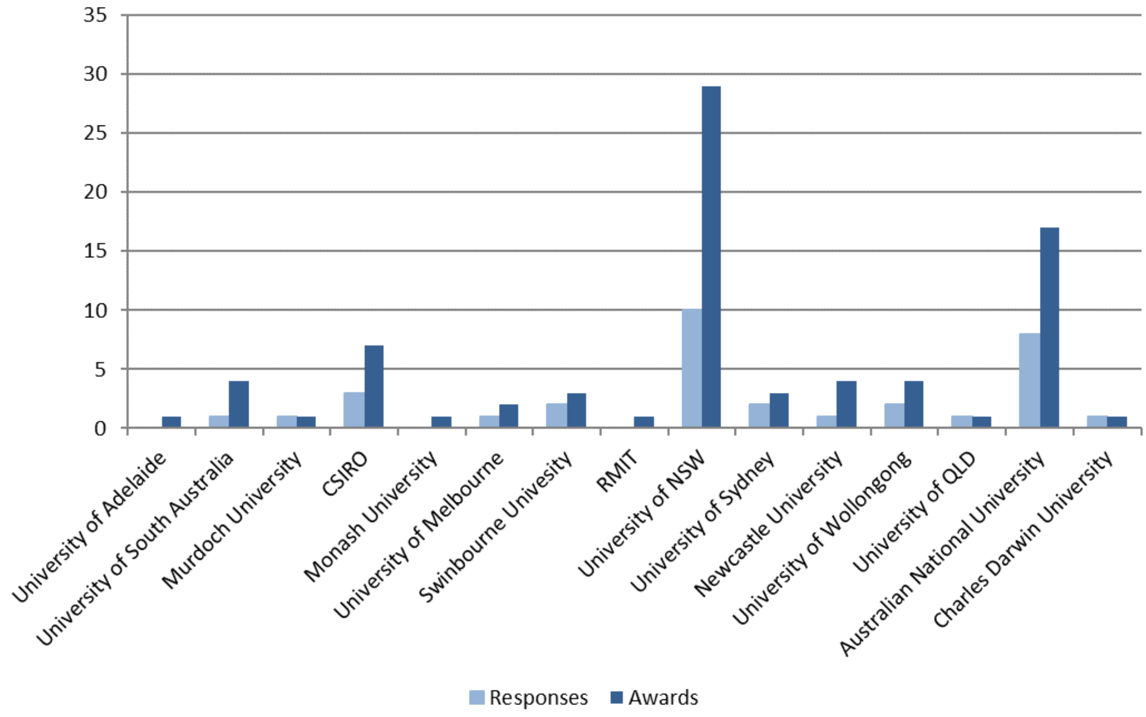


Figure 21: Number of Scholarship and Fellowship awards by institution and survey responses received

6.2.2. Research areas and aims

The majority (78%) of respondents had worked on PV related research during their award.

As shown in Figure 22, efficiency increase was the most common research goal (39%) with 24% aiming to develop a new concept and 18% aiming for manufacturing cost reductions. This was reflected in their expectations of the impact of their research on renewables, where 74% considered their results increased efficiency or reduced costs. This corresponds to findings of the overall Solar R&D program.

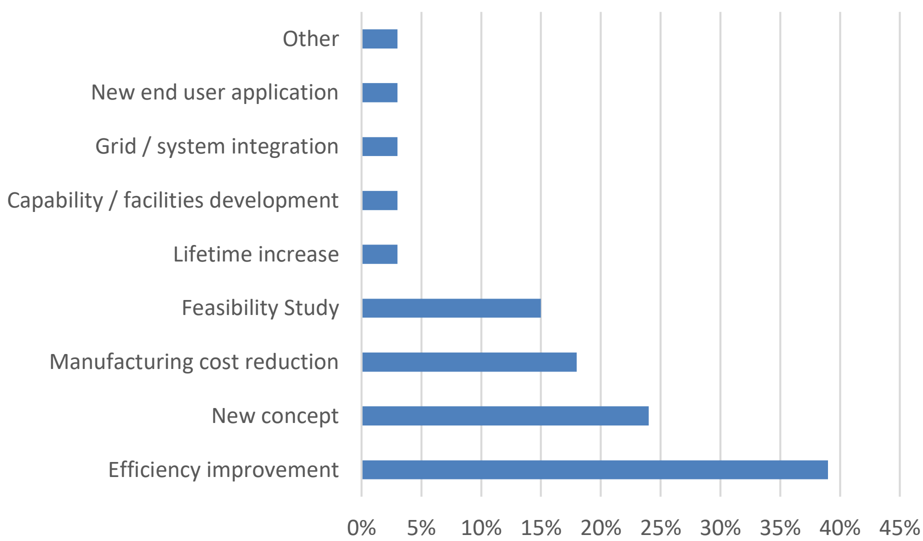


Figure 22: Scholarship and Fellowship Program - Key research aim

6.2.3. Research Publications

A total of 406 publications were reported. For these, 91% of respondents reported journal publications and 82% international conference presentations. Nine patents resulting from their work were reported as filed and four granted. The breakdown is shown in Figure 23 and represents a relatively high publication rate, though indicative of the high achieving cohort receiving ARENA awards.

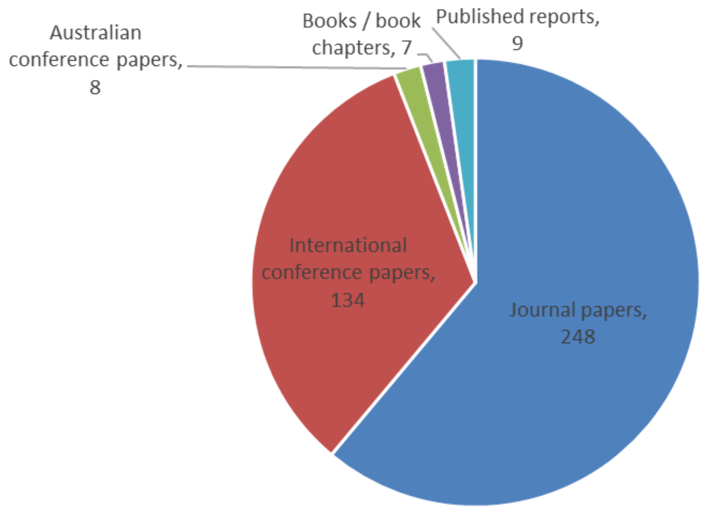


Figure 23: Breakdown of Scholarship and Fellowship Publications.

6.2.4. Post award activities

12 researchers indicated that they have been successful in receiving research grants as lead researcher since completing their ARENA funded scholarship or Fellowship. A total of over $12m in grants were reported, of which 60% were from ARENA and 30% from the ARC. In addition, 6 researchers had been part of a team receiving funding of over $72m, 80% of which was from the ARC. Ten respondents reported having received awards or prizes stemming from their ARENA funded work. The ARENA award recipients have used the opportunities provided to gain a foothold in the very competitive research funding area. Their success post award indicates excellent career prospects, which means that the award benefits will be long term. This is reflected also in the feedback provided in the survey, which is presented in Section 6.2.5.

A total of 181 students were supervised by 19 award recipients who answered this question, an average of 10 each, which indicates a high level of involvement in academic life amongst the award recipients, which in turn reflects the career ambitions of these early stage researchers.

75% of the 19 people who responded indicated that they had collaborated with international research groups since or during their ARENA award. The countries mentioned were Ireland, Singapore, Germany, USA, China, Italy, France, Poland and the UK. This is an excellent outcome for ARENA in developing international research contacts, which are likely to continue once established.

6.2.5. Feedback

85% of those who responded indicated that the ARENA award had been their first choice at the time, with some indicating that they felt honoured to have received it. Many indicated that it had been the foundation for their career, had opened up the world of solar research to them and had allowed them to work with world-leading researchers. 15 respondents indicated that they had subsequently received other awards. The breakdown of further awards received is shown in Figure 24.

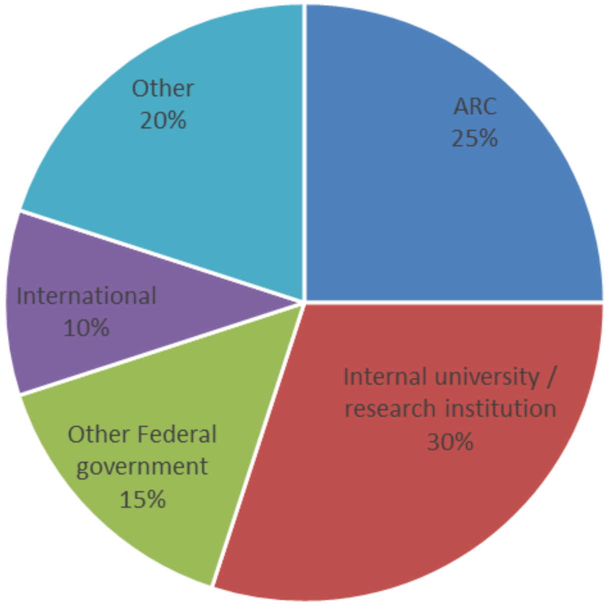


Figure 24: Subsequent awards received by ARENA PhD Students and Fellows.

Of 22 people responding to this question, 16 indicated that they were still involved in the same field of work. Six respondents reported that they were involved in commercialising their research.

Apart from one response questioning the ability of government to successfully choose and prioritise R&D funding areas, suggestions and comments on future ARENA Scholarships and Fellowships included:

- Allow fellowships for people with industry experience to re-enter academic work. Base selection criteria accordingly.
- It would be better to launch a fellowship for middle career researcher or a continuous support to the fellows who did a good job during the fellowship.
- More media coverage for the successful projects and candidates.
- Follow-up fellowships or funding.
- More PhD Scholarships.
- Add some additional funds for conference travel. Very difficult trying to network and collaborate without going to conferences.

- Original ASI program provided many more additional programs, e.g. media training and coverage, networking opportunities.
- Research support on top of Fellowship salary.
- Resume offering international visiting fellowships. This was really great for someone who is seeking to establish some autonomy in a field of their choice.
- Target early career researchers both at Post-Doc and junior academic levels.
- It is crucial that all participants have access to mentors in the solar industry. If suitable mentors are not available within Australia, someone overseas should be made available. Academia in Australia is sometimes like an 'echo chamber' and ideas that do not have relevance to the solar industry are often pursued. That is not to say pure research is not vital, but for outcome-focused programs like ARENA's, it is difficult for young researchers to simultaneously pursue a research career (focused on papers etc), while trying to do something that can lead to positive industry outcomes.
- Keep it focused on commercial outcomes.
- Provide more fellowships and reduce the funding amount for big ARENA deployment projects who would hire the Post-Docs.

Overall, these comments reflect the difficulties encountered by early career researchers and also the academic focus of Australian R&D and the difficulties around commercialisation and industry involvement.

7. CONCLUSIONS

Solar has been the fastest growing new energy technology over the past five years and is now expected to be a dominant energy technology globally over coming decades, with NREL projecting solar plus storage could provide 50% of US electricity by 2030[19], global installations of solar and wind expected to account for 80% of new capacity additions globally over the next 5 years[20] and account for 34% of world electricity by 2040[21]. In Australia, Bloomberg New Energy Finance is projecting 33 GW of small-scale solar and 27GW of large-scale solar by 2040[22].

ARENA funding has significantly boosted Australia’s solar R&D, and in turn the research outcomes and capability which has kept Australia in the forefront of the burgeoning new international solar industry. Key achievements typically build on a long-term research commitment, with funding spanning many years and the establishment of well-functioning research teams. Solar research funding provided by ARENA over the past decade has significantly improved Australian solar research facilities, maintaining Australia’s world leading role and bringing research facilities up to world class. This has facilitated a wider range of research projects and assisted in enhancing research-industry collaboration. Funding for early career researchers has been critical in keeping high achievers in Australia, which has further enhanced research outcomes.

Australian technology is expected to dominate the PV market over the next decade, with the PERC cell expected to be used in over 60% of commercial cells. The new hydrogenation technology has been demonstrated to increase the performance of low quality / low cost solar grade silicon wafers. This technology can be incorporated into current standard cell manufacturing lines, with minimal equipment change and 22 companies have already contributed to the research. Using current projections of approximate annual PV manufacturing levels of approximately 100GW per annum and a conservative module cost / sell price of US$0.50/W, and assuming the wafer cost is one third of the module cost and solar grade wafers are 50% cheaper than electronic grade, a global saving of some US$7.5BN per annum is possible.

ARENA funded research into new materials and technologies, including perovskites, tandem cells and CZTS, is also likely to see dominance in these new technologies, as they reach commercial production. This will include new, high efficiency, low cost, flexible and non-toxic materials which could be integrated into building and other new products within a decade. Commercialisation will be facilitated by the value stream from research through development and demonstration, and the strong links to the market and the key industry players, which have now been established.

While there are many new PV materials being developed in research laboratories around the world, Australia maintains the lead in developments most relevant to the mainstream commercial PV industry. This means that many Australian developments are able to have a

[19] https://www.energy.gov/eere/solar/sunshot-2030

[20] IEA, 2017, World Energy Outlook 2017.

[21] Bloomberg New Energy Finance, 2017, World new energy outlook 2017

[22] https://reneweconomy.com.au/australian-solar-capacity-now-6gw-to-double-again-by-2020-2020/

rapid and a large impact on mainstream PV products, with higher efficiencies and lower costs being passed through to consumers relatively rapidly. With crystalline silicon remaining the dominant technology in use worldwide (>90%) and with Australia's research dominance in this field, as well as the strong education and research ties which have been established between Australian research institutions and the key world manufacturers, Australia is in a good position to maintain this lead through strategic research funding.

For CST, the past decade of research funding has facilitated the establishment of a number of key research and demonstration facilities. Despite a lack of a commercial CST deployment in Australia, these facilities are now being used to develop a range of related technologies and components for use in new value streams, including solar fuels and industrial energy systems. Key development in high temperature processes have also improved the cost effectiveness of CST systems, including the increasingly valuable storage component.

As Australia moves towards higher levels of renewable energy deployment, in response to the climate change imperative and, increasingly, because renewable energy provides the lowest cost electricity, enabling R&D is becoming critical. Forecasting systems, energy storage and control technologies are now providing the elements necessary to integrate renewables into electricity systems which were designed for fossil fuels. New methods, both technical and regulatory, to manage both supply and demand will minimise the cost of deploying increasing amounts of renewable energy while maintaining system reliability and responsiveness.

Given that solar technologies are still only in their early phases of deployment, research remains crucial. Research priorities may change over time as the market environments evolve. Nevertheless, key efforts on technology improvement, such as higher efficiencies, lower costs, use of less toxic or more abundant materials, remain key drivers.

Research and industry hubs have played a key role internationally in focusing research and moving it through to market, as have long term commitments to research institutions. ARENA funding has been critical in supporting and developing research infrastructure which is now facilitating large-scale industry collaboration in PV (via ACAP, SIRF), CST (ASTRI), storage, data and forecasting (ASEFS, AREMI) and other associated research areas (such as nano-fabrication, quantum computing). Such institutions and hubs:

- reduce the volatility of research funding,
- ensure continued high level educational outcomes,
- secure employment for our leading graduates and top researchers,
- enhance the prospects for local industries, and
- provide links into the global industry.

APPENDIX A: ANALYSIS METRICS

Project Title

Reference Numbers

- ARENA Ref No.
- ASI Ref No.
- Other Ref No.

