

Australian Centre for Advanced Photovoltaics

Annual Report 2025



**Ultra low cost solar
through national
research collaboration**



Australian Centre for Advanced Photovoltaics

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Acknowledgement

ACAP acknowledges the Traditional Custodians of Country across Australia and their continuing connection to land, sea and community.

We pay our respects to Elders past and present.

Collaborators

AIKO  JA SOLAR



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Acronyms

Acronym	Meaning
ACAP	Australian Centre for Advanced Photovoltaics
AI	Artificial intelligence
AL-BSF	Aluminium back surface field
ALD	Atomic layer deposition
ANU	Australian National University
APSRC	Asia-Pacific Solar Research Conference
APVI	Australian PV Institute
ARENA	Australian Renewable Energy Agency
ASEAN	Association of Southeast Asian Nations
AusSi	Australian Silicon Study
BC	Back-contact
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CZTS	Kesterite
DPL	Daylight photoluminescence
ELICE	Empowering Emerging Leaders in Clean Energy
EU PVSEC	European Photovoltaic Solar Energy Conference
FAPbI₃	Formamidinium lead iodide
GW	Gigawatt
HJT	Heterojunction
IBC	Interdigitated back contact
IEC	International Electrotechnical Commission
IEEE PVSC 2025	IEEE Photovoltaics Specialist Conference
I-V	Current voltage
JCU	James Cook University
LCOE	Levelised cost of electricity
ML	Machine learning
MWh	Megawatt hour
NFACR	National Foundation for Australia-China Relations
NREL	National Renewable Energy Laboratory
OPV	Organic photovoltaic
PERC	Passivated emitter and rear cell
PHES	Pumped hydro energy storage

Acronym	Meaning
PL	Photoluminescence
Poly-Si	Polycrystalline silicon
PP	Program Package
PPVF	Printed Photovoltaics Facility
PSC	Perovskite solar cells
PV	Photovoltaic
PVPL	Photovoltaic Performance Laboratory
PVSEC-36	36th International Photovoltaic Science and Engineering Conference
RCz	Recharged Czochralski
rMC	Revised Material Circularity Indicator
SAMs	Self-assembled monolayers
SHJ	Silicon heterojunction
SIRF	Solar Industrial Research Facility
SNEC PV	SNEC PV & ES International Photovoltaic Power Generation and Smart Energy Conference & Exhibition
SPV	Surface photovoltage
TBC	TOPCon back contact
TCO	Transparent conducting oxide
TEM	Transmission electron microscopy
TOPCon	Tunnel oxide passivated contacts
TRAC	Transformative Research Accelerating Commercialisation
TW	Terawatt
TW4	Fourth Terawatt Workshop
ULCS	Ultra low-cost solar
UNSW	University of New South Wales
UNSW SPREE	UNSW School of Photovoltaic and Renewable Energy Engineering
UoM	University of Melbourne
UQ	University of Queensland
UT-TOPCon	Ultra-thin tunnel oxide passivated contacts
UV light	Ultraviolet light
UVID	Ultraviolet-induced degradation

Director's report



Executive Director of
the Australian Centre for
Advanced Photovoltaics
Professor Renate Egan

The Australian Centre for Advanced Photovoltaics (ACAP) builds on a long history of excellence in solar research in Australia. First motivated by the global energy crisis of 1973, the importance of developing solar photovoltaics has never been more critical than now. Through sustained research and technology development, Australia continues to deliver global impact in solar innovation and deployment, supporting industrially viable solutions for both energy security and climate change.

The momentum generated by ACAP's past success continued to build throughout 2025, driven by technology leadership, national collaboration, and strong ties to industry.

In 2026, ACAP will expand its impact and reach with the extension of the Centre through a further \$220 million program of work. The timely new program looks beyond 2030, with research and development activities targeting further cost reductions in solar through to 2040. The program of work is co-funded by the Australian Renewable Energy Agency (ARENA), UNSW, partner universities, research institutions and industry, and involves over 250 Australian researchers working in concert to achieve ARENA's ultra low-cost solar goals.

With continued advances in ultra low-cost solar, photovoltaic (PV) technology is set to transform our energy system, industries, transport, and the way we live.

Data from the International Energy Agency [IEA] [1] shows that solar PV is already the lowest-cost and fastest-growing source of new electricity generation, with estimates of nearly 700 GW installed globally in 2026 alone. [1] Experts predict 1,000 GW annual markets before

2030, showing tenfold growth from 100 GW in just 2017, and a 100-fold increase since 2010.

In Australia, 5 GW of solar was installed in 2025, bringing total installed capacity to more than 45 GW across rooftops and large scale systems. Australia retains global leadership in installed solar per capita.

Solar PV met more than 20% of the total electricity demand in the Australian National Electricity Market in 2025. Overall, renewable energy supplied over 40% of Australia's electricity needs for the year, and over 50% for the three months over summer. Supported by increasing investment in batteries and pumped hydro storage, the growth of solar and wind is driving demand for coal and gas to historic new lows.

The PV technology available today works, and should be deployed at scale as fast as possible. In doing so, we will continue to learn and improve. At the same time, achieving a zero-emissions economy and establishing Australia as a renewable energy superpower requires continuous innovation to push solar technologies even further and the costs even lower.

ARENA has set an ambitious vision for ultra low-cost solar, targeting electricity costs below \$20/MWh. ACAP's program of work aligns with this vision and Australia's broader ambitions.

New ACAP modelling (see case study "[How large is the industrial opportunity when solar becomes ultra low-cost?](#)") shows that the magnitude of the economic opportunity to Australia of ultra low-cost solar is far larger than most people realise. Australia could rely on 2,000 GW of solar to power a fully decarbonised domestic economy while powering large-scale production of green metals for

export – positioning Australia as a global supplier of green products while dramatically reducing national emissions.


This 2025 Annual Report presents progress and key developments from 2025. It introduces a new format, combining high-level program summaries with case studies that highlight the people, technologies, and achievements driving ACAP forward.

Continued investment in ACAP ensures Australia maintains its leadership in solar PV research. In 2025, ACAP was again ranked first globally for research quality and impact in photovoltaics, ahead of more than 100 international institutions, according to ScholarGPS .


ACAP continues to strengthen its industry engagement, attracting seven industry partners to join the ACAP Industry Consortium, securing multimillion-dollar research contracts with two major industry players, and contributing to leading industry reports and policy development in solar PV, energy storage, and electrification.

ACAP researchers were recognised nationally and internationally throughout the year. A new Sydney ferry named the Martin Green was launched in January 2025 in honour of Professor Green’s (UNSW) pioneering work in solar technology development; Professor Andrew Blakers (ANU) was appointed an Officer of the Order of Australia in the 2025 Australia Day Honours list; Associate Professor Heping Shen (ANU) received the IEEE Stuart R. Wenham Young Professional Award at the Photovoltaic Specialists Conference in Montreal; Professor Anita Ho-Baillie (University of Sydney) was awarded the 2025 Eureka Prize for Sustainability; and Professor Xiaojing Hao (UNSW) was elected a Fellow of the Australian Academy of Science.

In 2025, a program review of ACAP culminated in the release of *Setting the Pace of Solar Research in Australia*, highlighting key achievements from the first two years of ACAP’s second phase. The review informed new ambitions for ACAP beyond 2030, including the acceleration of research through integration of artificial intelligence and machine learning, expanded efforts in materials discovery, and re-investing in capacity and capability building.



In 2025, ACAP was again ranked first globally for research quality and impact in photovoltaics.



The outstanding work reported here is made possible through the vision and commitment of ARENA, which recognises the value of sustained long-term investment in research. ARENA supports ACAP not only through funding but also through active engagement in research strategy, knowledge sharing, and program governance. This partnership, backed by UNSW and our research and industry collaborators, underpins our achievements.

I thank all ACAP researchers for the significant effort and contributions made to the broad range of progress reported in the following pages. Of note, the ACAP Technical Program Group, formed in 2024, plays a central role in coordinating the technology planning and reporting. In 2025, program leaders included Associate Professor James Bullock (University of Melbourne), Dr Anthony Chesman (CSIRO), Professor Klaus Weber (ANU), Professor Bram Hoex (UNSW), Dr Chris Fell (CSIRO) and Professor Kylie Catchpole (ANU). With their leadership, we've strengthened collaboration, improved reporting and enhanced knowledge sharing across the program. I look forward to this continuing as ACAP grows.

In addition, 2025 saw Dr Wallace Wong and Associate Professor James Bullock step into ACAP leadership roles at the University of Melbourne, and Dr Jessica Jiang take on leadership for UNSW's ACAP research activities.