Status

- Active
- Closed
- Terminated

Funding Program

- ASI
- PDF
- SHARE
- R&D1
- R&D2
- R&D3
- ACAP
- ASTRI
- ERP
- ARP

Start Date, End Date, Duration

Funding Recipient / Lead Organisation

State

ARENA Funding Committed

Total Project Cost

Other funding:

- Research Institute Funding
- Industry Funding
- Other Participant Funding

Allocation of Budget

- Capital Equipment
- Staff Costs
- Other

Broad Technology Area

- PV
- CST
- Enabling

Specific Technology Area Level 1:

- Thermal (PVT)
- Concentrating (CPV)
- Inorganic (IPV)
- Organic (OPV)
- Organic - Inorganic (OIPV)
- Tower / Heliostat
- Trough
- Linear Fresnel
- Dish
- Enabling hardware
- Enabling software
- Other

Specific Technology Area Level 2:

- Materials Development
- Process Development
- Device Structure Development
- Performance Prediction
- Modelling
- Testing, Characterisation
- Policy and Regulation
- Resource information
- Systems
- Component Development
- Techno/Economic Analysis
- Manufacturing
- Demonstration
- Other

Specific Technology Area Level 3:

- Crystalline IPV
- Thin Film IPV/OPV/OIPV
- Multijunction IPV / OIPV
- Compound IPV
- Bulk Heterojunction OPV
- Linear Heterojunction OPV
- Dye Sensitised OIPV
- Perovskite OIPV
- Receivers
- Molten salt
- Heat transfer fluid
- Phase change storage
- Solid storage
- Process heat
- Thermoionic / thermoelectric
- Thermochemical storage
- Fuels production
- Organic Rankine cycle
- Brayton cycle
- Steam cycle
- CO2 cycle
- Co-Tri Generation
- Concentrators
- Other

Project Aims

TRL Start

TRL Completion (Actual or Forecast)

International Competitiveness Status

- world leading
- world competitive
- adaptation
- catchup

Target Market:

- All sectors
- Building sector
- Electricity networks
- Utility generation
- RE Industry
- Diesel Mini-grids
- SAPS
- Cell Manufacturers
- Module Manufacturers
- BOS manufacturers
- End Users
- CST Industry
- Community
- Investors
- Project developers
- Regulators
- Other

Primary Goal:

- New end use application
- Efficiency improvement
- Lifetime increase
- Sustainability improvement
- Market Study
- Feasibility Study
- Data Collection
- Capability / facilities development
- Deployment Productivity
- Grid / system integration
- Education
- Manufacturing cost reduction
- New concept
- Other

ARENA Priority Area:

- Improved affordability
- Security and reliability
- Innovation
- Skills
- Markets and regulation
- Accelerating uptake
- Improved energy productivity in transport, industry and buildings
- Exports

Project Outcomes

- Patents filed
- Patents granted
- Licenses
- Journal publications
- Other publications
- Presentations

Capability Development

- PhDs
- Post-docs and other skills
- Research facilities

Other Outcomes

A.1 Technology Readiness Level Definitions

Level	Summary
1	**Basic principles observed and reported:** Transition from scientific research to applied research. Essential characteristics and behaviours of systems and architectures. Descriptive tools are mathematical formulations or algorithms.
2	**Technology concept and/or application formulated:** Applied research. Theory and scientific principles are focused on a specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.
3	**Analytical and experimental critical function and/or characteristic proof of concept:** Proof of concept validation. Active research and development is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.
4	**Component/subsystem validation in laboratory environment:** Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.
5	**System/subsystem/component validation in relevant environment:** Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.
6	**System/subsystem model or prototyping demonstration in a relevant end-to-end environment**: Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.
7	**System prototyping demonstration in an operational environment:** System prototyping demonstration in operational environment. System is at or near scale of the operational system with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.
8	**Actual system completed and qualified through test and demonstration in an operational environment:** End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed.
9	**Actual system proven through successful operations:** Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.

APPENDIX B: ANALYSIS OF PV PROJECTS

B.1 Background

Australia has a more than 40 year history of PV R&D, particularly in the industry dominant, silicon-based technology area, and Australian researchers and experts associated with our research groups have been instrumental in the development of the global PV industry. Funding from ASI and ARENA has provided a significant boost to established research groups, as well as enabling new groups to emerge in other organisations, with the latter exploring new technologies and system components.

Of the 209 PV projects assessed, 15% were funded under ASI, 32% were PhDs and Post-doctoral fellowships and 38% were funded via ACAP.

Total funding allocated to PV research projects between 2009 and 2017 was $165m. Allocation of this funding by PV type (See Appendix A for definitions) is shown in Figure B1.

The bulk of expenditure has been for silicon-based PV R&D. This is unsurprising, given Australia's world-leading research at ANU and UNSW in this area, as well as the market dominance of Si-based PV mentioned above. Nevertheless, significant funding has been provided for new PV materials and technologies: principal among these improvements in cell efficiency from high levels of bulk and contact passivation (charge-state controlled hydrogenation and carrier selective contacts) and multi-junction (principally silicon sub-cell tandem) device structures.

Newly emerging and highly prospective perovskite devices have increased focus among all nodes, principally organic semiconductors, compound and new semiconductor materials (earth abundant, non-toxic CZTS in particular), and the translation of lab results to pilot manufacturing demonstration (CSIRO's printing and UNSW's Solar Industrial Research Facility, SIRF), in conjunction with increased focus on manufacturing cost and life-cycle analysis of prospective new technologies. ACAP funding is typically provided for infrastructure, materials and support services to projects funded by ARENA, the Australian Research Council, the host organisation, industry and others. For the analyses undertaken here, it has been allocated to the different PV research areas, according to the detailed work streams.

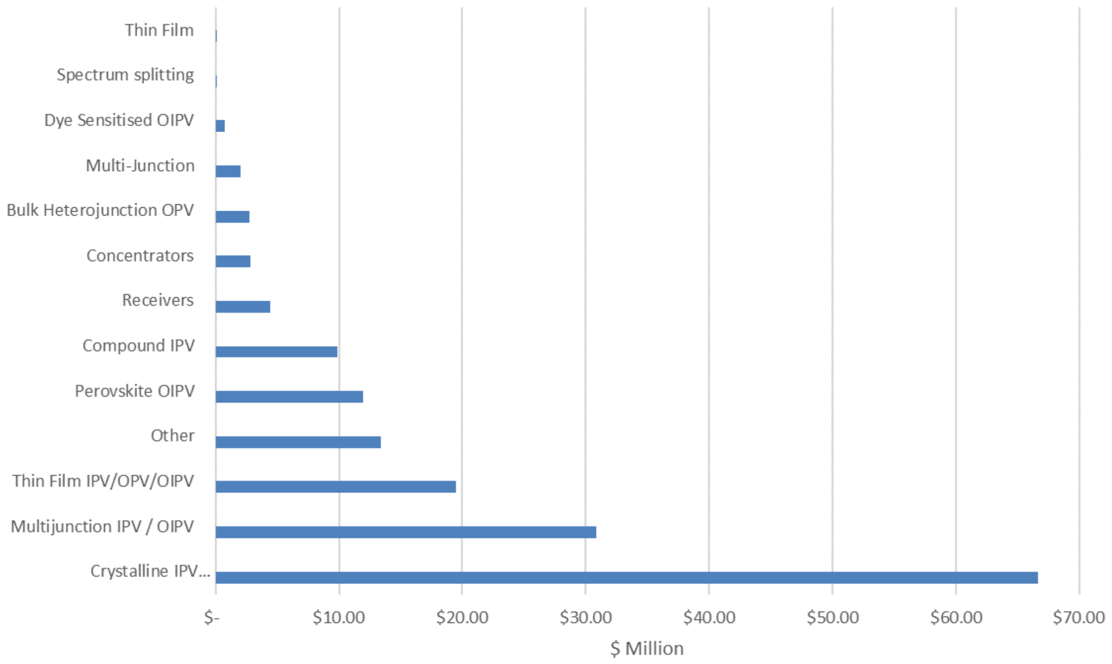


Figure B1: Allocation of PV Funding ($165m) by PV type

Key research achievements typically build on a long-term research commitment, with funding spanning many years and the establishment of well-functioning research teams. PV funding provided over the past decade has significantly improved Australian PV research facilities, maintaining UNSW's world leading role and bringing ANU and CSIRO facilities up to world class. This in turn has facilitated a wider range of research projects and assisted in enhancing research-industry collaboration. Funding for PhD scholarships and Post-doctoral fellowships has been critical in keeping top students and early stage researchers in Australia, which has further enhanced research outcomes. More detailed analysis of the scholarship and fellowship program is provided in Section 6 and Appendix E.

Project funding by primary research goal is shown in Figure B2 with developments in the key areas discussed below.

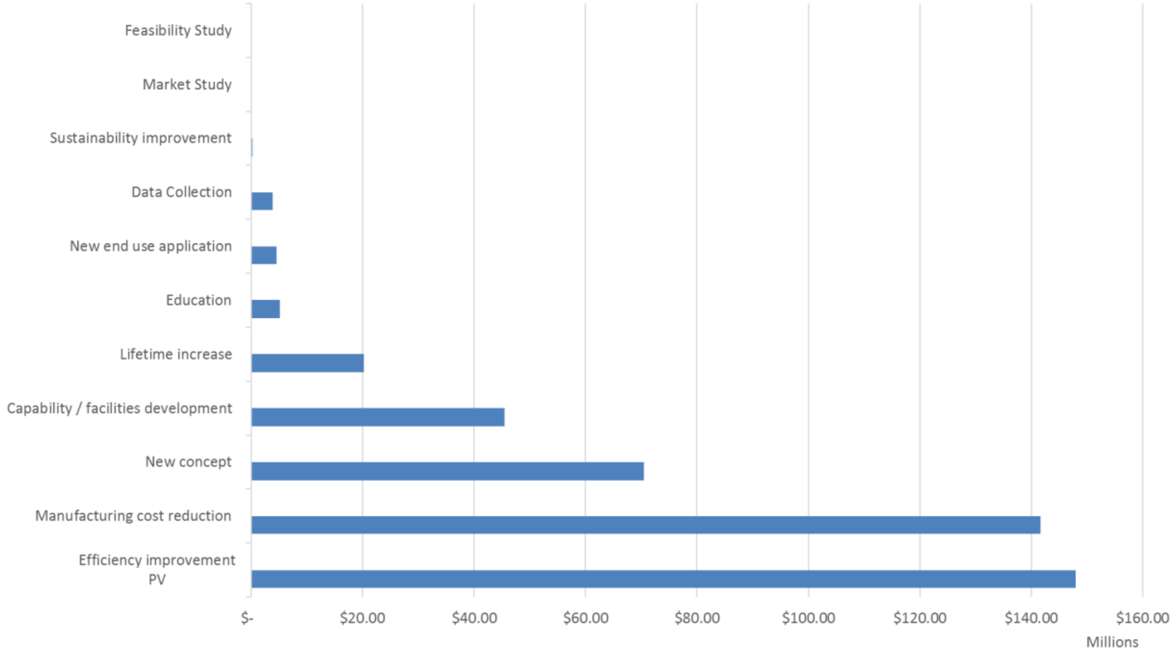


Figure B2: Allocation of $440m of PV R&D expenditure by primary goal.

B.2 PV Research Facilities

ARENA funding has been crucial to improving the research facilities which enable Australian researchers to maintain their world-leading research status, as well as to enter the field of demonstration scale research for commercial silicon and organic PV cell and module technologies and processes.

Of particular significance are the:

- Characterisation laboratories and cell process development at ANU
- Equipment for the Solar Industrial Research Facility (SIRF) at UNSW, including developing and demonstrating the silicon hydrogenation process
- CSIRO Clayton OPV and OIPV perovskite pilot production line, and
- Spin-off UNSW photoluminescence technology production facilities developed by BT Imaging
- GreatCell Solar perovskite pilot manufacturing demonstration facility in Queanbeyan NSW.

These have already enhanced industry linkages, producing a number of outcomes which are already widely used (including joint work with Trina Solar at ANU's characterisation laboratories to develop low cost, high efficiency cells, industry agreements with 11 PV manufacturers to further develop and implement the UNSW hydrogenation process, facilitating the testing of a range of new OPV and perovskite materials and processes, and development of new generation hardware and software for the BT Imaging inline inspection tools), and are likely to further improve the commercialisation of locally developed technology or techniques as equipment is added to these facilities and as skills are enhanced.

B.3 Improving Current PV Technology

The focus for silicon-based technology, which is the dominant technology in the current market, is on cost reduction. This is typically achieved in four key ways:

- New materials / manufacturing cost reduction,
- improved performance efficiencies - multi-junction device structures, highly passivated material bulk and surfaces, passivated carrier selective contacts, concentrating / spectrum splitting device structures, more effective light capture,
- multi-junction (principally, but not only, silicon based tandem) device structures, and
- improved methods of encapsulation, critical for perovskite devices (encasing solar cells for mechanical protection while maximising light transmission and minimising moisture ingress, which can otherwise significantly reduce module lifetimes).

B.3.1 New materials and manufacturing cost reduction

ARENA projects which have targeted material quality, novel materials identification and assessment, and demonstrated PV manufacturing cost reduction include:

- the UNSW charge-state controlled hydrogenation project (hydrogen-based material defect passivation, see Case Study), which increases the performance of cells made from low quality / low cost silicon material and has the potential for widespread industry use. It will both reduce material costs and improve power output over the life of the PV system.
- ANU's work, in conjunction with UNSW's hydrogenation, on high performance, low cost technology utilising pre-processed (Tabula Rasa anneal / phosphorus gettered) low grade UMG silicon wafers.
- UNSW's work on earth abundant, low-toxicity CZTS-Se kesterite compound semiconductor materials.
- Intense focus on highly promising perovskite materials, devices and stability. A wide-ranging review by UNSW of "silicon-like" closed-shell adamantine materials suitable for use as thin-film top cells in silicon tandem structures.
- Increased focus on manufacturing cost and life cycle analysis of new or emerging technologies.
- An estimate made by ANU of the potential benefits of the increasingly used technique of passivating material defects in solar cells at both the light collecting front surface (the emitter) and the rear metal conductor contact area (Passivated Emitter Rear Contact or PERC solar cell technology (see Case Study) indicates that a 5% relative efficiency improvement on 50% of Australian PV systems installed over the ten-year period 2018 to 2028, with average annual installation rates of 2 Gigawatts per year and average

area-related costs of $1,500 per kilowatt, translates to savings of $750 million. Worldwide, the savings could be 50 times larger, or over $37 billion[23].

Other projects aimed at improving current technology include the development of tandem (multi-junction) solar cells based on existing high performance silicon base cells with an added top cell which is better able to harvest the high energy (blue) spectral portion. Candidate top cell technologies include a range of mixed material type (or compound) semiconductor alloys (made up of elements within the III-V and II-VI classes of the Periodic Table and the promising class of materials called perovskites, although these so far face significant field exposure degradation (environmental stability) challenge.

In addition, significant effort has been invested in improving the performance of organic PV cell technology, utilising environmentally sustainable materials and processes, industrial scale-up of manufacturing processing and an intense focus on the highly promising metalorganic ammonium tri-halide perovskite material in stand-alone, tandem (see above) or dye sensitised solar cell structures.

B.3.2 Efficiency improvements

Higher solar cell efficiencies mean the same electricity output can be achieved from a smaller module. This in turn means reduced areas needed for deployment and hence also reduced material requirements for “balance of system” components such as support frames and cables. The latter flows through as per kW cost savings from cells to modules, to distribution and final system costs. As shown in Figure B2, one third of the PV projects cited efficiency improvement as a key research aim, indicating the significance of this issue for researchers and the PV sector generally.

There are a number of paths towards increased efficiencies:

- Introducing multi-junction device structures to better capture sunlight energy over the entire spectrum, typically focussing on cost-effective silicon based sub-cells with a suitable high bandgap top cells.
- Introducing high levels of bulk, surface and contact passivation, by charge-state controlled hydrogenation, annealing / gettering and carrier-selective contact methodologies.
- Improving the capture rate of incident photons via spectrum splitting architectures,
- Reducing degradation of materials (critical to highly unstable perovskites) and carrier transfer processes over time.

Techniques being explored under the ARENA program which continue to make incremental improvements include methods of creating the cell voltage by either removing the need for induced junctions, or improved introduction of dopant elements (typically boron or phosphorous) into the semiconductor structure, improving the capture of light energy (optical enhancement)

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[23] Andrew Blakers, 2016, Submission to the ARENA Advisory Panel in response to a request for comment on ARENA’s General Funding Strategy and Investment Plan.

via plasmonic or nanostructured surface structures and novel surface texturing. Significant advances in the latter, which have good prospects for commercial take-up, have been made.

B.3.3 Encapsulation

Another key area requiring research effort is encapsulation, the various methods used to house and protect solar cells from damage or from environmental factors, such as moisture. New technologies, such as perovskites and high blue response silicon solar cells (those utilising fabrication techniques designed to significantly improve the cell response to the high energy (blue) portion of the sunlight spectrum), require better encapsulation techniques to ensure adequate capture of the cell performance improvements and stable performance in the field over long timeframes. Although much of the current research focus is on proof of concept, future work on encapsulation will be crucial to their success. ARENA funded activities which are relevant here include the novel cell interconnection work at UNSW investigating in-situ (direct metallisation of encapsulants) and rear contacting and the novel encapsulation and flexible, coated solar cells being investigated at CSIRO.

B.4 Advanced PV Concepts

New cell types and materials promise a range of new PV applications for which large area crystalline silicon cell structures may not be ideally suited (for instance, flexible, indoor or semi-transparent modules). In the past, a range of small area silicon, such as the ANU "Sliver" cell or thin film technologies, have dominated research efforts. The focus of ARENA funded projects has been on organic and organic-inorganic PV, such as the work on identifying, understanding and synthesising advanced organic materials at the University of Melbourne, University of Queensland, and CSIRO, as well as perovskites at all ACAP nodes and Greatcell (formerly Dyesol) and the earth abundant and non-toxic class of copper-zinc-tin-sulphur (CZTS) kesterites, which have the potential to displace the environmentally toxic or increasingly scarce materials in CdTe and CIGS thin film technologies. Other projects include thin film cells mounted on steel supporting substrates, CZTS coated cell structures on glass and steel and recrystallised thin film silicon on glass.

Longer term projects look at non-silicon based multi-junction device structures (OPV-OPV, OPV-perovskite, and the more exotic hot-carrier and quantum dot based cell structures. Developments in OPV, polymers, perovskites, CZTS were discussed earlier.

Tandem cells and spectrum-splitting architectures provide the means to improve cell efficiencies above the limits of single junction silicon cells and therefore could result in cells with double the current efficiencies within a decade. Commercialisation of tandem cells involves the addition of processing steps to existing manufacturing infrastructure, rather than the complete re-design of production facilities, and so could potentially be achieved relatively quickly.

Spectrum-splitting architectures are providing significant performance improvement but require further work for commercial development. Projects are underway on spectrum splitting architectures at ANU, RMIT and UNSW.

In 2016, UNSW reported a world record conversion efficiency for unfocused light of 34.5% using a 28-cm^2 four-junction mini-module embedded in a prism that splits the incoming sunlight into four bands, using a four-junction cell receiver to extract energy from across the sunlight spectrum. They have also recently reported a 40.6% world record 4-terminal concentrating result for a 287cm^2 aperture area device.

In addition to efficiency, key research areas for these new cell types include stability and material selection. ARENA funding has facilitated a range of research projects involving characterisation, modelling and fabrication of different material combinations and processes in a systematic effort to identify key characteristics needed for stable, efficient and non-toxic cells.

Research into advanced concepts will provide the technologies of the future. ARENA has supported a number of developments in the nano-technology area, which show promise for future cell structures. These include up-conversion, where the energy of photons below the conduction threshold are combined to reach the threshold and thus become available for use by the cell. Examples include work at UNSW on nano-material structures and layers and enhanced light capture at the cell surface, such as the work at ANU on plasmonics, using nano-scale particles (such as silver and carbon). These concepts are at an early stage of exploration and it is too early to assess which, if any, of the many avenues being explored will eventually result in feasible and cost effective methods. Nevertheless, proof of concept has been achieved under a number of ARENA projects and this work remains crucial for continued development of photovoltaic technologies.

B.5 Commercial Issues and Trends for PV

For commercial success, the key issue remains cost reduction. The industry now is global, of material size and fiercely competitive. Cost improvements provide significant advantage and industry interest in commercialising research outcomes is often driven by cost reduction potential.

Collaborative partnerships between research organisations and industry, which have been facilitated by ARENA projects, are providing researchers with immediate feedback on commercial feasibility and priorities and allowing researchers to learn and speak the language of the manufacturing industry. Coursework in PV Manufacturing is now in place at several universities (UNSW / ANU for example), and industrial scale facilities allow the demonstration of manufacturing parameters industry vitally relies on – yield, total cost of ownership / cost of product, capacity planning / dynamic process flow modelling. The new industrial-scale facilities which allow demonstration of new technologies – the UNSW Solar Industrial Research Facility (SIRF), CSIRO Clayton - will be crucial to retaining Australia’s world-leading research edge and commercially promoting the outcomes. The trend internationally for many key research competitors has been to establish such facilities in conjunction with local industry.

Much of the ARENA research on silicon technologies involves work with commercial partners. The Hydrogenation project has 22 industry partners interested in further development prior to commercial adoption. The Power Cube project involves Australian start-up company Raygen. ANU’s Sliver cell technology has involved commercial partners.

Key opportunities for commercialisation of organic PV (OPV) and other new technologies will also require investment in manufacturing-scale demonstration facilities, in collaboration with interested industries. In this regard, ARENA has supported Dyesol (now Greatcell) in its development of perovskites, as well as Bluescope Steel, in its development of thin film / BIPV products, including CZTS. Continued efforts are required to encourage collaboration between industry and key researchers.

As the PV industry matures, more advanced research facilities are needed. ARENA has funded advanced characterisation facilities at ANU (ASI Foundation Project) and other centres, as well as activities in advanced technologies utilising nanofabrication techniques. As technologies move into areas of very high performance and novel materials and manufacturing techniques, researchers will increasingly be accessing novel characterisation and processing technologies, such as synchrotron beam line soft x-ray spectroscopy, neutron scattering crystallography, soft impact (Argon ice-ball) ToF SIMS (time-of-flight secondary ion mass spectrometry) and nano-fabrication techniques.

B.6 Implementation Issues and Trends for PV

While PV manufacturing is dominated by China and South East Asian countries, on the deployment level, local capacity remains crucial to cost effective utilisation and will become increasingly important as PV module costs drop.

Regulatory and political hurdles remain a key factor in global success rates for PV. For example, soft costs (permits and approval processes) in the US[24] keep prices there much higher than in Australia, where standard connection agreements were negotiated a decade ago for small systems. Conversely, Australia has yet to develop standardised procedures for commercial-scale systems and, though growing, these remain a significantly lower proportion of overall systems than in equivalent sized PV markets worldwide. Similarly, large scale PV systems deployed in the Middle East and elsewhere are now reaching contracted at or below AUD0.03[25], while Australian systems to date have been significantly more expensive, with higher costs of capital and immature deployment procedures playing a major role. However, recent auctions by ARENA and State Governments in Australia have achieved or set prices below AUD 0.06/kWh, indicating that deployment experience is being developed, finance risk factors can be reduced with government guarantees, and so the large-scale market may start to increase.

B.7 Resourcing Issues and Trends for PV

Australia produces world-leading PV specialists but, without local opportunities, the majority of these experts go overseas for industrial employment. Australian - trained technologists retain key positions in all the leading PV manufacturing facilities, including Suntech, CSun, JA Solar, CSG Solar, Sunrise, Canadian Solar, REC Solar, Hanwha, Tetrasun / First Solar[26], as well as in some of the successful deployment companies, such as Sungevity.

ASI/ARENA support of PhD and Post-doc positions has been instrumental in establishing a new generation of skilled personnel for both research and deployment. This group is now proactively exploring new technologies and new business opportunities. ARENA project funding has served to retain them in Australia longer than has typically been the case.

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[24] Rocky Mountain Institute, 2014, *Lessons from Australia: Reducing Solar PV Costs through Installation Labour Efficiency*, RMI and Georgia Tech Research Institute. http://www.rmi.org/simple.

[25] https://cleantechnica.com/2017/10/07/the-birth-of-a-new-era-in-solar-pv-record-low-cost-on-saudi-solar-project-bid/

[26] Martin A. Green, “Global Perspectives and Insights on PV in China”, presentation at Freiberg PV Technical Workshop.

Investment issues arise from lack of local investor experience with renewables, as well as lack of long term policy stability. Significant investment was made by both local and international companies when the RET was expanded to 45,000 GWh in 2008. After 2013, prolonged political uncertainty around the target saw the market stall, with many businesses failing and investors pulling out. The CEFC and ARENA plugged the gap to an extent, and continuing price drops are now driving investment. Nevertheless, clear policy drivers are critical to future renewable energy market development, regardless of technology cost decreases.

Energy market reform is also a key element in driving investment decisions, since the current market structure does not necessarily favour new players or the new opportunities available, largely through PV, for customer-based solutions. ARENA has supported a number of policy and market-related projects through its R&D and other programs, including via the Australian PV Institute, the Clean Energy Council and the Electricity Networks Association.

Projects include integrating high penetration PV systems into the NEM, models for community owned solar farms, social license to operate utility-scale solar and Australian involvement in IEA PV Power Systems and Solar Heating and Cooling activities.

B.8 PV Industry Engagement Opportunities

PV researchers are working within a global industry, and so need to work with the leading global companies. Collaborative research is a good way to start industry engagement. Through the ARENA projects, Australian universities are now working with the top PV manufacturers, via their commercialisation arms, rather than through establishment of a separate local manufacturing industry.

Industrial-scale demonstration is critical to industry engagement, to ensure researchers are cognisant of industry production issues and can examine all the ‘real’ costs of production in the manufacturing chain. The new Advanced Manufacturing course at UNSW, which targets industry related issues, was part funded by ARENA via the Australian Centre for Advanced Photovoltaics (ACAP). Outside of ARENA, Australian Research Council Linkage grants and Cooperative Research Centres have provided an important facility by directly involving industry in the research. In parallel, focussed funding to Centres of Excellence has provided a useful way for industry to know that they are dealing with the top researchers. However, industry also looks for R&D tax concessions and other funding opportunities to cover research costs and compete with industry across the world.

Australia remains a leading PV research hub but increasingly competes against countries which focus heavily on establishment of new industry sectors, including support for large-scale solar demonstration facilities, such as the Solar Energy Research Institute Singapore (SERIS), Taiwan’s Industrial Technology Research Institute (ITRI), Hong Kong Technology Park, the European based centres (Fraunhofer Institute for Solar Energy Systems (FhG ISE), and the Scandinavian OPV focussed technology centres (Technical University of Denmark, DTU).

The Chinese Torch program[27] has seen the establishment of 54 Science and Technology Industrial Parks, which now contribute around 50% of the country’s R&D and 7% of China’s

[27] Blank, S., 2013, China’s Torch Program: The Glow that can Light the World, The World Post, June 12, 2013, http://www.huffingtonpost.com/steve-blank/chinas-torch-program-the-_b_3063069.html.

GDP. Interestingly, the first Torch precinct outside China is to be established at the University of NSW and will include energy research[28].

These large 'technology parks' allow manufacturers to share the costs of training, infrastructure and materials supply, while working synergistically in the development of new products and processes. A similar clustering of support companies served to maintain the Australian car industry for many decades, and has left a legacy of skilled personnel and specialist companies. 'Vertical integration' of PV manufacture in China, via co-location of infrastructure facilities and related industries, has been one of the contributors to lower costs and rapid development. Such integration has now moved to individual companies, with silicon manufacture through wafer, cell and module production, as well as systems design and deployment. This also means that the significant PV players are now large companies, since small entities, which made up the industry in early years, are no longer able to compete.

B.9 Analysis of PV Funding Allocation and Effort

B.9.1 Research Process

Allocation of funding by "Process" is shown in Figure B3. The most significant investment has been in projects focussed on improving manufacturing processes. This is linked to the focus on efficiency improvements for silicon-based technologies, as well as to the development of new technologies.

Other important research areas are exploration of advanced materials for the next generation of PV technologies, and device structure development and characterisation (again linked to the commercial focus of silicon-based research).

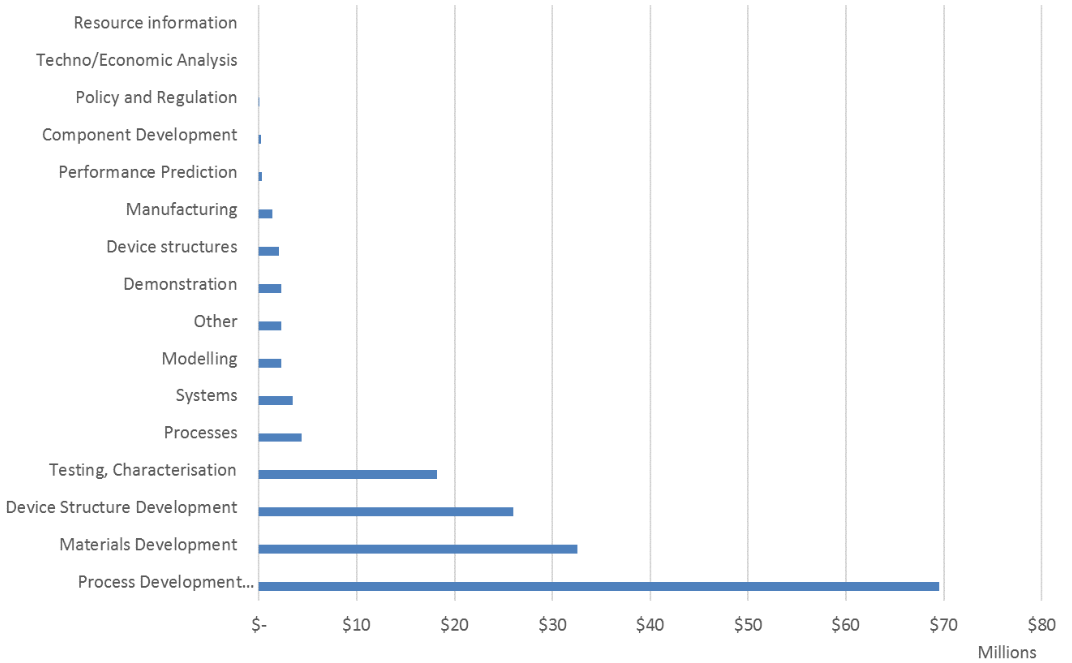

Figure B3: Allocation of PV funding by Research Process

[28] Asian Scientist, 2016, China's Torch Program launches US$77m Australian Precinct, 28 April, 2016, http://www.asianscientist.com/2016/04/topnews/china-torch-us77-million-australia/

B.9.2 Technology Readiness Level

PV R&D funding has been provided to projects expecting to achieve final TRLs across the full TRL spectrum, as shown in Table B1. This indicates a well-balanced research effort, which should result in a continued stream of outcomes over time. Note that, for many projects, a TRL could not be estimated or was irrelevant, due to the nature of the research (for instance, market studies). For this assessment, the 66 PV Scholarship and Fellowship awards which had been allocated TRLs have been excluded.

Table B1: Allocation of PV R&D funding by Technical Readiness Level (TRL) at project start and anticipated at project completion

TRL Start	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Total**
TRL Finish										
2	7									7
3	16	16								32
4		14	4							18
5	2	28	4	3						37
6	1	7	4	6	2					20
7		1	7	2		2				12
8		2		1	3		2			8
9					1	1		1	1	4
Total	**26**	**68**	**19**	**12**	**6**	**3**	**2**	**1**	**1**	**138**

B.9.3 Lead organisation

Allocation of funding sorted by the organisation leading the research project is shown in Figure B4 and again reflects the dominance of UNSW and ANU in PV research, but also shows active research across a range of industry and other research groups.

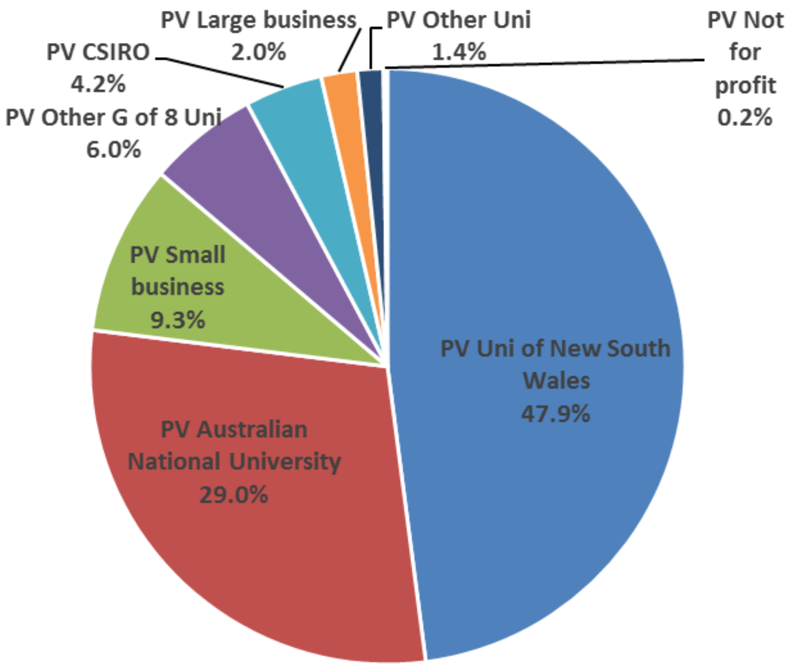

Figure B4: PV R&D funding ($165m) by lead organisation

APPENDIX C: ANALYSIS OF CST PROJECTS

C.1 Background

By the end of 2017, global installed CST power generation capacity had increased to around 5.1 GW as shown in Figure C1. Spain and the US are where most development has occurred but, in the last few years, activity in other regions has grown, particularly in China, Chile, the Middle East, North Africa and South Africa.