Finally, I am pleased to report that ACAP has achieved its 2025 milestones, on time and within budget – representing another major step towards attaining the significant long-term objective of delivering ultra low-cost solar. I look forward to continued progress in 2026 and beyond as we work towards realising the vision.

Professor Renate Egan
Executive Director

Reference

[1] <https://iea-pvps.org/snapshot-reports/snapshot-2026/>


About ACAP

The Australian Centre for Advanced Photovoltaics (ACAP) was established in 2013 to develop next-generation photovoltaic technologies and to provide a pipeline of opportunities for performance improvement and cost reduction.


ACAP is a nationally coordinated research collaboration, led by the University of New South Wales (UNSW), with founding partners including the Australian National University (ANU), the University of Melbourne (UoM), Monash University, the University of Queensland (UQ), and CSIRO Manufacturing. In 2022, the Centre expanded to include CSIRO Energy and the University of Sydney, further strengthening its research capability and national reach.

Working closely with domestic industries and international partners, ACAP supports the acceleration of photovoltaic innovation beyond what individual organisations can achieve alone, enabling the translation of research into real-world impact. It contributes to high-impact research both nationally and internationally.

ACAP is supported by the Australian Government through the Australian Renewable Energy Agency (ARENA) to deliver advances in early-stage research and innovation in solar photovoltaics. ARENA's vision for Ultra Low-Cost Solar includes reducing the cost of solar electricity to below \$20/MWh to help decarbonise our electricity system and improve the competitiveness of potential future clean industries, such as renewable hydrogen and low-emissions metals. ARENA funding is matched by at least equivalent contributions from partners and institutions and builds on a strong track record of research outcomes, including impacts in intellectual property generation, technology transfer, and industry development.



ACAP contributes to high-impact research both nationally and internationally.



The ACAP working program reflects ARENA's Ultra Low-Cost Solar goals and Australia's ambition to be a renewable energy superpower, with objectives and tasks delivered across six technical Program Packages (PPs):

PP1: Silicon Solar Cells

Deliver an improvement in cell efficiency to over 30% by building on the silicon solar cell to make the most of the available energy in sunlight.

PP2: Emerging Materials

Develop the emerging materials needed to support next-generation photovoltaic technologies and contribute to performance improvements required for higher-efficiency solar cells.

PP3: Tandem Solar Cells

Deliver high-efficiency tandem solar cells through research focused on finding the best material combination and developing the best device structures.

PP4: Device to Module

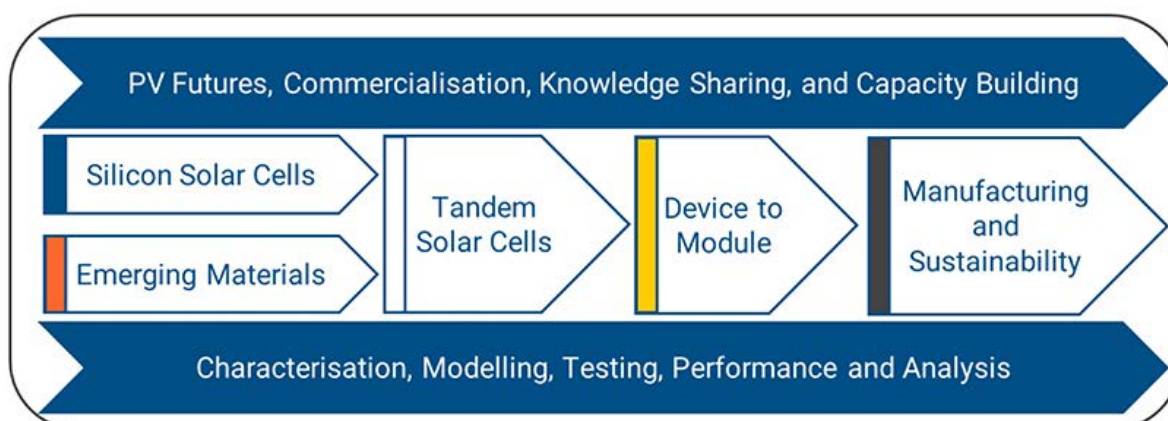
Translate research cell results into high-performing, reliable, and durable modules, answering research questions on interconnection and encapsulation of individual cells to deliver long operating lifetimes for manufactured modules.

PP5: Manufacturing and Sustainability

Drive down cost by focusing on the sustainability and manufacturability of new technologies at terawatt scale.

PP6: PV Futures and Knowledge Sharing

Accelerate the transition to a solar-powered future through scenario setting, training the next generation of photovoltaic researchers, and knowledge sharing.



Diagrammatic representation of the ACAP program.

To support the delivery of these program objectives, ACAP operates under a structured governance framework.

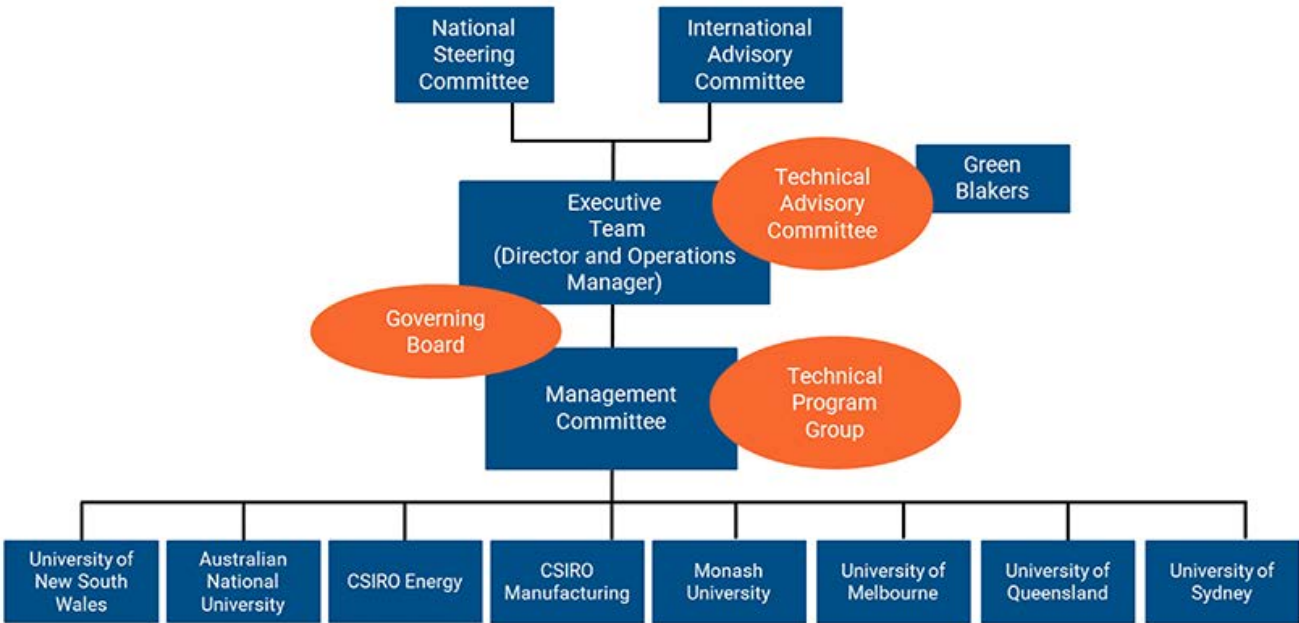
The Executive Team, led by an Executive Director, manages the day-to-day operations of ACAP. It reports to a Governing Board chaired by an independent member. The 2025 Governing Board includes representatives from ARENA and Project Participants.

Operational oversight is provided by a Management Committee, chaired by the Executive Director. The Committee includes ARENA representatives and Principal Investigators from each Project Participant. The Management Committee is responsible for planning and operations, including approving project and funding recommendations, research oversight, and coordination across the ACAP network.

The Technical Program is guided by a Technical Program Group, with representation from across the ACAP research institute partners.

The ACAP Executive and Management take advice and guidance on strategy, research progress and international collaboration from a National Steering Committee and an International Advisory Committee; and on technical direction from a Technical Advisory Committee.

In 2026, ACAP will move to its third phase and will see some changes in governance.



ACAP Organisational chart, 2025.