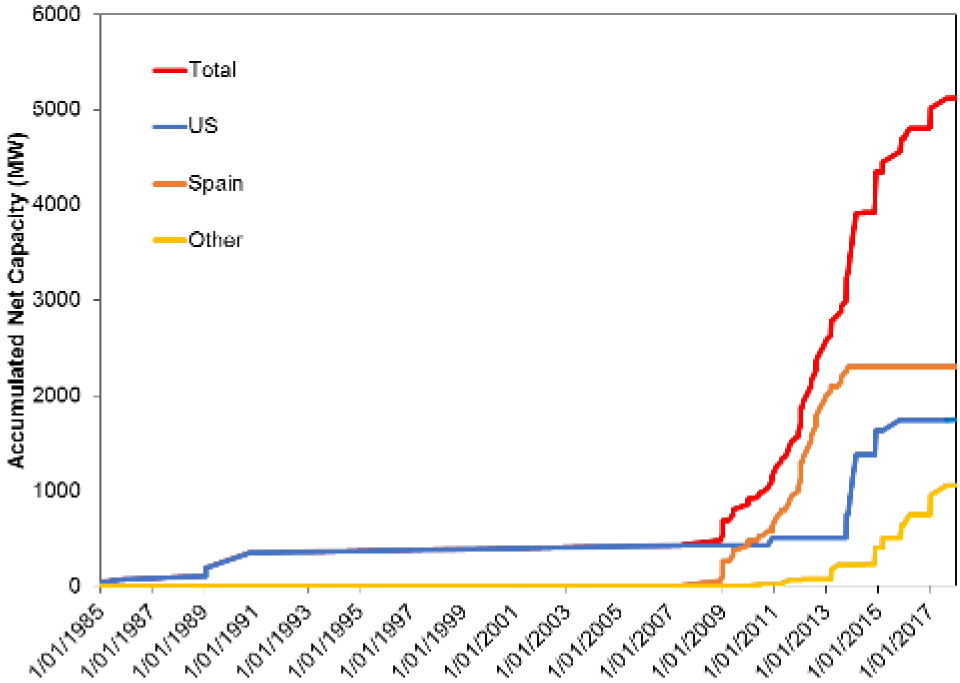

Figure C1: CST Installed capacity growth, (ITP, 2018).

The 2012 Concentrating Solar Power (CSP) in Australia study[29] predicted that the cost-revenue gap in Australia between existing electricity generation and solar thermal power systems is likely to close before 2030. More recent analysis forecasts the cost-revenue gap is likely to close much sooner. Australian and US research efforts, combined with overseas deployment activities, have contributed to this improved market outlook.

[29] IT Power Australia, 2012, *Realising the Potential for Concentrating Solar Power in Australia,* Report for the Australian Solar Institute.

The forecast cost of electricity from the IEA's *2014 Technology Roadmap: Solar Thermal Electricity* is illustrated in Figure C2.

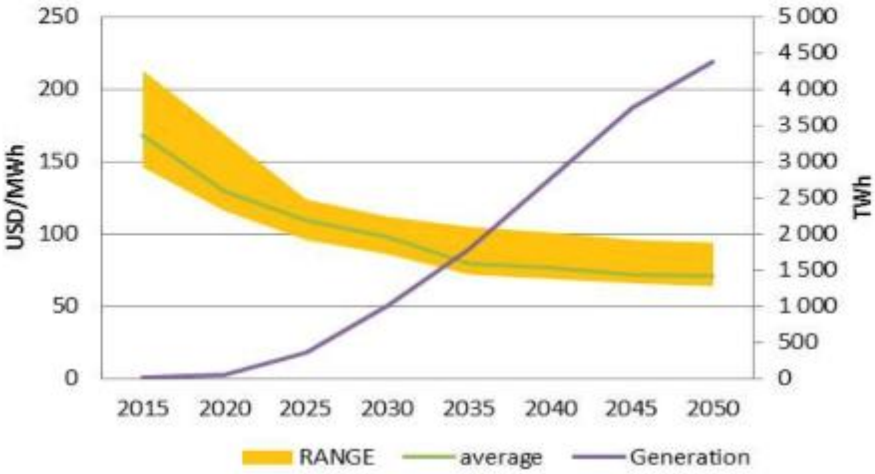

Figure C2: Forecast Cost of Electricity and Generation for CST Power Systems, (IEA, 2014).

Cost figures for Australia from 2015 and 2017 indicate that $150/MWh should be currently achievable in this country[30].

Globally, the CST power industry is dominated by a handful of large players in project development and equipment manufacture. These companies have only had a small presence in Australia as, to date, Australia has not had the market conditions needed for large-scale deployment of CST technologies.

If the CST sector is compared to wind and PV, it can be observed that, globally CST is currently around 2% of the size of the PV sector in installed capacity and annual investment. However, the growth trends for all three of these technologies have a similar pattern, but with different timings. The trajectory of PV is similar to that of wind, but a decade behind. CST shows the same pattern but another decade behind PV. The deployment capacity of CST in 2016 is very close to that of PV in 2006. While the future prospects for CST technologies are huge, deployment in the short term will depend on policy settings in the key sun-belt countries where it is most applicable.

The bulk of current CST construction is using the mature trough technology, with tower systems the next most mature. Linear Fresnel is at an earlier stage of commercial deployment. The French energy conglomerate, AREVA, purchased the start-up company Ausra, which had developed a Linear Fresnel system that had its origins in Australia. Before exiting the business, AREVA completed a 125 MW_e system in India[31], but failed to complete the 44 MW_e Solar Boost project at Kogan Creek[32] in Australia.

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[30] *Pathways to Solar Thermal Electric cost reduction - Perspectives from the Abengoa Perenjori Study*. Prepared by IT Power for Abengoa March 2015. SolarResereve ASTRI workshop presentation, Melbourne June 2016

[31] http://social.csptoday.com/markets/india's-pv-led-solar-growth-casts-eyes-performance-csp-projects

[32] http://reneweconomy.com.au/2016/kogan-creek-solar-boost-should-be-completed-29923

Dishes are the least mature approach, with activity largely confined to demonstration systems. However, dishes offer the highest system efficiencies and could well make a comeback as distributed field systems with thermochemical or other energy conversion approaches.

Prior to the establishment of the ASI, CSIRO had established its National Solar Energy Centre in Newcastle and reached a view that high temperature approaches via tower systems was the best strategic approach for R&D activities. This was a prescient choice that came before the general industry consensus emerged in this direction. It was motivated by the understanding that higher concentrations and temperatures allowed more complex energy conversion systems to be operated and higher electricity generation efficiencies to be achieved. In addition, the tower approach was more open to a new Australian initiative than the well-established international efforts in trough systems, and also offered a larger set of useful and challenging R&D topics.

ANU had a history of CST investigation dating back to the early 1970's. From that early stage, Dish systems were chosen as the core area of interest. As with CSIRO's thinking, the benefits of high concentration and high temperatures were central to this, plus the key points that dishes offer the highest optical efficiencies of all CST approaches and are more modular for production and investigation.

Thus, at the formation of the ASI, a consensus quickly developed that high concentration, high temperature systems should be the priority and this thinking largely continues today and is very much the priority of ASTRI. The possibility of work with linear concentrators was not precluded, however, non-concentrating, low temperature solar thermal work was.

Of the 48 projects analysed in the CST category (plus 20 ASTRI sub-projects), the largest number were under the original ASI program. However, there have been a significant number of fellowships awarded from ARENA since the end of ASI. Continuing projects have been under various programs and ASTRI currently plays a key role for institution-based research.

C.2 CST Research Groups and Facilities

In 2009, the ANU and CSIRO CST groups were recognised by ASI as the main Australian CST research organisations. Since 2009, Australia has seen a large increase in resourcing for CST R&D via ASI and ARENA. A wide range of organisations have received support. Among the research institutions, CSIRO, ANU and the University of Adelaide have the largest CST research programs. There are also CST research groups at the University of Queensland, QUT, RMIT, UNSW, UniSA and other organisations, with growing industry linkages.

The Australian CST research community is strongly engaged with the international research community, particularly via:

- the IEA SolarPACES program[33], and
- the strong linkages with US institutions that have followed from the US-Australia Solar Energy Collaboration and ASTRI initiatives.

The recent evolution of the three largest groups is briefly reviewed here.

[33] www.solarpaces.org

C.2.1 Australian National University

ANU has worked on CST activities since the area was pioneered in the early 1970s. Support from ARENA has been central to recent growth of capability at the ANU group. ANU has had three ARENA funded projects, a post doc fellowship and two R&D projects as well as a key membership role in ASTRI, in addition to a pos tdoc fellowship in 2012 and a project on dish receivers ending in 2015 originating from the ASI program.

As well as the world leading dish research facilities (notably including the 500m^2 SG4 'big' dish), new laboratory facilities have been established with internal investment and support from ARENA. These include a new 45 kW$_e$ high-flux solar simulator test facility and a sodium test laboratory.

C.2.2 CSIRO

The Newcastle Solar Research Centre was established in 2005 with the first tower system and the SolarGas process of solar reforming methane as key research areas. CSIRO has significantly increased its CST capability with ARENA funding and is also the lead agency for ASTRI. Major new CST research infrastructure includes:

- A 1 MW$_{th}$ heliostat field and tower system with extensive instrumentation and control room facilities, complementing the existing 750kW$_{th}$ field,
- Steam test loop,
- High temperature laboratory,
- Thermal energy storage system, and
- Supercritical CO_2 test rig.

CSIRO aims to maximise industry involvement in its research. This alignment, plus its status as the country's lead national research organisation, has facilitated a range of strong industry collaborations in the CST area. Key industry partners to date include Abengoa, GE, Mitsubishi Heavy Industries and Toshiba. Abengoa was involved in several projects and this gave CSIRO's work a direct input into a leading international commercial CST developer.

CSIRO's Newcastle Solar Research Centre is likely to be well utilised by researchers and industry for many years to come.

C.2.3 University of Adelaide

The University of Adelaide made a strategic decision to target activities in CST in 2009. This initiative was led by their Centre for Energy Technology and built on a strong background in combustion systems, which led to a particular focus on hybrid CST and fuel driven systems.

CST research activities were initially expanded via ARC linkage and State Government support. The first CST grant from ASI came in the form of a post-doctoral fellowship examining solar fuels, but the major growth in their activities has come via their subsequent membership of ASTRI, which allocated a $0.4m per year budget for their lead role in the solar fuels project and other work on receivers and energy storage. Key laboratory facilities have now been established and enhanced, including a high-flux solar simulator.

The University of Adelaide has been awarded a $4.5m grant for investigating CST applications for the Bayer Alumina Refining process, in conjunction with CSIRO, UNSW, Alcoa, Hatch and IT Power.

C.2.4 University of South Australia (UniSA)

UniSA's main CST research focus has been on high-temperature thermal energy storage. A test facility for high-temperature storage materials that was established with ASI funding has been the basis for ongoing research on phase-change storage materials and systems and their integration with solar thermal systems. Four PDF scholarship projects have been conducted at the laboratory. In addition, UniSA is leading the PCM storage research within ASTRI.

C.3 Improving Current CST Technology

Research efforts to reduce the cost of energy include a focus on reducing deployment costs and improving system efficiency. Efficiency in turn is a product of the subsystem efficiencies:

- Optical efficiency - how reflective are the mirrors, eg heliostats, and how accurate are they at directing the light into the receiver.
- Receiver efficiency - how much of the energy intercepted is absorbed rather than lost from re-radiation and other heat losses.
- Heat transport efficiency - reduced by heat losses from conduction through insulation and parasitic energy for pumping requirements.
- Storage efficiency - reduced by heat losses from conduction through insulation and other mechanisms.
- Power cycle conversion efficiency - losses from taking heat and converting it to electricity or other useful products.

Optical efficiency is addressed in conjunction with improved heliostat or collector designs. Significant international efforts have already gone into this area. In Australia, Raygen, Vast Solar, CSIRO and ASTRI are all making original contributions to heliostat design.

Receiver efficiency is increasingly critical, as higher temperature receiver designs are developed for tower systems. It is a key topic for both Australian and International R&D. The ANU bladed receiver project is an example of a novel idea for re-working the geometry of a tower receiver with blade shaped elements that suppress convective heat loss. It is a joint project with the US Sandia laboratories, a partnership that followed the ASI initiatives aiming at encouraging Australia and US solar research collaboration. It aims to identify optimised arrangements that should improve receiver efficiency with minimal increase in capital cost and is the subject of a patent.

Storage and transport efficiencies are already high, although there is still room for improvement. For those sub-systems, the effort is more directed at cost reduction and development of approaches compatible with higher operating temperatures and without the challenges of solar salt's high freezing point. Vast Solar's approach of using sodium as the heat transfer fluid has the potential to provide benefits in this area.

The biggest limiting factor on overall solar to electric conversion efficiency is the power cycle used. So far, commercial CST systems have all used steam turbine power blocks. These are a mature technology with little scope for further efficiency improvement. However, their efficiency is increased by higher steam temperatures and pressures. This is one of the reasons why tower systems are increasingly favoured over trough systems.

C.4 Advanced CST Concepts

Globally, two key areas of effort seek to provide a step change improvement in power turbine cycle efficiency:

- utilising an air turbine plus steam turbine combined cycle system, and
- development of the supercritical CO_2 cycle.

The combined cycle approach is used with natural gas fired turbines in the power industry and provides conversion efficiencies of around 55 to 60%. To adapt it to solar operation, receiver systems that heat air to more than 1000°C are needed. This has been demonstrated internationally and CSIRO has also tested an air receiver in conjunction with Mitsubishi Heavy Industries. Development of an energy storage system compatible with such temperatures is a further key R&D challenge. The ANU's investigation of high temperature thermochemical energy storage targets this application.

The supercritical CO_2 cycle offers excellent potential for achieving a conversion efficiency of around 50%, with more modest inlet temperatures of around 700°C. A significant effort is being invested in the US and elsewhere in the development of CO_2 turbines. The University of Queensland is showing good progress on developing a unique, smaller (sub 5 MW) sized CO_2 turbine and CSIRO has two CO_2 turbine related projects.

Other new energy storage technologies have been investigated, in addition to the thermochemical project at ANU. These include CSIRO with a system based on Alumina balls with CO2 as heat transfer fluid. UniSA has worked for many years on advanced phase change based systems and continues this under ASTRI. Graphite Energy Pty Ltd received support for an integration project involving tower mounted integrated thermal storage receivers using graphite.

Another key area of advanced work that offers great commercial potential in the longer term is the direct thermal production of solar fuels. This has been the subject of a detailed roadmap study by CSIRO. The study showed strong potential for solar thermal fuel production to be cost effective in a low carbon world and identified a potential future market for production of hydrogen rich fuels for energy export markets, such as Japan and Korea.

At a practical level, CSIRO continues to explore solar driven methane reforming. ASTRI is also examining a range of solar fuel processes, including gasification of biomass and coal. Internationally, much advanced work examines the thermochemical splitting of water and CO_2 to produce pure solar fuels.

Industrial process heat innovations have been targeted with CSIRO's project to apply small scale troughs to providing process heat for solar driven air-conditioning. The MUSIC (Micro Urban Solar Integrated Concentrator) project at RMIT is developing a new roof mounted evacuated tube based micro-concentrator system that seeks to produce 200°C process heat with minimal moving parts. CSIRO have also tested the application of solar troughs to the thermal regeneration of post combustion capture of CO_2. Most recently The University of Adelaide has commenced a project investigating CST applications for the Bayer Alumina Refining process, in conjunction with Alcoa.

C.5 Whole of CST System Integration

CST systems are by their nature complex and whole of system integration has naturally been a major part of the industry's effort. With the great success in reducing the cost of PV systems, CST is no longer the cheapest source of variable solar electricity. However, it does have a clear advantage when systems with several hours of storage are sought.