CAPACITY BUILDING

27

**MASTERS
STUDENTS**

23

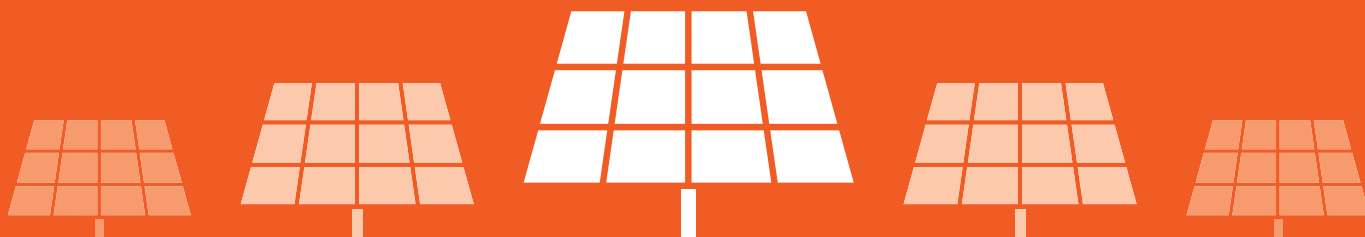
**EARLY CAREER
RESEARCHERS**

35

**HONOURS
STUDENTS**

29

**PhD
STUDENTS**



19 PARTNERS

7

**AUSTRALIAN
RESEARCH
PARTNERS**



10

**INDUSTRY
RESEARCH
PARTNERS**



2

**INTERNATIONAL
RESEARCH
PARTNERS**



Highlights

ELICE – Connecting Australia and China’s next generation of clean energy leaders

The Empowering Emerging Leaders in Clean Energy (ELICE) program, initiated in 2025 by the University of New South Wales (UNSW) and the Australian Centre for Advanced Photovoltaics (ACAP), is building a platform to strengthen collaboration between emerging clean energy leaders in Australia and China. Supported by a grant of AUD \$500,000 from the National Foundation for Australia-China Relations (NFACR), the program brings together early-career researchers, industry professionals and entrepreneurs to foster knowledge exchange, leadership development and long-term partnerships in the rapidly evolving clean energy sector.

Over 80 emerging clean energy leaders from academia, industry, and policy across Australia and China have come together through the ELICE program.

The program is delivered through a series of targeted workshops designed to address different aspects of clean energy collaboration. The first workshop, held in Shanghai, China, focused on entrepreneurship and innovation, providing participants with insights into pathways from research to commercialisation and opportunities to engage with leading clean energy companies and startup ecosystems. The second workshop, held in Sydney, Australia, focused on advanced technologies and research collaboration, offering a platform for participants to exchange perspectives on clean energy technologies and to explore opportunities for future joint research.

Over 80 Australian and Chinese emerging clean energy leaders from academia, industry, and policy have come together.

Across these activities, participants engaged in technical presentations, roundtable discussions, and site visits, enabling in-depth exchanges covering a wide range of topics across the clean energy landscape, including solar cells, battery storage, hydrogen generation and storage, smart grids, AI applications, as well as clean energy policy and investment. These interactions have supported the development of a growing network of emerging leaders while strengthening connections between research, industry, and policy communities.

ELICE Program Lead Dr Jessica Yajie Jiang highlighted the importance of the initiative in building meaningful connections across borders. “ELICE is designed to bring together emerging leaders from different sectors and backgrounds, creating opportunities for them to learn from each other and to build lasting collaborations.

“By connecting research, industry and policy communities across Australia and China, we aim to support not only knowledge exchange, but also the development of future leaders who can drive innovation in clean energy.”



ELICE Workshop 1 participants in Shanghai, China.

The ELICE program is enabling future innovators to work across borders and disciplines.

The ELICE program has received strong support from senior leaders across government, academia, and industry in both Australia and China, underscoring its significance as a platform for advancing bilateral collaboration in clean energy.

Distinguished representatives have supported and participated in ELICE program activities, including Professor Bronwyn Fox AO, Deputy Vice Chancellor (Research and Enterprise) at UNSW; The Honourable Matt Thistlethwaite MP, Assistant Minister for Immigration and Assistant Minister for Foreign Affairs and Trade; Mr Gary Cowan, Chief Executive Officer of the National Foundation for Australia-China Relations; Mr John Williams, Australia's Consul-General in Shanghai; Mr Jianmin Jin, Counsellor for Science and Technology at the Consulate-General of the People's Republic of China in Sydney; and Mr Tao Qin, Deputy Director of the China Association for International Exchange of Personnel, alongside leading experts from Australia and China.

Their engagement reflects a shared commitment to strengthening Australia-China cooperation and supporting the next generation of clean energy leaders.

The ELICE program contributes to strengthening the global clean energy ecosystem by enabling future innovators to work across borders and disciplines. As the global transition to sustainable energy accelerates, initiatives such as ELICE will play an increasingly important role in shaping the next generation of clean energy leadership.

ELICE Workshop 2 participants in Sydney





Scientia Professor Martin Green was awarded the Faraday Medal. Pictured here with wife Judy Green in London.

Special recognition for ACAP researchers in 2025

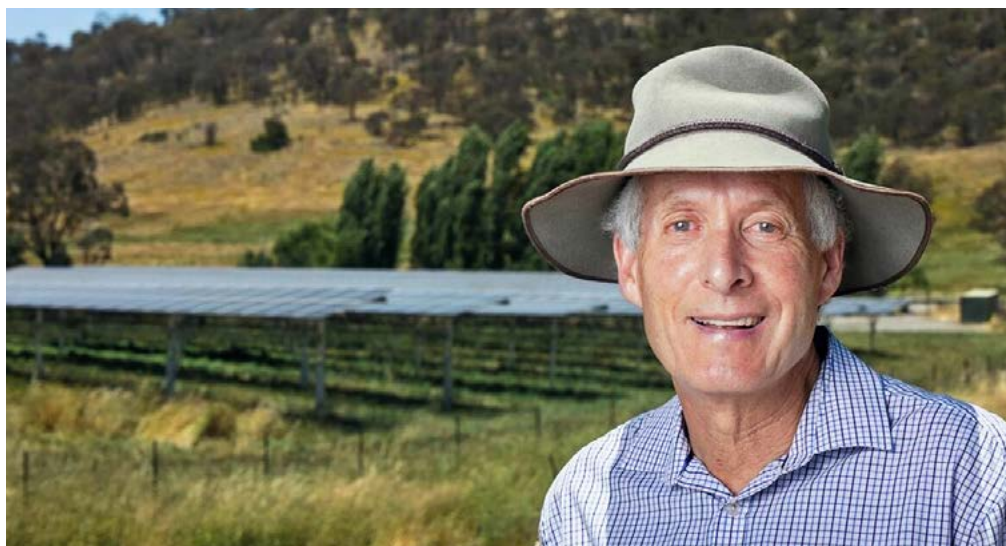
Researchers from the Australian Centre for Advanced Photovoltaics (ACAP) received major national and international honours in 2025, reflecting their central role in transforming solar energy into the world's lowest-cost electricity source and advancing the next generation of photovoltaic technologies.

ACAP founder Scientia Professor Martin Green (UNSW Sydney) was awarded the prestigious Faraday Medal in 2025, one of the world's most respected engineering honours. He also received the 2025 Goswami Prize from the US National Academy of Inventors for "Lifetime Achievement for Innovations in Energy and Sustainability". Professor Green is widely regarded as the 'father of modern photovoltaics' for pioneering high-efficiency silicon solar cells, including PERC technology, and the first design of TOPCon technology, both of which dominate global solar production. His work underpins the dramatic cost reductions that made solar the cheapest form of electricity in history. In a distinctly Australian tribute, a new Parramatta River Class ferry was named in Professor Green's honour. The Martin Green ferry is an enduring and highly visible recognition of his contribution to modern life.

Scientia Professor Martin Green had the distinctly Australian honour of having a new Sydney Ferry named after him. Seen here with wife Judy Green at the ferry's launch.



Emeritus Professor Andrew Blakers (ANU) was appointed an Officer of the Order of Australia in 2025. This is one of the nation's highest civilian honours and recognises distinguished service of national significance. As co-inventor of PERC technology and a leader in pumped hydro energy storage, his contributions span both photovoltaics and the broader clean energy system.



Emeritus Professor Andrew Blakers (ANU) was appointed Officer of the Order of Australia (AO) in January 2025.
Photo: Sitthixay Ditthavong

Associate Professor Heping Shen (ANU) was awarded the prestigious international Stuart R. Wenham Young Professional Award at the IEEE Photovoltaic Specialists Conference. This conference is the longest-running and one of the most rigorous international meetings in the field. The award recognises outstanding early- to mid-career contributions and highlights Associate Professor Shen's leadership in developing cost-effective and scalable tandem solar cell architectures.