A CST system can be designed to have variously sized solar field, storage system and power block. For CST systems with no storage, the lowest cost of energy is achieved when the solar field is larger than required by the power block at peak solar conditions, with a fraction of the field being defocussed at these times. Adding thermal storage has the advantage that the full output from the solar field can be utilised, thus improving annual performance. This lowers the LCOE, with the minimum LCOE occurring with around 15 hours of storage (see Figure C3), although this may not provide an optimal economic return.

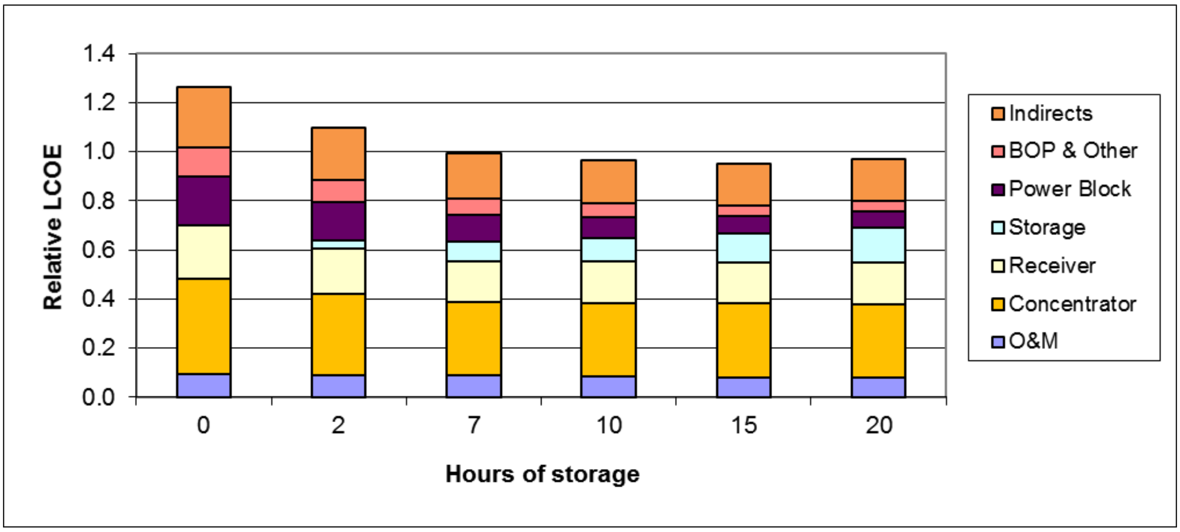


Figure C3: Modelling LCOE as a function of storage hours for a molten salt tower plant for Longreach Qld[34].

Current thinking is that the optimal economic return may be offered by a configuration with around six hours of storage that acts as an intermediate / peaking plant. This offers the best way to complement very high levels of variable renewables. One of the key advantages of tower systems over trough is that the higher temperature difference produced between the hot and cold tanks of the thermal storage system makes the storage considerably more cost effective.

[34] *Pathways to Solar Thermal Electric cost reduction - Perspectives from the Abengoa Perenjori Study*. Prepared by IT Power for Abengoa March 2015

C.6 Implementation Issues and Trends for CST

Despite the strong support for CST R&D over recent years, Australia has failed to complete construction of a utility-scale plant. This can be attributed to a range of factors:

- The need for bespoke design and large projects due to the inherent inefficiency of smaller steam turbines.
- Dominance of coal-fired capacity in the NEM, meaning that the benefits of CST systems in regards to flexibility, grid support and ancillary services are not recognised or valued to the extent they would be in a future system with large penetrations of variable renewable generation.
- No technology or time of generation differentiation in the Renewable Energy Target, to reflect the real time value of energy supply linked to energy demand, such that the lowest LCOE technology (wind) dominates.
- Early mover CST project failures, resulting in an adverse perception about the role and capability of CST as a cost effective component of a future energy supply.

A consequence of the lack of a utility-scale CST system is that policy makers, financiers and the community have not had the chance to develop a familiarity and understanding of the technology first hand in Australia.

CST power systems are inherently of utility-scale, not-withstanding efforts to drive them down to smaller modular systems in the 10's of MW_e. Thus the capital investments needed are significant, with the additional challenges that brings. To date, there has been a cost gap between the realistic income stream that a CST power plant could produce and its annualised cost. While this gap is closing faster than many expected, wind and PV are forecast to be the main beneficiaries of the RET under its current rules and end date of 2020.

C.7 Resourcing and industry engagement for CST R&D

Since 2009, Australia has seen a significant increase in resourcing for CST R&D. A total of $96m has been allocated to CST R&D by ARENA/ASI so far. However, funding peaked at the end of 2014 and currently declines over the coming years. Most ARENA/ASI funded projects have already been completed or are scheduled for completion in 2018. The only major ongoing projects are the second stage of the ASTRI program currently scheduled for a further 2+2 years starting in mid-2018, and CST in the Bayer Alumina process project, which is scheduled for completion in 2021.

Whether this trend in declining R&D funding continues will depend on future positions of Government and ARENA. The consequence of declining funding would be a large number of newly trained PhD graduates and post docs unable to continue their work in Australia and under-utilised research facilities.

In the absence of a clear path to deployment of CST in Australia, the large international CST companies have had only a small presence here. Consequently, it has been hard for the various research groups to form meaningful commercial partnerships. A notable exception was Abengoa Solar, which partnered with CSIRO for two key projects.

Vast Solar has emerged as an important new Australian CST company. They worked hard to obtain initial partial support via a small grant and a PhD scholarship. Technical progress has been made as they have progressed through a series of funded projects and are now in the process of commissioning a 1.1 MW_e pilot system that incorporates many innovative approaches.

There are also major opportunities for CST to displace gas for supply of heat to industry. This may provide opportunities to further develop local capacity. The recently awarded project to the University of Adelaide to work on supply of solar thermal heat to Alumina refining in collaboration with Alcoa is a good example. While solar thermal air-conditioning faces many economic challenges, the match between the resource and the load means research and demonstration projects, such as the one lead by CSIRO, are likely to attract global interest.

C.8 Analysis of Funding allocations and effort

C.8.1 Technology type

The breakdown of funding by concentrator type is shown in Figure C4. It can be seen that Tower systems dominate. This reflects the overall dominance of CSIRO in CST research, the initial strategic decision by ASI to give priority to high concentration systems and then by ASTRI to also follow the tower route. This is a stronger emphasis of effort than might be found in other countries where the presence of a strong industry sector with a commitment to trough systems would bring with it an effort to address the more incremental R&D issues to improve existing trough technology.

R&D funding related to trough technology comprises pilot projects for the demonstration of new CST applications (e.g. for CO_2 capture from power plants) and novel technology developments such as the micro-urban solar integrated concentrator, a new compact combined heat and power collector for roof-top integration.

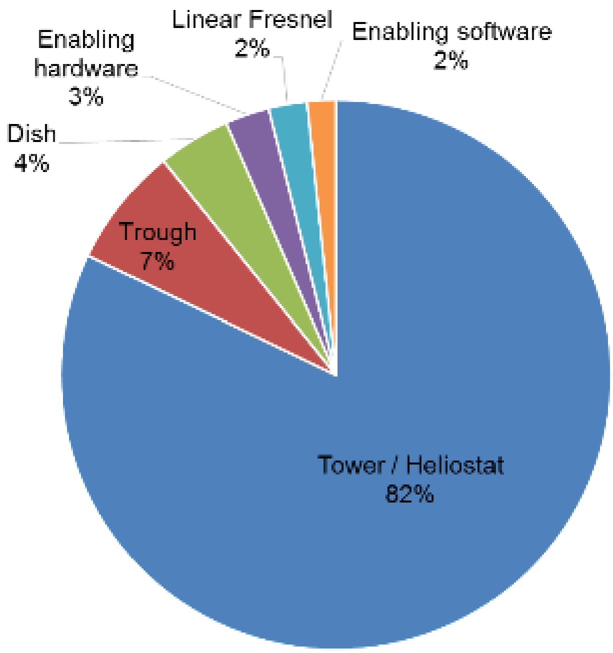


Figure C4: CST R&D funding ($96m) by concentrator type

C.8.2 Research area

In line with ARENA priorities, all projects are attempting to advance the industry in some manner, within the overall goals of cost reduction and increased deployment. Thus the aim of a project is to either reduce the cost of delivered energy, increase its value and applicability or otherwise support its progress to or in the market. The projects have been analysed across a range of alternative methods for doing this, as shown in Figure C5.

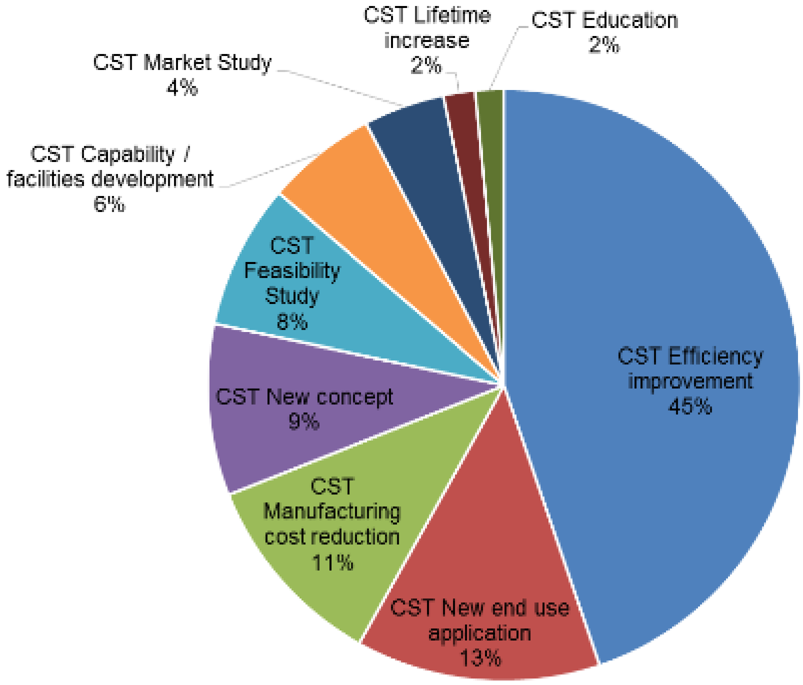


Figure C5: CST R&D funding ($96m) by type of research.[35]

Efficiency improvements have received highest priority with nearly half of all funds invested in this area. This is a sensible approach to prioritisation. As a relatively new technology, CST offers several opportunities for efficiency improvements, ranging from reduced optical losses in the solar field to receivers with reduced heat losses and new power cycles operating at higher temperatures. Advances in efficiency improvement developed in Australia, if they can be found at close to the same capital cost, directly translate to lower levelised cost of energy. As such, they are much more likely to be taken up by global players than are changes to manufacturing approaches in order to reduce costs. The large global players in the industry have intense in-house commercial-in-confidence efforts to improve their manufacturing processes and they are unlikely to look to Australian organisations for significant input on this.

Efforts in Australia in the manufacturing of components need to rely largely on local start-up companies to either initiate them or commercialise them, if they are going to be taken up in the

[35] A decrease in the sections for manufacturing cost reduction and an increase in efficiency improvement can be observed compared to our previous report in 2016. This shift is mainly due to a reassessment of the work within the ASTRI program, which was previously considered to mainly target cost reductions and has now been attributed to multiple targets including efficiency improvements, and others.

market place. Typically, these efforts focus on domestic market needs, such as technologies specifically designed for off-grid/fringe-of-grid applications.

Another focus area was on new concepts and new end use applications, which combined received 22% of funds. These categories comprise new technological approaches that may lead to step changes in efficiency, cost or value of product, or promise to open up new markets for CST. Examples include concentrated solar fuels technologies, new high-temperature storage materials, or introduction of CST into industrial processes for poly-generation (combined heating, cooling, power generation) or CO_2 capture and storage.

Also of significant importance have been feasibility and market studies, which form the foundation of long-term strategic decisions and provide valuable guidance for R&D and deployment efforts. An example is the concentrated solar fuels roadmap which showed the potential of and likely pathways to an Australian renewable energy export sector and increased the awareness of the opportunity among stakeholders and decision makers.

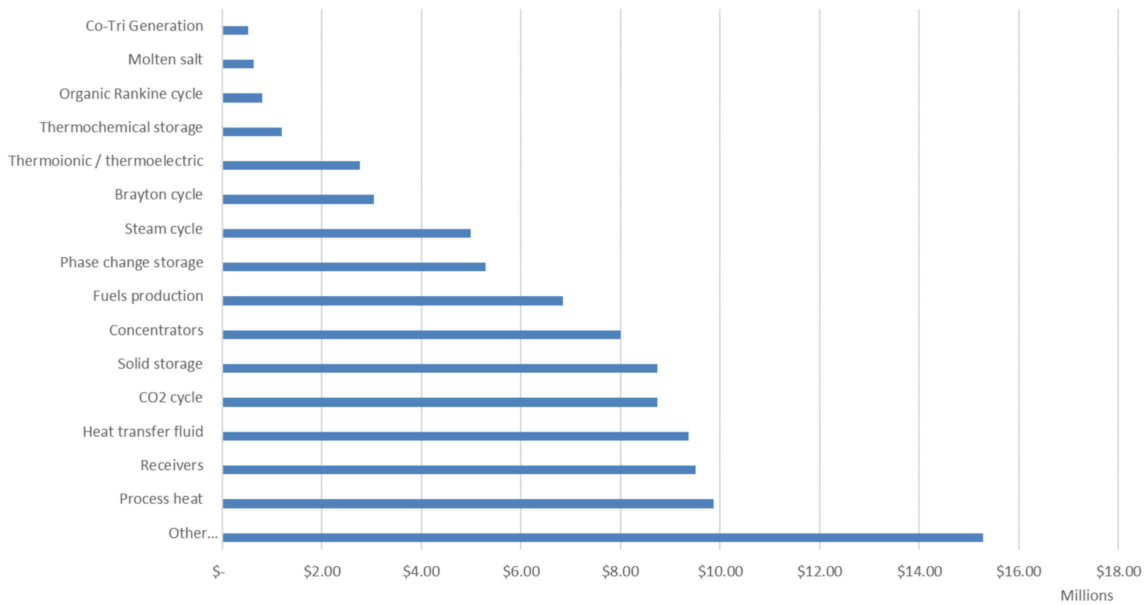


Figure C6: CST R&D funding ($96m) by technical subject.

Alternatively, if projects are sorted by the direct technical subject examined, the results are as shown in Figure C6. Research funding has been spread over several technical areas, both in terms of technological areas and applications. Major investments have been made into new power generation technologies, receivers and heat transfer and thermal storage media, with the overarching goal of enabling operation at higher temperatures and with lower heat losses in order to improve the overall efficiency of CST power plants. This is consistent with overseas work that seeks to find step changes in innovation.

Besides on and off-grid power generation, target CST applications included industrial and domestic process heat, solar fuels production and poly-generation.

The category “Other” includes cross cutting work not easily attributed to one category at this level, which is likely to benefit multiple technological areas or systems as a whole. Examples include research on alternative power blocks, development of new solar research facilities and technology road-mapping, techno-economic system modelling and educational activities.

C.8.3 TRL Progression

The starting TRL and likely TRL's at the end of the funded projects (excluding scholarships and fellowships) are shown in Table C1 and span most of the range. Many should be quite high. As a research area, CST tends to be more applied in nature and there are many projects that are attempting to bring a concept to the pre-commercial levels of TRL 5 or 6. There are, however, less projects that aspire to reach TRL 7 or 8, which might be seen if a company actually deploying the technology was the driver behind the work. At the other end, there is still work at or below TRL 2, representing very new concepts.

Table C1: Starting TRL and anticipated TRL at completion of CST projects

TRL Start / TRL Finish	1	2	3	4	5	6	7	8	9	Total
1										**0**
2	3									**3**
3		3								**3**
4		5	4							**9**
5			7	4						**11**
6			2	3	7	1				**13**
7						2	1			**3**
8								1		**1**
9										**0**
Totals	**3**	**8**	**13**	**7**	**7**	**3**	**1**	**1**	**0**	**43**

C.8.4 Organisation

Examining the funding committed to CST projects by lead organisation (Figure C7) it is seen that the two institutions that had established R&D groups on CST before the creation of ASI and ARENA, ANU and CSIRO, received the largest individual contributions, sharing about half of all funds, while the other universities combined received approximately one third of all funds.

Large businesses are a small sector, reflecting the low presence of the large global players in Australia, in turn reflecting that the industry is not yet established here. The small businesses as a class are quite strongly represented. This includes, Graphite Energy, Granite Power and Vast Solar.