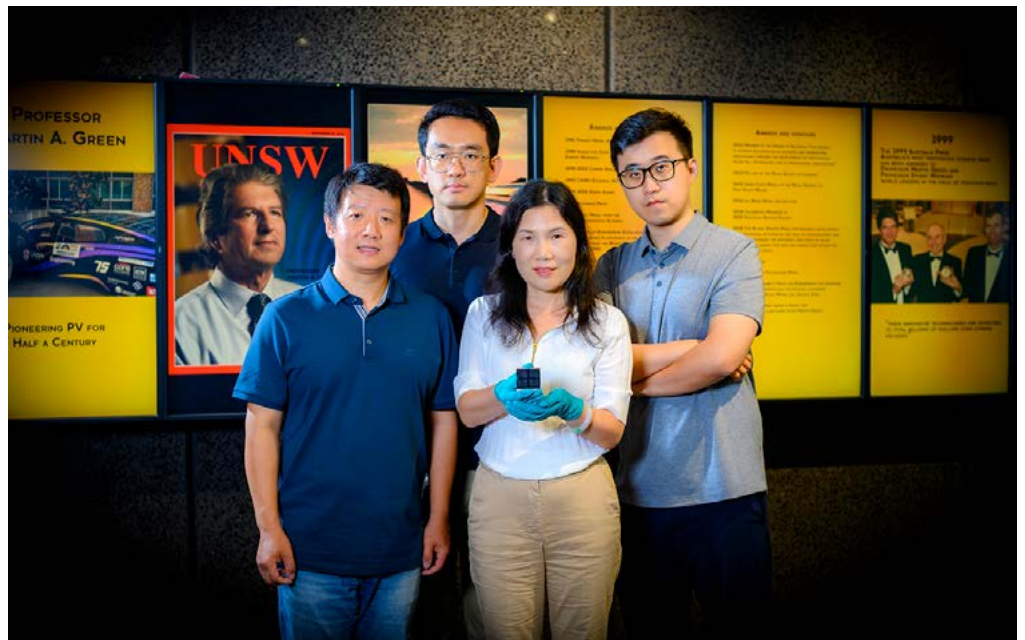
Associate Professor Heping Shen (Australian National University) was awarded the Stuart R. Wenham Young Professional Award.



Professor Anita Ho-Baillie (University of Sydney, ACAP Node Lead) received the 2025 Eureka Prize for Sustainability.

Professor Anita Ho-Baillie (University of Sydney, ACAP Node Lead) received the 2025 Eureka Prize for Sustainability. The Eureka Prizes are widely regarded as the “Oscars of Australian science”, and this award recognises her leadership in perovskite solar cells. Her work on improving durability and scalability is accelerating the commercialisation of perovskite–silicon tandem technologies and has the potential to push efficiencies beyond 40 percent.

Scientia Professor Xiaojing Hao (UNSW Sydney) was elected a Fellow of the Australian Academy of Science in 2025, one of the highest honours for scientific achievement in Australia. Professor Hao is a global leader in thin-film photovoltaics and has driven record efficiencies in kesterite (CZTS), an earth-abundant and non-toxic material with strong potential for low-cost, sustainable solar. Her team’s innovations in defect control are advancing CZTS as a viable partner for tandem solar technologies.



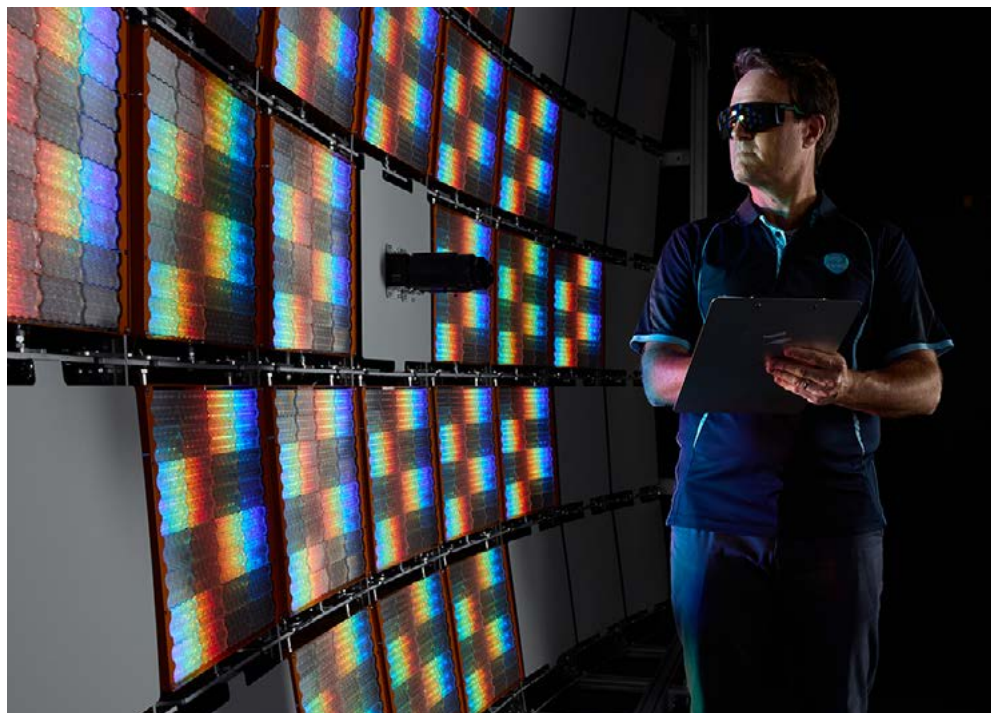
Scientia Professor Xiaojing Hao (UNSW Sydney) was elected a Fellow of the Australian Academy of Science in 2025. Pictured here with her kesterite research team. Photo: Rob Largent

Together, these honours highlight the depth and continuity of ACAP’s research excellence. They span foundational silicon breakthroughs through to cutting-edge tandem and thin-film technologies, and demonstrate Australia’s sustained global leadership in solar innovation.

Shaping global rules for next-generation solar performance

As solar technologies rapidly evolve, one challenge is becoming increasingly critical: how to measure performance and reliability in ways the world can trust. Through leadership in international standards development, ACAP is helping define the rules that will underpin the global deployment of both silicon and perovskite solar cells.

This work is led by two key figures within the ACAP research network. Dr Chris Fell (CSIRO Energy), who leads ACAP's Program Package 5 Manufacturing and Sustainability, is at the forefront of international efforts to establish measurement standards for emerging photovoltaic technologies. Professor Bram Hoex (UNSW Sydney), who leads Program Package 4 Device to Module, is driving global understanding of reliability challenges in advanced silicon solar cells.



ACAP Technical Lead Dr Chris Fell plays a leading role in the International Electrotechnical Commission (IEC) working groups developing a new global standard for perovskite device measurement.

For perovskites, the challenge is fundamental. These materials exhibit time- and history-dependent behaviour, making their performance difficult to measure consistently. Without agreed protocols, key performance parameters cannot be reliably verified, and commercial investment remains constrained.

These efforts position ACAP as a global authority not just in solar innovation, but in the systems that validate it.

Through CSIRO's Photovoltaic Performance Laboratory (PVPL), Australia's only NATA-accredited PV test facility, ACAP researchers are directly addressing this barrier. Dr Fell plays a leading role in the International Electrotechnical Commission (IEC) working groups, contributing to the development of a new global standard for perovskite device measurement (IEC 60904-1-4). This work is essential to enabling bankable, comparable performance data as the technology approaches commercialisation. (See case study: ["CSIRO's PVPL test lab leads international perovskite standards."](#))

In parallel, ACAP is shaping how the world assesses the long-term reliability of silicon solar cells. As TOPCon technology becomes dominant in global manufacturing, ultraviolet-induced degradation (UVID) has emerged as a key risk factor. Professor Hoex and his team at UNSW are leading the international effort to understand the mechanisms behind UVID and translate this knowledge into practical testing protocols.

Working closely with industry partners and contributing directly to IEC discussions, the Hoex Group's research is now informing emerging global standards for UV testing. Notably, while international industry representatives may formally lead some standards activities, much of the underpinning data and scientific insight comes from ACAP-supported research, highlighting Australia's outsized influence on global practice.

Professor Bram Hoex (UNSW), ACAP Technical Lead, delivering a plenary presentation on the progress of the UVID testing standard at EU PVSEC 2025.



Professor Hoex delivered a plenary presentation on the progress of the UVID testing standard at EU PVSEC 2025 and is a regular presenter on a webinar series produced by Sinovoltaics, a PV quality assurance company that educates its partners on commercial silicon reliability.

(See case study in PP.4 Device to Module [“Shaping industry standards for UV-induced degradation in TOPCon.”](#))

Together, these efforts position ACAP as a global authority not just in solar innovation, but in the systems that validate it. By ensuring that next-generation technologies can be measured accurately and consistently, ACAP is helping to unlock investor confidence, accelerate commercial deployment, and support the transition to a truly global clean energy future.

Australia’s next generation of PV research leaders

At the Australian Centre for Advanced Photovoltaics (ACAP) building world-class solar technology goes hand in hand with building world-class people. The careers of Dr Jessica Yajie Jiang (UNSW), Associate Professor Wallace Wong (University of Melbourne), and Associate Professor James Bullock (University of Melbourne) show how sustained investment in talent is strengthening Australia’s leadership in photovoltaic (PV) research and accelerating the path to ultra low-cost solar.



Dr Jessica Yajie Jiang (UNSW)

Dr Jessica Yajie Jiang

ACAP Node Lead UNSW, ACAP Senior Research Fellow, Industry Consortium Manager, ELICE Program Lead

Dr Jessica Yajie Jiang represents a new generation of globally connected PV leaders. After completing her PhD under Scientia Professor Martin Green, she progressed through an Australian Renewable Energy Agency postdoctoral fellowship and an early ACAP fellowship. She describes this support as pivotal in enabling independent research and industry engagement.

Today, as a Senior Research Fellow and UNSW ACAP Node Leader, she leads projects spanning silicon, perovskite, and III-V technologies, and has secured more than \$22 million in funding. Her work targets both breakthrough efficiency and real-world deployment. Dr Jiang's leadership extends to developing the next generation of clean energy researchers through the ELICE program, and building critical partnerships with global manufacturers through the ACAP Industry Consortium.

Reflecting on her journey, Dr Jiang notes, "ACAP provided the essential platform for me to conduct my research, propose new ideas, and build connections with industry. It allowed me to grow from an early-career researcher into a leader shaping future technology directions."



Associate Professor James Bullock
(University of Melbourne)

Associate Professor James Bullock

ACAP Node Co-lead for the University of Melbourne and Technical Lead for Program Package 1 Silicon Solar Cells

At the University of Melbourne, Associate Professor James Bullock's experience highlights how targeted fellowships translate into research capacity and leadership. Awarded an ACAP fellowship in 2019 after returning from the United States, Bullock used the support to establish his research group and pursue industry-relevant innovation in passivated contacts for silicon solar cells. His work improves the efficiency of mainstream silicon technologies, directly contributing to lower electricity costs and scalable deployment.

In 2025, he stepped into national leadership roles as ACAP Node Co-lead and Technical Program Lead for Program Package 1, Silicon Solar Cells. This reflects the growth of his research program and his influence across the sector.

"ACAP has enabled me not just to build a research group, but to help shape the direction of silicon PV research in Australia," he says. "That continuity, from early support through to leadership, has been critical in delivering impact at scale."



Associate Professor Wallace Wong
University of Melbourne

Associate Professor Wallace Wong

ACAP Node Co-lead at the University of Melbourne

Associate Professor Wallace Wong's career demonstrates the long-term value of sustained support. Beginning with early fellowships that predated ACAP, he helped shape Australia's research strength in emerging PV materials.

Now an ACAP Node Co-lead at the University of Melbourne, his work focuses on advanced energy materials and tandem technologies to augment silicon and meet ultra low-cost solar targets. Alongside scientific contributions, Wong emphasises mentorship as a core outcome of research investment.

"What motivates me most is taking fundamental ideas through to proof-of-concept, and training the next generation along the way," he explains. "ACAP has been critical in supporting both, enabling discovery, translation, and the development of people."

When early-career scientists are given the resources, networks and industry connections to succeed, they multiply impact by building teams, attracting investment, and delivering innovation. ACAP's integrated model is not just advancing solar technology. It is securing Australia's position as a global leader by growing the talent base that will define the future of photovoltaics.

ACAP Industry Consortium – a powerful platform for global collaboration

In 2025, seven tier-1 globally recognised solar manufacturers, including AIKO, JA Solar, Trina Solar, LONGi, Huasun, Tongwei, and Yingfa, joined the ACAP Industry Consortium. Launched in 2024, the Consortium works to strengthen collaboration between ACAP's leading photovoltaic researchers and global solar manufacturers to accelerate the development and deployment of next-generation solar technologies, while also supporting development of a skilled workforce for the sector.

Together, these companies represent a diverse cross-section of the global PV industry, spanning leading commercial technologies including PERC, TOPCon, heterojunction (HJT), and back-contact (BC) architectures, reflecting both the current state-of-the-art and emerging directions in high-efficiency solar cell development.

ACAP Founder and Chair of the Consortium, Scientia Professor Martin Green says, “Rapid progress in photovoltaic technologies relies on close interaction between research and industry and the Consortium is a powerful platform to grow those connections and collaborate on mutually beneficial research.”

Prof Martin Green and other ACAP members toured AIKO’s production facility in 2025.



JA Solar representatives visited UNSW SPREE in 2025. (l-r) Dr Jessica Yajie Jiang (ACAP), Mr Aiqing Yang (JA Solar Executive President), Prof Ned Ekins-Daukes (UNSW SPREE Head of School), Prof Renate Egan (ACAP), and Dr Zi Ouyang (JA Solar CEO).



In a defining piece of work published in Joule in early 2026, titled [“State-of-play of contending silicon photovoltaic technologies”](#),^[1] Prof Green and senior ACAP researchers joined technical leads from Consortium partners AIKO Solar, LONGi, Huasun, JA Solar, and Trina Solar to provide an overview of past research and discuss the strengths and weaknesses of competing silicon PV technologies.

These companies represent a substantial share of global module production and the paper brings together expertise spanning both laboratory innovation and gigawatt-scale manufacturing. The collaboration highlights the depth of trust ACAP has established with the world’s leading PV manufacturers. Read more in the case study for Program Package 6, [“ACAP’s global collaborations and high impact publications”](#).

In 2025, ACAP representatives visited manufacturing facilities of AIKO, JA Solar, Trina Solar, Huasun and Tongwei, gaining valuable insights into industrial processes and production environments. Representatives from JA Solar and Yingfa met with ACAP leaders and researchers at UNSW to understand the unique research capabilities and facilities in the ACAP network.

Dr Jessica Yajie Jiang, Manager of the ACAP Industry Consortium, says, “Through reciprocal visits and ongoing technical exchange, we are building strong and meaningful partnerships with industry. These interactions allow us to better understand real manufacturing challenges while also ensuring that our research can contribute directly to industry-relevant solutions.”

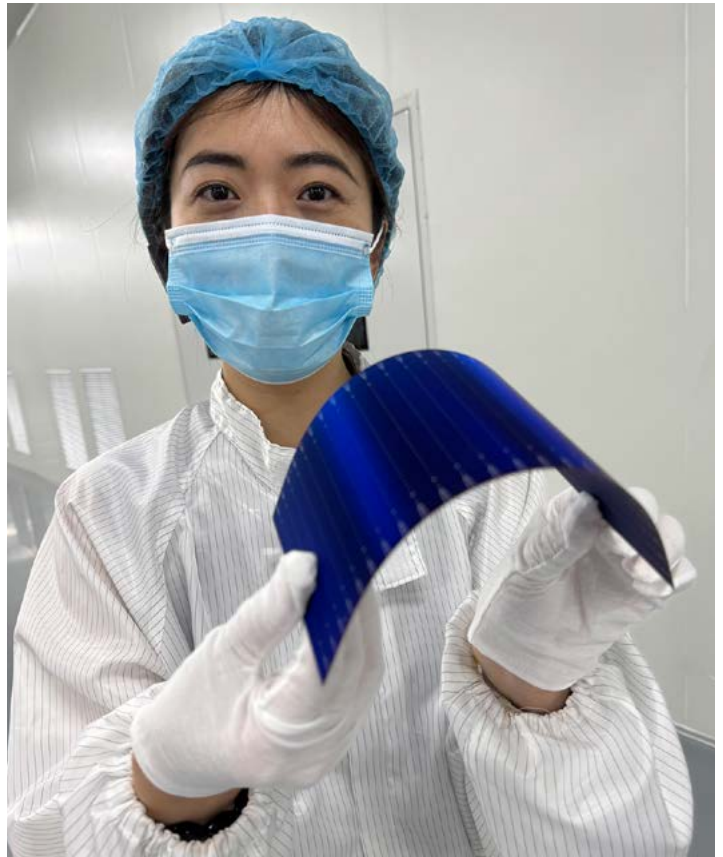
The Consortium plays an important role in talent development by enabling PhD training linked with industry engagement, offering students exposure to real-world challenges and industry perspectives. PhD program research topics are aligned with both industry needs and ACAP’s strategic priorities.