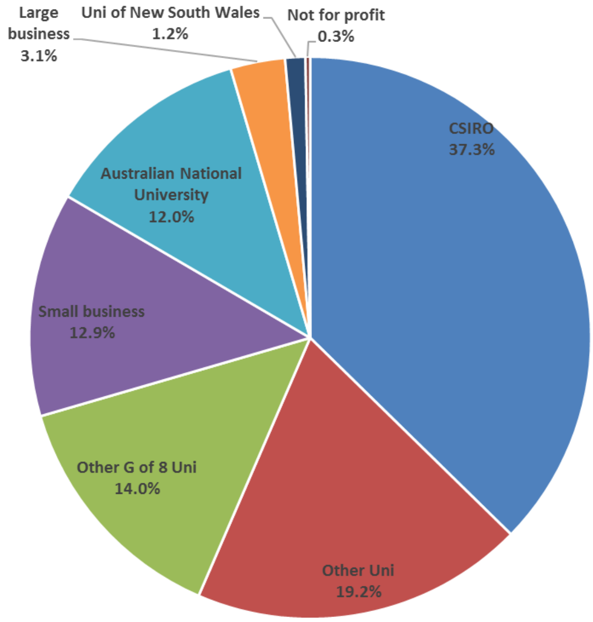


Figure C7: CST R&D funding ($96m) by organisation.

There has been a strong progressive growth in the level of activity and capability in CST R&D activity in Australia since 2009. So far, the support has been reasonably consistent and none of the newly strengthened groups has suffered a major end to funding, which can happen with off again / on again initiatives. ASTRI appears to be playing a very important role of ensuring stable funding over an extended period for the groups involved with it.

CSIRO has experienced some very high levels of funding in the period up to 2014 but it has fallen quite rapidly since then. This may present a challenge to that organisation. Helping to mitigate this apparent effect, CSIRO does have relatively large internal funding (compared to universities) to work with as well as ongoing involvement in ASTRI. Also, large amounts of the initial funding have contributed to major investment in facilities and laboratories that will serve for many years going forward. Central to this is their new solar tower test facility that was built as part of their first ASI foundation project. Subsequent projects have used this facility and each has contributed to the experimental systems, instrumentation and supporting laboratories.

APPENDIX D: ANALYSIS OF ENABLING PROJECTS

Total funding committed to enabling R&D projects between 2009 and 2017 was $30.6m, supporting 38 projects. This facilitated $74.3m in Total Project Value.

For these 38 projects, most involved both software and hardware. Though they were categorised as 26 with primarily a software focus and 12 with primarily a hardware focus in Specific Technology Area 1. A breakdown of the enabling funding commitment by Specific Technology Area 2 is shown in Figure D1. Table D1 summarises enabling project numbers and budgets.

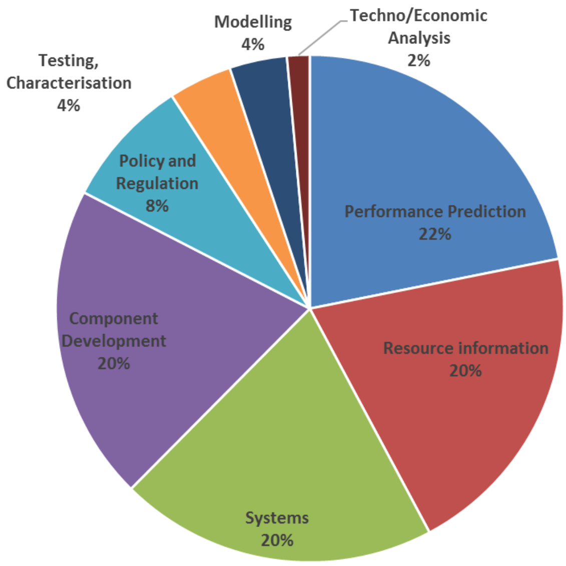


Figure D1: R&D Funding allocations for Enabling projects by category ($30.6m).

Table D1: Overview of enabling projects by category.

	No. of projects	ARENA Funding $m	Total Project Value $m
Performance prediction	7	6.69	16.22
Resource information	4	6.23	7.10
Systems	8	6.20	18.41
Component development	5	6.17	20.04
Policy and regulations	9	2.54	5.22
Testing, characterisation	2	1.24	2.68
Modelling	2	1.12	3.53
Techno/economic analysis	1	0.44	1.11
Totals	**38**	**30.63**	**74.31**

The largest enabling funding commitment was for Performance Prediction, ($6.7m). Five PV specific projects, one CST specific project and one project that benefits both technologies were funded in this category. The projects ranged from $50,000 to support a PhD student to model the financial value of Direct Normal Irradiance forecasts for a CST plant, to $3.1m to develop the Australian Solar Energy Forecasting System (ASEFS). Another project worth highlighting from this category is CSIRO's outdoor testing facility for performance assessment of PV modules under real life conditions.

The next largest enabling funding commitment was for Resource Information, ($6.2m). Four projects were supported, ranging from $100,000 to $5m to improve resolution and access to solar data across Australia. These projects included developing one minute solar data and solar resource assessments that were all precursors to the solar resource data now available from the AREMI website.

The Systems category involved 8 projects with $6.2m in funding. This category involves a wide range of projects including battery developments, hydrogen production, re-deployable hybrid systems, virtual power stations as well as control and management systems.

The Component Development category involved 5 projects with $6.2m in funding. These projects included research to develop and test a sky camera for cloud prediction, battery developments plus a drone camera system and software for inspecting large solar plants.

The Policy and Regulation category involved 9 projects with $2.5m in funding. This category involves a diverse range of projects from supporting PhD students studying issues with integrating high penetration PV systems into the NEM, distributed energy markets, models for community owned solar farms, increasing the uptake of PV in strata residential developments, social license to operate of utility-scale solar and Australian involvement in IEA PV Power Systems and Solar Heating and Cooling activities.

The Testing & Characterisation category had two projects, one examining phase change materials for energy storage and the other analysing the actual variability of PV outputs at various locations to develop improved estimates for maximum penetration of PV without storage.

The Modelling category also had two projects, one investigating micro-grids and the other developing real-time PV simulations for electricity networks.

The Techno/economic Analysis project was a feasibility study for a micro-grid for a new residential development.

The enabling projects funding amounts by ARENA priority are shown in Figure D2.

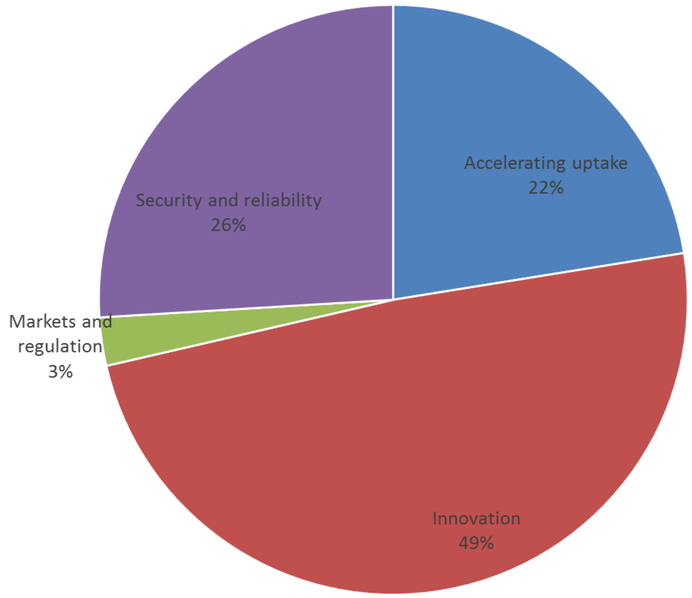


Figure D2: R&D Enabling projects funding by ARENA priority area.

The enabling projects funding by primary goal is outlined in Figure D3.

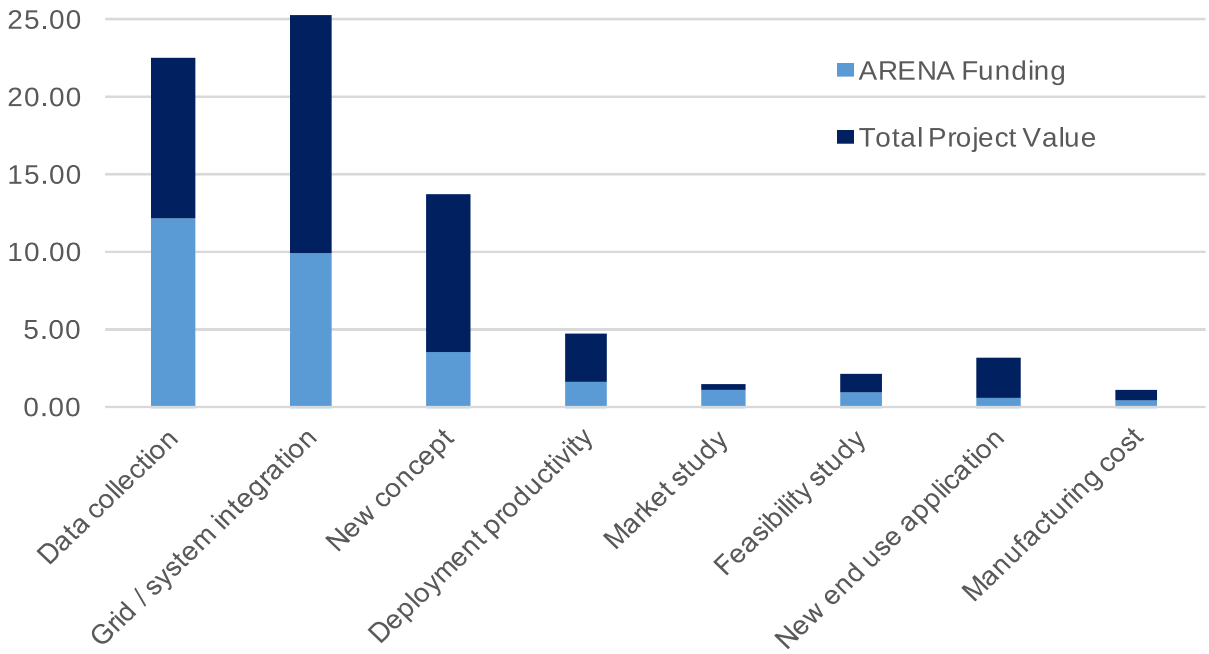


Figure D3: R&D Enabling projects' Total Project Value ($74.3m) by primary goal.

Of the 38 projects, there were 24 projects where allocating a TRL was not appropriate. For the 14 projects for which a TRL was assessed, Table D2 outlines the range and forecast TRL progress.

Table D2: Overview of 14 enabling projects by TRL progress.

TRL Start / TRL Finish	1	2	3	4	5	6	7	Total
2	1							**1**
3	1							**1**
4		1	1					**2**
5			1	1				**2**
6				1	1	1		**3**
7			1			2		**3**
9							2	**2**
Total	**2**	**1**	**3**	**2**	**1**	**3**	**2**	**14**

D.1 Integration Issues and Trends

A key research area for enabling technologies is solar generation integration and strategies to allow solar technologies to work with existing energy systems or develop new systems which are better suited to a renewable energy future. There are some research areas which benefit both options, such as better resource data, forecasting of weather patterns, system performance and prediction and better management of customer loads. For example, the Australian Solar Energy Forecasting System (ASEFS) has been incorporated with the existing Australian Wind Energy Forecasting System and is designed to allow AEMO to project expected generation from solar power generators in the short, medium and long term. This tool will become increasingly important as the amount of PV generation in the NEM increases.

The development and demonstration of sky camera technologies enables cloud detection and prediction for maximising solar PV utilisation in diesel mini-grids. This project has significantly advanced the technology and brought costs down to the point that sky camera technologies are likely to become widely deployed.

The trend in PV applications is away from PV-only systems to interconnection of PV into other energy systems, such as hybrids with diesel or wind, or central grids. The latter include both smaller-scale systems connected via inverters to low voltage distribution networks, or larger central power stations connecting into main grids via high voltage inverters and dedicated substations. While batteries have long been included in off-grid PV systems, the trend is to incorporate them into grid systems as well, providing extra levels of functionality and control options. ARENA enabling projects include various battery developments, hydrogen production, re-deployable hybrid systems as well as control and management systems.

ARENA has had separate programs targeting off-grid and grid integration, as well as the Emerging Renewables and Advancing Renewables programs, all of which target demonstration and deployment, and hence systems issues, so there are relatively few projects under the R&D program.

While improvements in inverter and storage technologies continue to be important, the key research questions centre around the hardware and software necessary for control of individual system components, as well as the load. Management of supply and demand, as well as voltage, power factor, frequency and harmonics are increasingly important as PV penetration levels increase. New battery technologies are providing interesting solutions, although many are in the early stage of development and deployment, with limited field experience so far available. Nevertheless, at the distribution grid level, PV is providing new opportunities for individual end users or groups of users in suburbs or towns to reduce purchased electricity, be self-reliant during periods of grid disruption or move to total self-sufficiency. These trends and opportunities are transforming electricity systems around the world, as well as the infrastructure and institutional arrangements which have been in place for the past five or more decades. ARENA's R&D Round 2 supported a number of projects which focus on new electricity system issues, including storage options and new business models for solar deployment.

As solar penetration levels increase, a range of other information is needed. As previously mentioned, ARENA has funded projects which aim to improve PV performance forecasting, such as improved models and weather datasets, cloud cover tracking, modelling the financial value of DNI forecasts, analysis of distributed generation, real time simulations and inspection systems. These will assist utilities to deal with higher PV penetration levels and develop improved electricity sector modelling tools and techniques to manage power quality.

These issues are also being addressed in the diesel mini-grid market where high penetration PV systems and increasing distributed generation are being managed. The use of storage to mitigate intermittency is requiring the development of innovative control systems and communication tools. ARENA's support to assist the development of improved management systems is assisting in decreasing the cost of implementation across Australia's many diesel mini-grids.

ARENA has also funded projects which examine new market structures and new technical solutions, such as distributed energy markets, mini-grids, fringe-of-grid solutions and community-based PV system ownership. These projects have identified opportunities for new ways of increasing renewable generation. Micro-grids are being investigated by several organisations and, to commence the process of exploring their potential benefits, several deployment projects are likely to be required.

Electricity storage and electric vehicles are also forecast to have large impacts on existing infrastructure and investigating the optimal ways of managing this is likely to become increasingly important.

APPENDIX E: PHD AND POST-DOC SURVEY

E.1 Background

ASI and then ARENA have directly funded 34 PhD scholarships and 46 Postdoctoral Fellowships. Others have been funded indirectly via ACAP and ASTRI. A survey was sent to the 80 directly funded scholarship and fellowship recipients. 33 responses were received. For many R&D projects, these awards have provided the key labour source for the research undertaken and have therefore been crucial to the success of the initial projects. The skilled research base created now comprise many of the lead researchers for new or extension projects subsequently funded.

PhD scholarships fell into two categories: top-up awards ranging from $20,000 to $50,000 for students in receipt of ARC or university scholarships; full scholarships ranging from $50,000 to $120,000 over 3 to 4 years. 13 of the 34 award recipients responded to the survey.

For the Postdoctoral awards, funding provided ranged from $7,000 for short visits to international renewable energy institutions to over $400,000 for 4 year research projects. 23 of the 46 recipients responded to the survey.

E.2 Questionnaire

1. Name
2. Gender
3. What type of ARENA award have or did you receive?
4. The institution in which the majority of your ARENA Scholarship or Fellowship research was/ is conducted
5. State or Territory in which most of your research was or is being conducted
6. For PhD Scholarships, where did you complete your undergraduate degree?
7. For Post-doc Fellowships, where did you complete your PhD?
8. Year of ARENA Scholarship or Fellowship award
9. Year Scholarship or Fellowship ended or will end
10. Age at start of Scholarship or Fellowship
11. Broad Research Area
12. Specific technology area
13. Research focus
14. What was the TRL at the start of your research?
15. What was the TRL at the end of your research?
16. What was the goal of your research
17. What is/was the intended application for your research outcomes?
18. How will your research improve the competitiveness or supply of renewable energy?
19. During your Scholarship or Fellowship, were your research objectives delayed for any reason?