Prof Renate Egan, Executive Director of ACAP, says, “By creating opportunities for PhD training and industry engagement, we are helping to build a highly skilled workforce that will support the continued growth of the global solar sector.”

UNSW and ACAP members toured the Tongwei production facility in 2025.



Dr Jessica Yajie Jiang, ACAP Consortium Manager visiting the Huasun production facility, with a 60 μm wafer in June 2025.



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Silicon Solar Cells

Program Package 1

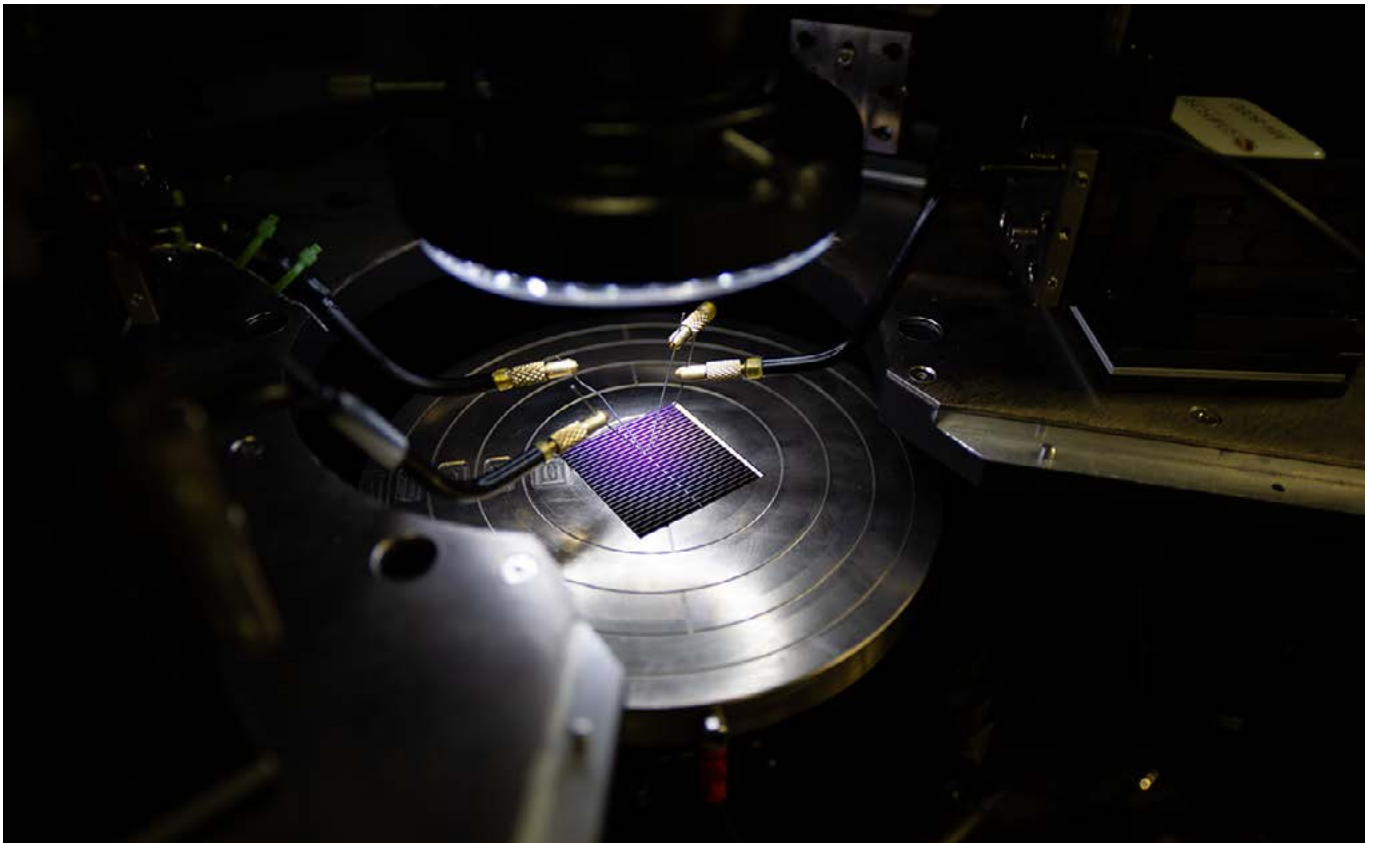


Technical Program Lead
Associate Professor
James Bullock
University of Melbourne

Program Package 1 (PP1) accelerates the development of next-generation silicon solar cells through coordinated advances in materials, interfaces, device architectures, and characterisation techniques.

By combining fundamental studies with industrially relevant fabrication and modelling approaches, the research targets pathways to achieve higher efficiencies and a lower levelised cost of electricity (LCOE).

Key challenges include achieving further improvements in surface passivation, wafer quality, and thinner cell architectures, as well as enhancing light-trapping strategies, reducing front-surface reflection, and minimising parasitic absorption. In parallel, there is a critical need to significantly reduce the reliance on silver in metallisation to support scalable and cost-effective manufacturing.



Solution pathways

1. **Silicon materials:** Enhancements in wafer quality, resistivity uniformity, and impurity gettering directly improve bulk lifetimes, enabling higher-efficiency cells and greater process yield.
2. **Silicon surfaces and interfaces:** Development of low-recombination, low-absorption passivated polysilicon and metal-oxide contacts improves surface passivation and optical transparency, boosting device efficiency.
3. **Advanced silicon devices and fabrication technologies:** Novel nanotexturing, streamlined back contact patterning methods, and ultra-low-silver metallisation strategies improve light trapping, reduce reflection, and greatly cut dependence on silver.
4. **Characterisation and modelling techniques:** Advanced characterisation and modelling tools enable precise optimisation of passivation, interfaces, and contact properties, accelerating reductions in recombination, parasitic absorption, and optical losses.



Key progress in each pathway

Silicon materials

Achieving the ultimate efficiency potential of silicon solar cells requires exceptionally high bulk electronic quality in silicon wafers. Led by ANU, the ACAP team continues to lead global efforts to improve solar cell performance by optimising silicon materials and focusing on the control and management of impurities and defects at all stages of the process.

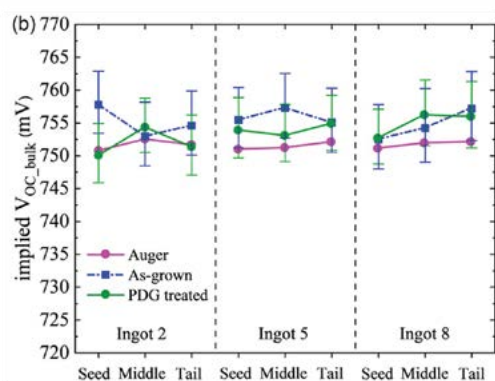


Figure PP1. 1 Implied open circuit voltages measured on Sb-doped ingots with/without a gettering process compared to the Auger limit, showing excellent performance is attainable in the as grown state.

Ensuring a narrow resistivity distribution along the ingot is vital for maximising yield, as the strong sensitivity of solar-cell efficiency to wafer resistivity makes uniformity critical to reducing the LCOE.

In 2025, research efforts focused on using antimony (Sb) instead of the commonly used phosphorus (P) for n-type doping to achieve a more uniform wafer resistivity, as well as exploring improved gettering strategies to enhance material quality. The ANU team, in collaboration with LONGi, investigated industrial Sb-doped n-type silicon wafers grown using the Recharged Czochralski (RCz) method. Results showed excellent bulk lifetimes and implied voltages at the Auger limit in the as-grown state (Figure PP1. 1), with only the ingot tail requiring gettering to reach optimal performance.

Fundamental studies confirmed that Sb-doped ingots exhibit a more uniform axial resistivity than P-doped ingots, with accurate dopant distribution modelling requiring both segregation and evaporation effects. These results, which are part of an ongoing ACAP contribution to improving silicon material quality, are highlighted in the case study [“ANU and LONGi shape industry direction for manufacturing high-performance silicon wafers”](#) and demonstrate the potential of Sb-doping for high-efficiency, cost-effective silicon solar cell production.[1]

Parallel investigations into gettering mechanisms revealed that iron decoration significantly enhances the recombination activity of oxide precipitates, while phosphorus gettering effectively reverses this effect, restoring carrier lifetimes. Cooling rate variations had a negligible impact on oxide-related recombination behaviour.[2] Further studies examined the impurity gettering properties of doped polycrystalline silicon (poly-Si) contacts featuring a nanoscale SiO_x interlayer.[3]

Using atom probe tomography (APT) and scanning transmission electron microscopy (STEM), researchers mapped three-dimensional atomic interactions among dopants, oxygen, and iron (Fe) impurities. A newly identified “O-lean” interfacial region above the oxide was proposed to play a key role in passivation. Additionally, the discovery of Fe gettering via co-clustering with P_4V (a vacancy surrounded by four nearest neighbouring P atoms) clusters and oxygen provides the first experimental validation of this mechanism, offering valuable insights for optimising doped poly-Si contact performance and overall solar cell efficiency.

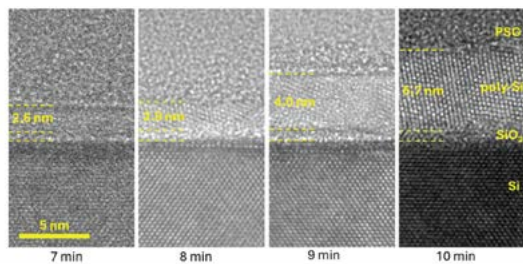



Figure PP1. 2 Cross-sectional TEM images of UT-TOPCon contacts, which can achieve record low J_0 values below 1 fA cm^{-2} .


Silicon surfaces and interfaces

Low-loss surfaces and interfaces are essential to realising the full performance potential of silicon solar cells. In one focus area, an ANU and the University of Melbourne collaboration has advanced the development of high-transparency, low-recombination, and low-resistivity passivated contacts, as well as high-performance, novel passivation layers.

Over the past year, significant effort has been directed towards the development of ultra-thin tunnel oxide passivated contacts (UT-TOPCon) to minimise optical losses in TOPCon solar cells and further enhance device efficiencies.[4] A major milestone was achieved with record-low surface recombination currents of $J_0 = 0.8 \text{ fA cm}^{-2}$ on planar and 1.3 fA cm^{-2} on textured substrates, using sub-3 nm n^+ poly-Si layers, whose cross sections are shown in Figure PP1. 2.



Significant effort has been directed towards the development of ultra-thin tunnel oxide passivated contacts.



The optimised 2.9 nm poly-Si/SiO₂/Si structure delivered specific contact resistivities of 2.5–5 mΩ·cm², while maintaining structural integrity and minimal parasitic absorption. Transmission electron microscopy (TEM) and electrochemical capacitance-voltage (ECV) analyses confirmed controlled dopant diffusion and revealed a grain structure transition that defines the passivation limit near 2.6 nm of poly-Si. Incorporating these optical and electrical parameters into full devices, simulations predicted up to a 0.5% absolute efficiency improvement for single-junction Si cells and a 0.7 mA·cm⁻² J_{GEN} gain in Si-perovskite tandem configurations.

An alternative strategy to improve the transparency of poly-Si contacts is to add a small concentration of carbon. A team at UNSW has further advanced plasma-enhanced chemical vapour deposition (PECVD)-based n⁺ and p⁺ poly-Si/SiO_x passivated contacts by incorporating carbon doping to widen the bandgap and reduce parasitic absorption along with synergistic interfacial oxide engineering to improve passivation performance.[5]

In parallel, substantial progress was made in integrating ultrathin poly-Si contact layers with various metal-oxide barrier layers to preserve contact and passivation properties during metallisation and high-temperature processing. Titanium oxide (TiO₂) barrier layers were developed and demonstrated to protect thin poly-Si passivated contacts,[6] while aluminium-doped zinc oxide (AZO), combined with different capping layers, successfully maintained contact performance and passivation quality up to 500 °C during extended anneals.[7]

Beyond UT-TOPCon structures, team members from ANU contributed to progress by completely removing the poly-Si layer in favour of pure metal oxide-based contacts.[8] [9] Using atomic layer deposition (ALD), they developed zinc oxide (ZnO) films doped with either aluminium or boron, with tuneable dopant levels that allowed systematic evaluation of contact resistance, passivation strength, and optical properties. Optimised doping levels yielded impressive results, achieving iV_{oc} and ρ_c values of 731 mV and 33 mΩ·cm² for B-doped ZnO and 730 mV and 16 mΩ·cm² for Al-doped ZnO.

These results were further improved by optimising annealing conditions and layer thicknesses. Because the excellent passivation relied on an Al_2O_3 capping layer, the team also established a selective etching process that preserved surface passivation while enabling efficient carrier transport.

This work, which is part of a long-standing effort devoted to the development of metal oxide contacts, is described in the case study [“10 years in the pipeline – ACAP collaboration delivers industry-ready, high-performance, low-cost passivating contacts”](#). The work was presented by Dr Lachlan Black as an invited talk at the 2025 National Renewable Energy Laboratory (NREL) Workshop on Crystalline Silicon.[8]


Finally, zinc sulphide (ZnS) was explored as a promising new dielectric layer for surface passivation, aiming to simplify device fabrication and reduce levelised cost of electricity (LCOE). Using ALD with a zinc precursor and H_2S gas, $\text{ZnS}/\text{Al}_2\text{O}_3$ stacks on both n-type and p-type silicon substrates were optimised, achieving outstanding passivation with $J_{0s} \approx 3 \text{ fA}\cdot\text{cm}^{-2}$. This excellent performance positions ZnS as a leading next-generation dielectric material for silicon surface passivation.

Advanced silicon devices and fabrication technologies


Novel methods for processing and patterning silicon solar cells have been developed, enhancing device efficiencies and reducing costs. Detailed simulations of industrial cell structures have been conducted, and pathways to further improvement identified.

Building on these developments, research in 2025 focused on thinner silicon, advanced contacting processes, and smart patterning to reduce silver. Working with industry partners on record cells has enabled the team to identify further ultra low-cost solar opportunities.

A large proportion of the remaining potential gains in silicon solar cells are centred on improving short-circuit current densities. This year, PP1 researchers have



PP1 researchers have been exploring novel nanotexturing research to reduce reflection and increase light trapping.



ANU and University of Melbourne teams have also explored inkjet printing as a maskless, digitally patterned, liquid-based technique suitable for ultra low-cost solar manufacturing.

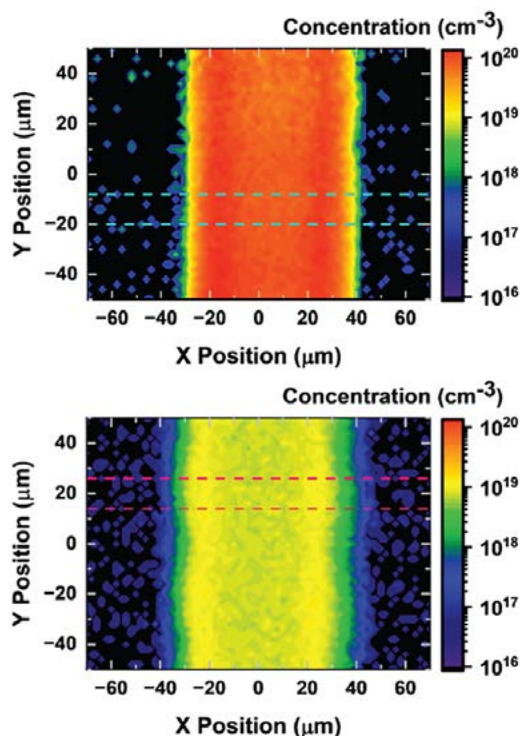


Figure PP1. 3 Controlled phosphorus (top) and boron (bottom) dopant concentration achieved using ink-jet printing.

been exploring novel nanotexturing research to reduce reflection and increase light trapping.

This topic was explored in a plenary talk at SNEC 2025, delivered by ACAP founder Professor Martin Green, more details of which can be found in the case study "[Professor Martin Green compared tiny pyramids on silicon's surface for improved sunlight absorption – and big performance gains](#)". Such methods will be especially relevant as trends towards thinner silicon wafers continue, motivated in part by material cost reductions and higher V_{OC} potential. Work in this area under PP1 has demonstrated the use of 70 μm thick silicon in TOPCon cells with an efficiency over 24%, which, to the best of our knowledge, is a record for this cell architecture and thickness combination.

The ANU and the University of Melbourne teams have also explored inkjet printing as a maskless, digitally patterned, liquid-based technique suitable for ultra low-cost solar manufacturing.[10] By replacing traditional complex doping steps with inkjet-printed doping, this approach reduces process steps, chemical use, and material waste. The project aims to simplify the formation of localised poly-Si passivating contacts for advanced structures such as TOPCon and interdigitated back contact (IBC) solar cell architectures.