20. How many presentations have you made since commencing your ARENA Scholarship or Fellowship?
21. How many publications have you authored or co-authored since commencing your ARENA Scholarship or Fellowship?
22. List what you consider your top three publications as first or corresponding author
23. How many patents on your research have been lodged since commencing your Scholarship or Fellowship?
24. Which countries / areas are covered by your patent applications?
25. How many patents on your research have been granted since commencing your Scholarship or Fellowship?
26. What is your current H index
27. Has your Scholarship or Fellowship research been covered by the media?
28. Have you been awarded any research grants subsequent to your Scholarship or Fellowship? If so, please enter the approximate A$ value of the grants awarded in which you were lead researcher.
29. Has your research group been awarded grants in addition to those entered in Qn 27 above? If so, please enter the approximate A$ value of the grants awarded in which you were part of the research team.
30. How many students have you supervised since commencing your ARENA Scholarship or Fellowship?
31. Have you collaborated with an international research group since commencing your ARENA Scholarship or Fellowship? If yes, please specify
32. Have you received any formal recognition (awards, prizes etc) since commencing your ARENA Scholarship or Fellowship? If so, please specify.
33. Are you involved in commercialising your research outcomes?
34. Have you been employed in your field of research since completing your ARENA Scholarship or Fellowship?
35. How would you describe the value of the research that you were able to undertake during your Scholarship or Fellowship? Please describe the impact on your career and as well as the contribution to advancing renewable energy.
36. Was the ARENA Scholarship or Fellowship your first choice?
37. How do you describe the ARENA Scholarship or Fellowship in your CV or at interviews?
38. What other Fellowships or awards have you received?
39. Do you have any suggestions for improving future ARENA Scholarship or Fellowship programs?
40. Are you happy to be contacted for further information about your research?

E.3 Survey Results

Recipient backgrounds

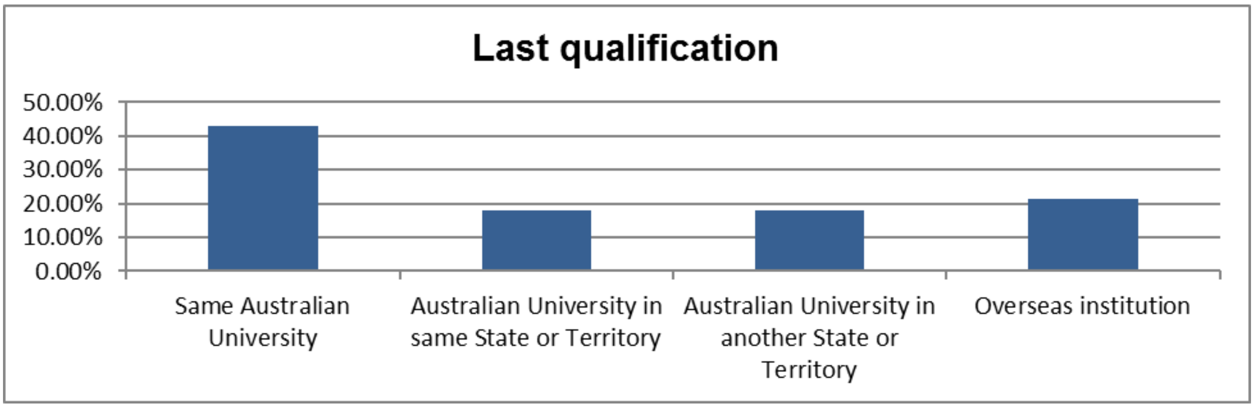
There were 12 females in the initial list of 80 award recipients (15%). 4 females responded to the survey, out of a total 33 respondents (12%).

The average age of respondents at the start of their scholarship or fellowship was 28, with ages ranging from 23 to 34 years.

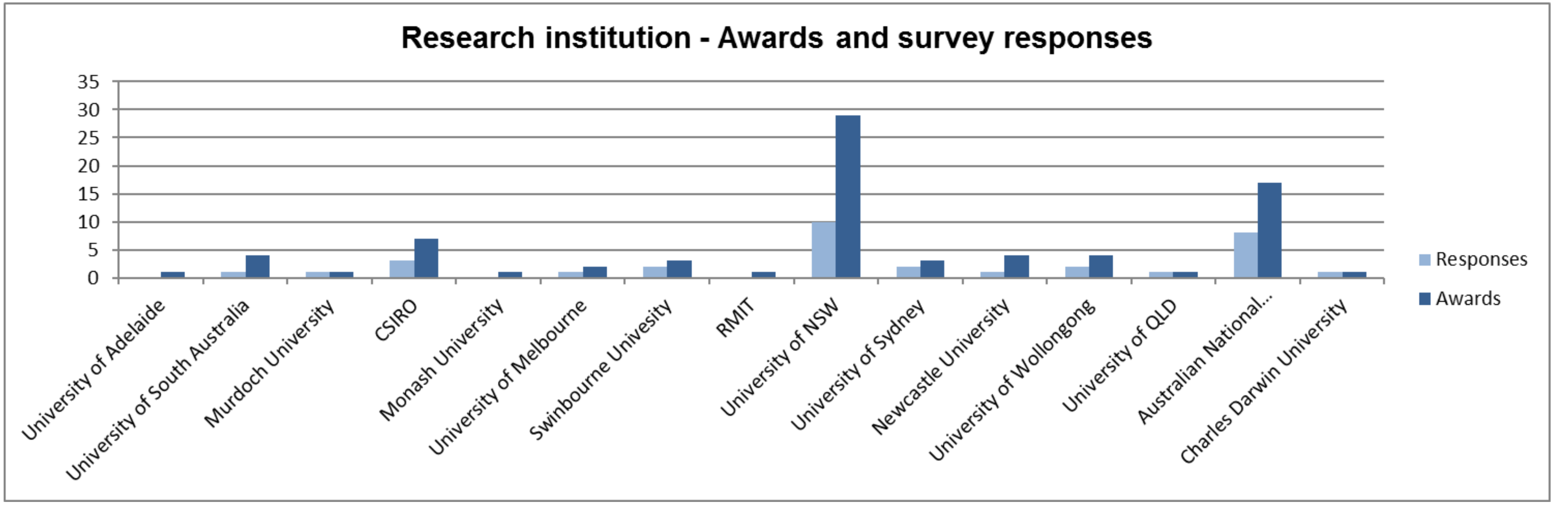
The average award duration was 3 years and ranged from several months to 5 years.

Only 10 recipients noted delays in completing their work. Of these, 4 were delayed due to personal circumstances.

43% of respondents had attended the same university for their previous qualification. 21% had qualified overseas.

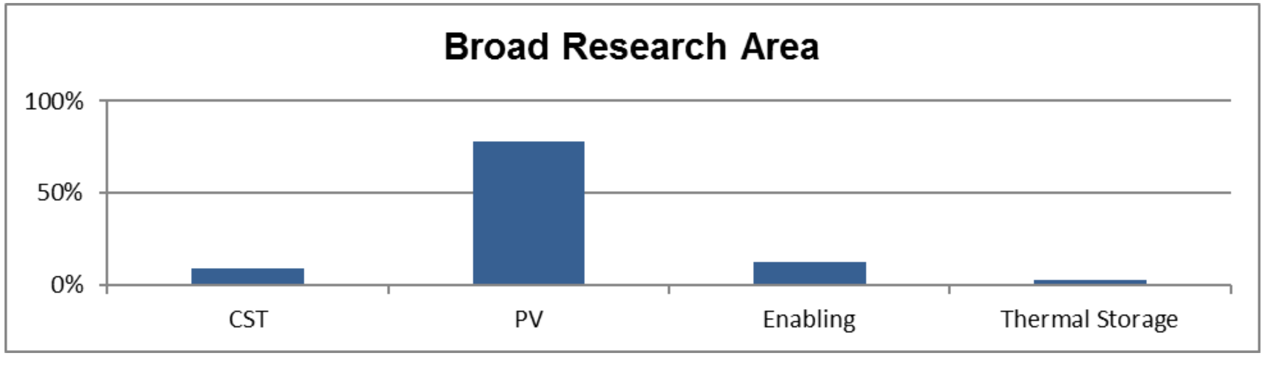


Awards had been granted for research at 15 Institutions. 12 of these were represented in the survey responses.

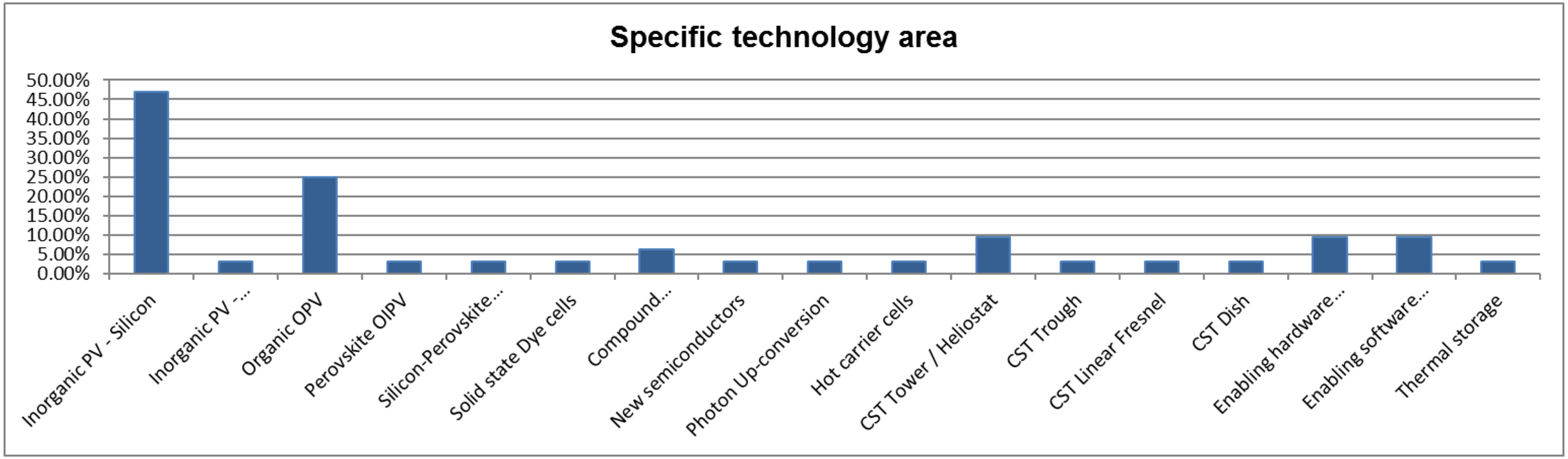


Research areas and aims

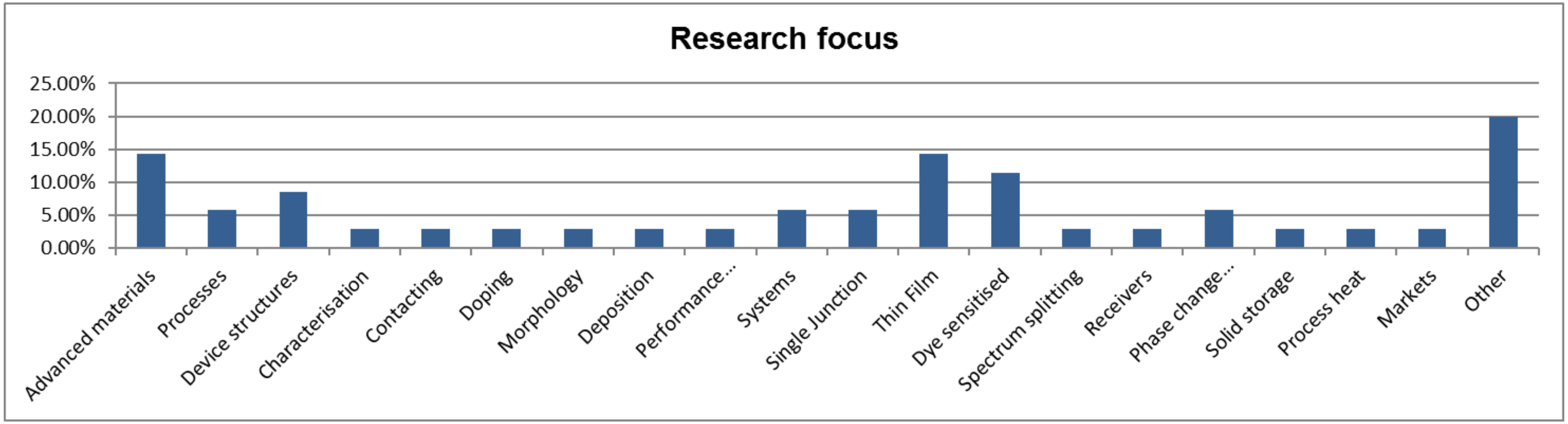
78% of respondents had worked on PV related research during their award.



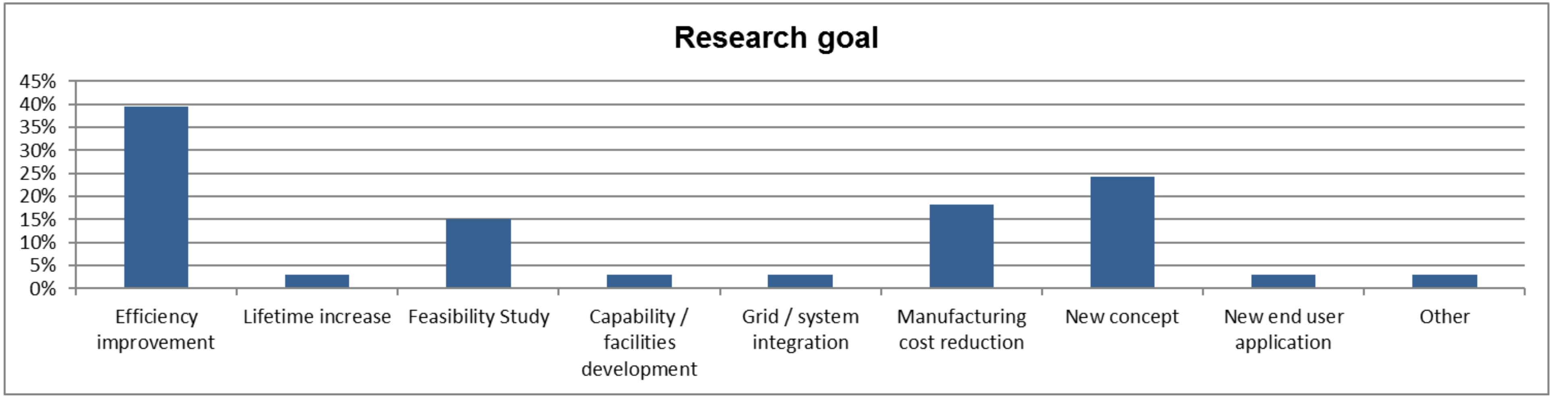
47% had worked on Silicon PV and 25% on organic PV.



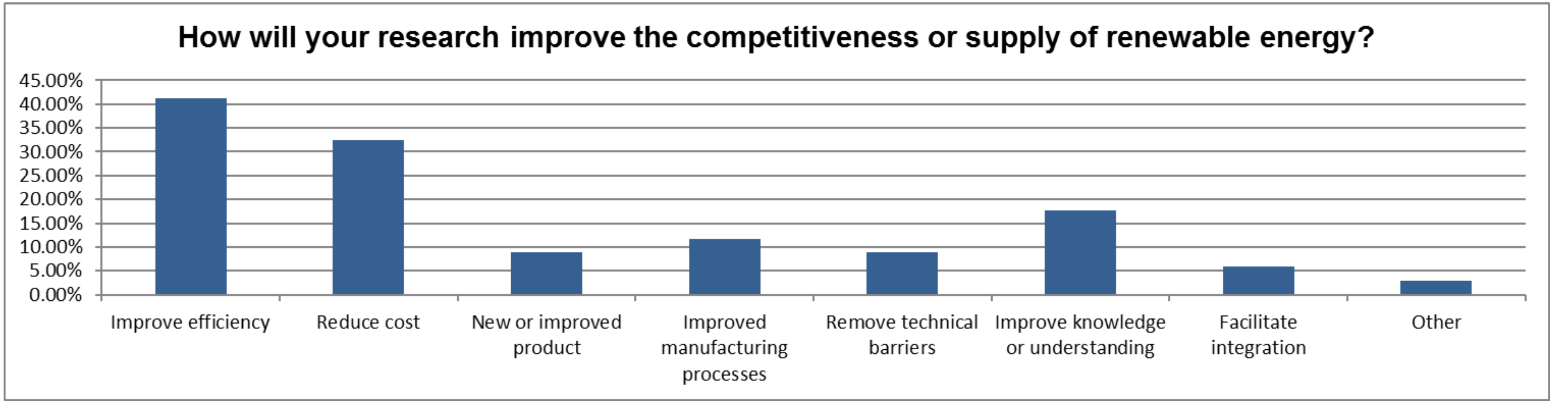
Advanced materials, thin film cells and dye sensitised cells were the most common focus area.



Efficiency increase was the most common research goal (39%) with 24% aiming to develop a new concept and 18% aiming for manufacturing cost reductions.



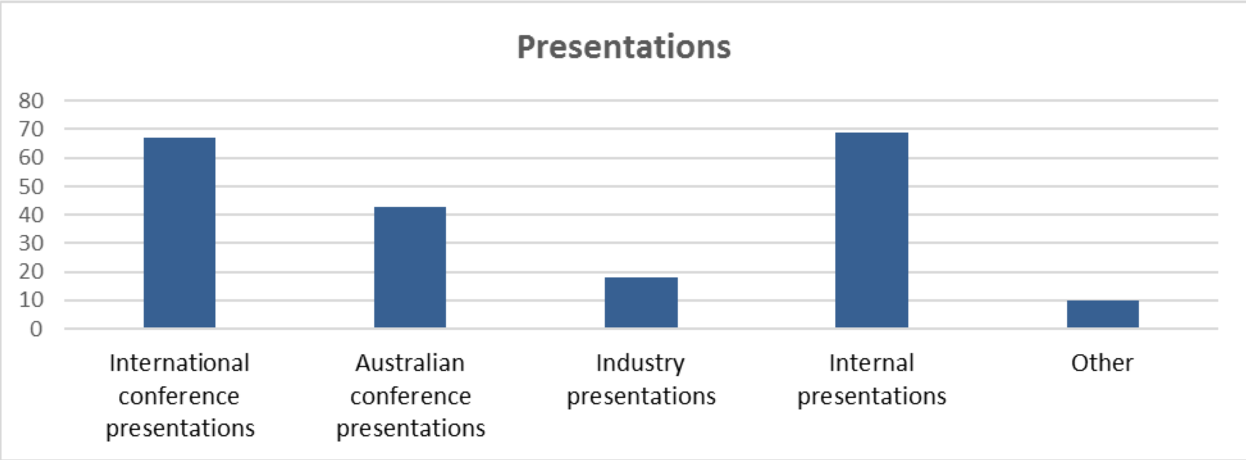
This was reflected in their expectations of the impact of their research on renewables, where 74% considered their results increased efficiency or reduced costs.



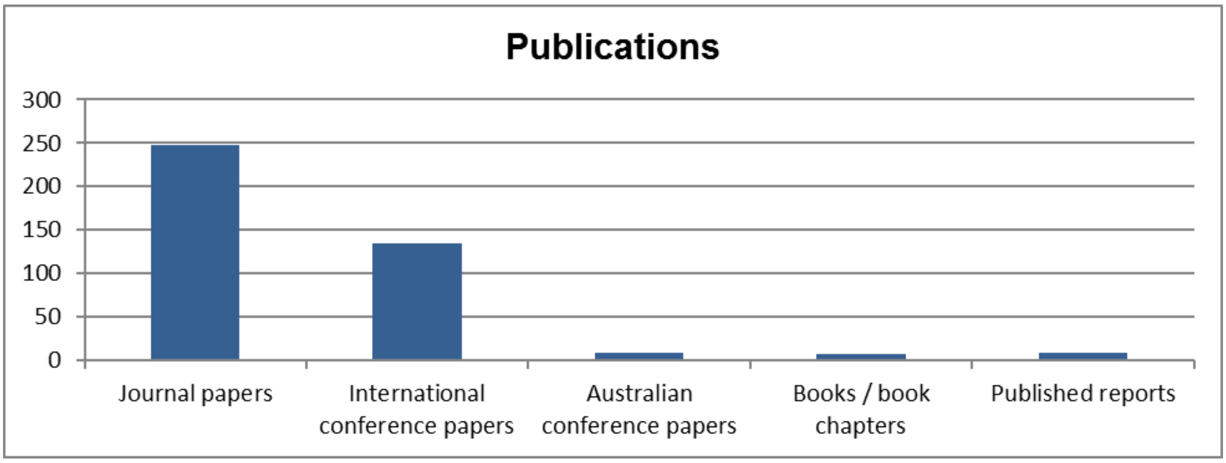
__Research Outcomes__

The average increase in technology readiness level (TRL) was 1.6, with 52% of projects increasing by one point on the scale and 21% increasing by 2 points. While 31% of projects increased from 1 to 2 or 2 to 3 (basic principles and concepts), indicating work was at a fundamental level, 31% also finished at TRL 6 or 7 (prototype and pilot scale).

A total of 207 presentations were reported, with 95% of respondents reporting international conference presentations and 77% Australian conference presentations.



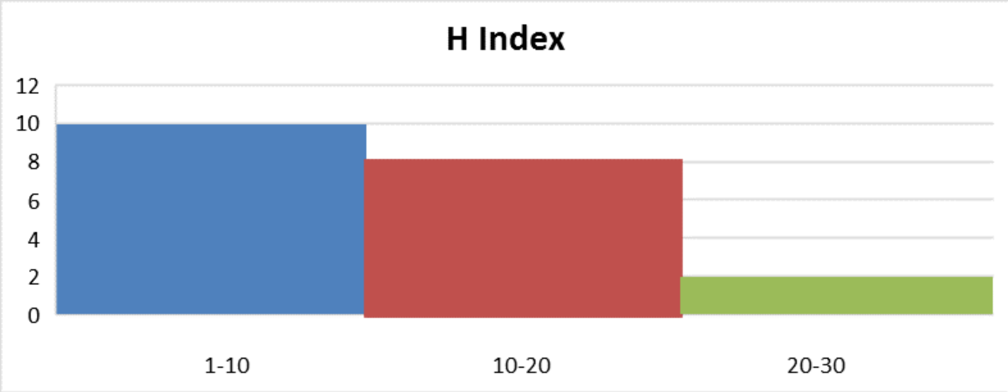
A total of 406 publications were reported. For these, 91% of respondents reported journal publications and 82% international conference presentations. Nine patents resulting from their work were reported as filed and four granted.

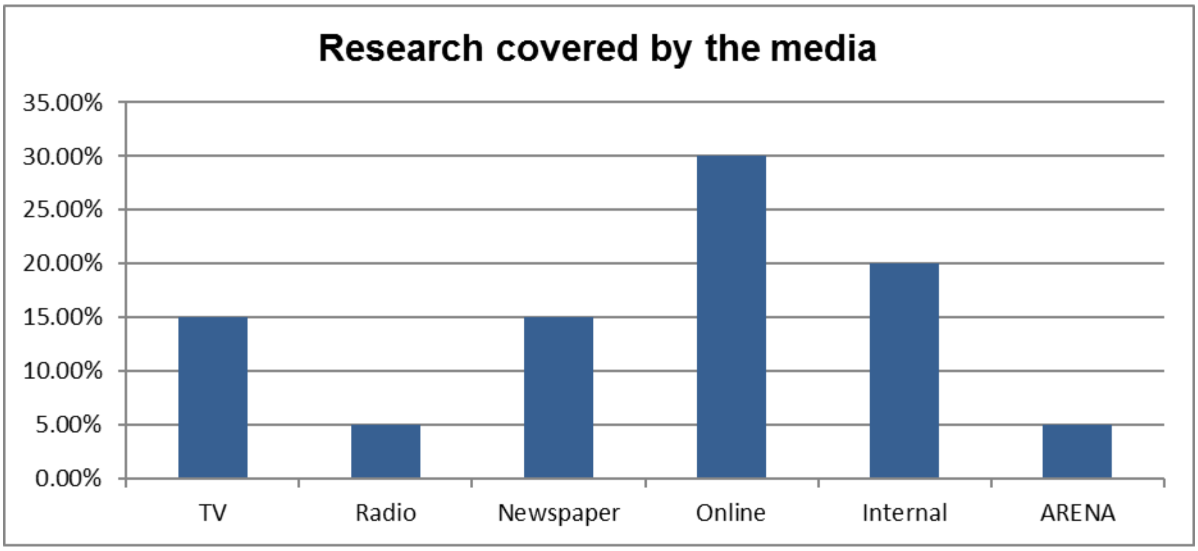


In terms of publication impact, the average H index[36] reported was 12, with the majority of respondents in the range 1-10, but 2 in the range 20-30, which would be considered exceptional for early stage researchers. As would be expected, these latter are now senior academics and heads of research programs.

18 reports of media coverage were cited of which 30% were online.

[36] The H index reflects the number of publications by an author as well as the number of times their publications have been cited by others. It is a numerical indicator of how productive and influential a researcher is.





Post award activities

12 researchers indicated that they have been successful in receiving research grants as lead researcher since completing their ARENA funded scholarship or Fellowship. A total of over $12m in grants were reported, of which 60% were from ARENA and 30% from the ARC. In addition, 6 researchers had been part of a team receiving funding of over $72m, 80% of which was from the ARC.

A total of 181 students were supervised by 19 award recipients who answered this question, an average of 10 each.

75% of the 19 people who responded indicated that they had collaborated with international research groups since or during their ARENA award. The countries mentioned were Ireland, Singapore, Germany, USA, China, Italy, France, Poland and the UK.

Specific institutes mentioned were:

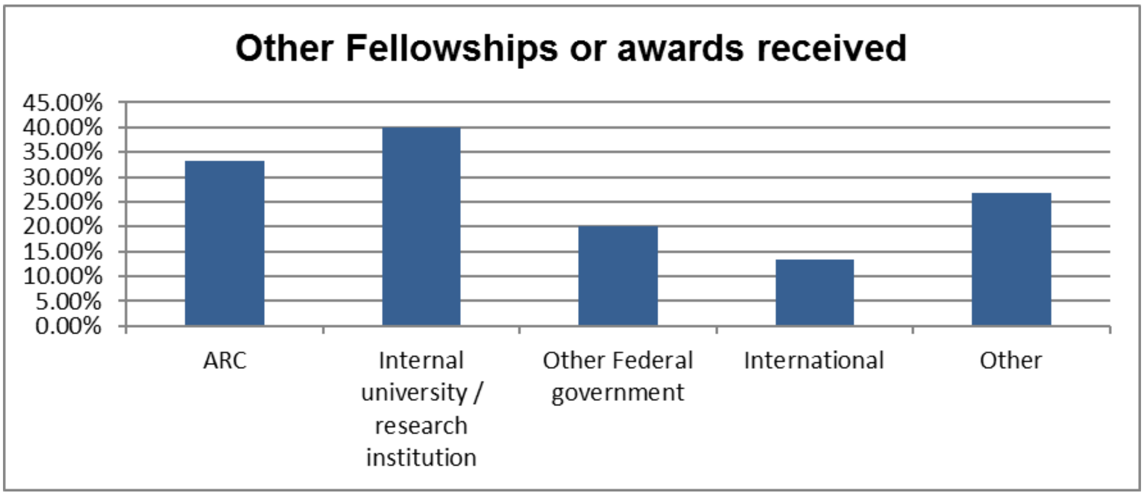
- The German Aerospace Center Institute of Solar Research
- CLARITY, Dublin City University
- Fraunhofer ISE
- University of Freiburg
- Helmholtz-Zentrum Berlin for Materials and Energy

- Karlsruhe Institute of Technology,
- Max Planck Institute for Polymer Research,
- Georgia Institute of Technology
- MIT
- University of Texas Austin
- Wuhan University of Technology
- University of Padova
- University of Manchester
- National Institute of Applied Sciences of Lyon (INSA)
- Fraunhofer ISFH
- University of Warwick.

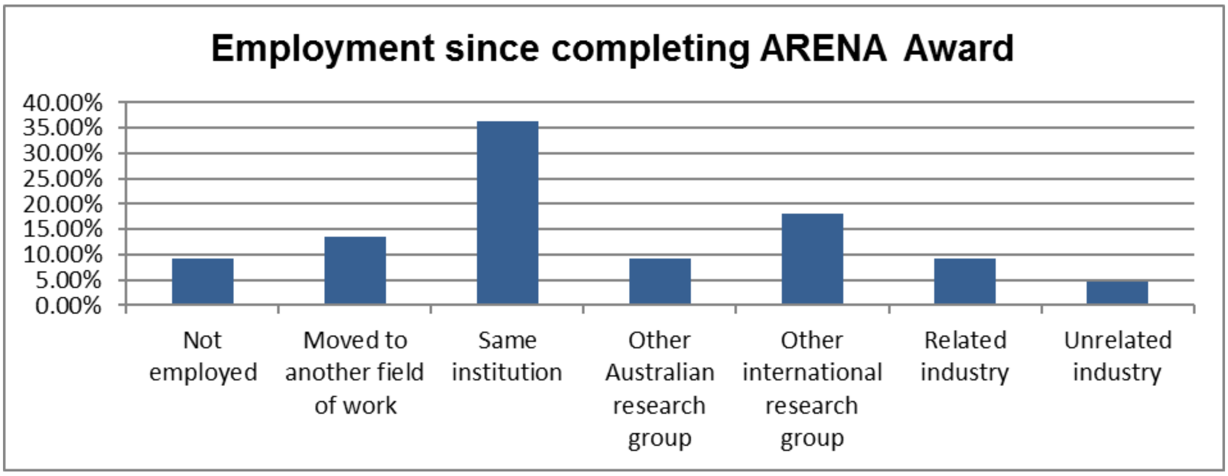
Ten respondents reported having received awards or prizes stemming from their ARENA funded work. These included:

- WA Premier's Student Scientist of the year: 2014 runner-up
- Eureka Award Finalist: Innovative Use of Technology
- Blue skies research award, UNSW
- UNSW Three-Minute- Thesis People's Choice Award, 2011
- Australian Solar Institute Three-Minute- Thesis PhD Award, 2012
- Australian Solar Institute Three-Minute- Thesis People's Choice Award, 2012
- IEEE PVSC Best Student Presentation Award, 2013
- Australian Institute of Physics (NSW) Postgraduate Medal, 2013
- IEEE PVSC Best Poster Award, 2014
- University of Melbourne Dean's Award for Research Excellence 2015
- The Humboldt research fellowship
- Tall Poppy Award Fulbright Fellow
- Outstanding Achievements of Young Alumni Uni. of Sydney
- Myer Innovation Fellowship
- Helen Beh Citizenship Award
- SPIE Optics & Photonics Education Scholarship
- CUDOS Outreach Award
- ANSTO 2015 Eureka prize
- ARC DECRA.

85% of those who responded indicated that the ARENA award had been their first choice at the time, with some indicating that they felt honoured to have received it. Many indicated that it had been the foundation for their career, had opened up the world of solar research to them and had allowed them to work with world-leading researchers. 15 respondents indicated that they had subsequently received other awards.



Of 22 people responding to this question, 16 indicated that they were still involved in the same field of work. Six respondents reported that they were involved in commercialising their research.



Apart from one response questioning the ability of government to successfully choose and prioritise R&D funding areas, suggestions and comments on future ARENA Scholarships and Fellowships included:

- Allow fellowships for people with industry experience to re-enter academic work. Base selection criteria accordingly.
- It would be better to launch a fellowship for middle career researcher or a continuous support to the fellows who did a good job during the fellowship.
- More media coverage for the successful projects and candidates.
- Follow-up fellowships or funding.
- More PhD Scholarships.

- Add some additional funds for conference travel. Very difficult trying to network and collaborate without going to conferences.
- Original ASI program provided many more additional programs, e.g. media training and coverage, networking opportunities.
- Research support on top of Fellowship salary.
- Resume offering international visiting fellowships. This was really great for someone who is seeking to establish some autonomy in a field of their choice.
- Target early career researchers both at Post-Doc and junior academic levels.
- It is crucial that all participants have access to mentors in the solar industry. If suitable mentors are not available within Australia, someone overseas should be made available. Academia in Australia is sometimes like an 'echo chamber' and ideas that do not have relevance to the solar industry are often pursued. That is not to say pure research is not vital, but for outcome-focused programs like ARENA’s, it is difficult for young researchers to simultaneously pursue a research career (focused on papers etc), while trying to do something that can lead to positive industry outcomes.
- Keep it focused on commercial outcomes.
- Provide more fellowships and reduce the funding amount for big ARENA deployment projects who would hire the Post-Docs.

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