Both n^+ and p^+ poly-Si passivating contacts were successfully defined using liquid dopant sources and co-annealed in a single step, demonstrating compatibility with scalable inline processing. Interdigitated n^+ and p^+ poly-Si passivating contacts were formed simultaneously, using inkjet printing with contact line widths as narrow as 60–70 μm , as shown in Figure PP1. 3.

Unintended cross-doping mechanisms were identified and mitigated using a spin-on SiO_x capping layer, with results presented at the 36th International Photovoltaic Science and Engineering Conference (PVSEC-36). The front-side localised poly-Si contacts for an n-type rear-junction TOPCon cell were further demonstrated, achieving accurate alignment to metal fingers on textured surfaces.


In parallel, the team investigated industry-relevant laser-enhanced contact methods to improve performance and laser roughening of back surfaces for optical pathlength enhancement.

In the laser-enhanced contact study, they examined the effect of an additional light anneal following laser processing.[11] This treatment increased series resistance, localised to the front metal/silicon interface, likely due to hydrogen accumulation. Although dopant deactivation was negligible, structural contributions, such as interfacial glass thickening, could not be excluded. The series resistance increase was reversible after a subsequent laser enhancement step, underscoring the importance of applying the laser-enhanced contact last in the fabrication sequence to preserve TOPCon cell performance.

The second laser study focused on how laser fluence affects rear poly-Si contact roughness, passivation, and resistivity. All processed samples showed surface roughening, with passivation losses recoverable after hydrogenation at low-to-moderate fluences, achieving optimal iV_{oc} (~716 mV) after treatment at 0.28 J/cm^2 . Enhanced external quantum efficiency signals above 700 nm indicated improved optical pathlengths, and all samples exhibited low contact resistivity ($<10 \text{ m}\Omega\text{-cm}^2$).



There is significant work aimed at reducing or eliminating silver use in silicon solar cells.



There is also significant work aimed at reducing or eliminating silver (Ag) use in silicon solar cells. UNSW researchers have developed a novel “silver dash” technique [12] which decouples the functions of metal-Si contact formation and finger conductivity without sacrificing efficiency, opening more opportunities for the application of non-Ag pastes in PV.

Pilot production results led to the fabrication of over 25%-efficient full-sized TOPCon solar cells and, separately, demonstrated ultra-low-silver metallisation down to 2 mg/W, achieving over 80% silver savings using existing toolsets. These levels are sufficient for multi-terawatt scale annual PV deployment using only 20% of the global silver supply, and are compatible with existing production toolsets.



Simulations showed that transitioning to a TOPCon back-contact architecture could raise efficiencies towards 28%.



In addition, completely silver-free metallisation schemes are being developed at UNSW using laser contact opening together with aluminium pastes for both TOPCon and back contact solar cells.[13]

Finally, and with near-term outcomes aligned with Ultra Low-Cost Solar goals, researchers use advanced simulation and analysis tools SunSolve and Quokka3, to quantify optical, electrical, and resistive losses in commercial TOPCon cells.

By working closely with industry partner Jinko Solar on an analysis of the 26.66% champion TOPCon cell, the team confirmed that near-theoretical V_{OC} had been achieved, with further opportunities possible due to shortfalls in J_{SC} and fill factor due to resistive and optical limitations. Simulations showed that transitioning to a TOPCon back-contact architecture could raise efficiencies towards 28%. These findings are part of a larger collaboration between ANU, University of Melbourne (UoM), and JinkoSolar and are highlighted in the case study [“Record studded ANU–Jinko partnership redefines TOPCon’s near term prospects to over 27%.”](#)

The work was presented as a plenary talk by Professor Daniel Macdonald at the IEEE PVSC 2025.[14]

Characterisation and modelling techniques

Advancing silicon solar cells requires not only new materials but also improved characterisation and modelling techniques. This year marked an important milestone in a long-term ACAP-supported project on artificial intelligence-enabled, contactless I-V characterisation. The technology, developed by Professor Ziv Hameiri’s team, is set to be commercialised in partnership with BT Imaging through the TRaCE Lab to Market Fund. See the case study [“UNSW collaboration delivers revolutionary, faster, cheaper, and more powerful solar-cell testing technology”](#) in this chapter.

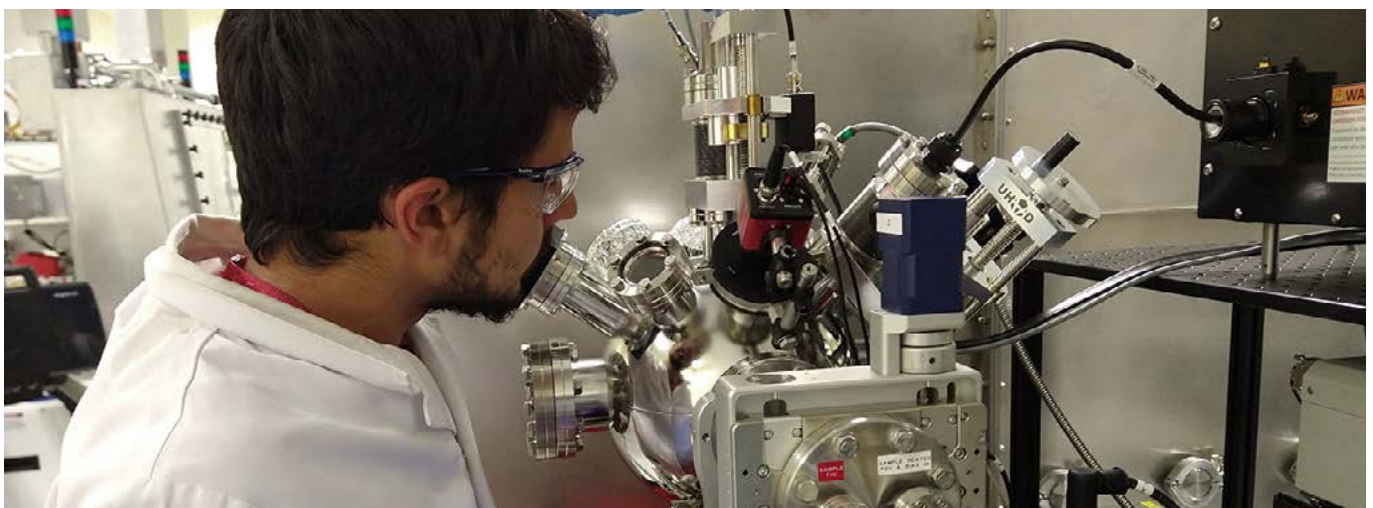
The team has gone further to apply capacitance–voltage analysis, impedance spectroscopy, Kelvin probe, and surface photovoltage measurements to study silicon surfaces and interfaces, linking their properties to device performance. Recent work has focused on advances in surface mapping enabled by a recent ACAP infrastructure investment in a specialised Kelvin probe analysis tool, pictured in Figure PP1.4

The aim is to accurately measure the surface work function of transparent conductive oxides and examine how UV light and ambient conditions, such as oxygen and vacuum, affect these measurements. Using the surface photovoltage capability of the Kelvin probe system, they also characterise heterocontacts for new top-cell absorbers in silicon-based tandem cells.

This year, the work function of transparent conducting oxides (ITO, FTO, and AZO) was measured, finding that UV exposure lowers the work function, while oxygen restores it – a result that is reproducible across cycles.

The study further explored UV illumination to reduce the AZO work function and improve contact resistance, with promising preliminary results. Surface photovoltage measurements of Cu_2O with ZnO , AZO, and SnO_2 revealed a negative surface photovoltage for SnO_2 , indicating junction formation. These findings highlight the value of Kelvin probe techniques for evaluating carrier-selective contacts and advancing high-efficiency, low-cost solar technologies.

Figure PP1. 4 Advanced Kelvin probe analysis tool.



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Case study



Record studded ANU–Jinko partnership redefines TOPCon’s near term prospects to over 27%

Macdonald says the timeline between identifying a loss mechanism and implementing a solution in mass production can be as short as 12 months.

At IEEE PVSC Professor Dan Macdonald presented a compelling analysis of JinkoSolar’s record-setting 26.7% TOPCon cell, outlining the next steps that will push mass production efficiencies beyond 27% within just a few years.

In front of a full auditorium at the IEEE PVSC in Montreal, one of the world’s leading silicon solar cell experts presented a compelling analysis of JinkoSolar’s record-setting 26.7% TOPCon cell, outlining the next steps that will push mass production efficiencies beyond 27% within just a few years.

Since 2016, Professor Dan Macdonald and his PV Research Group at the Australian National University have partnered with JinkoSolar, the world’s largest solar cell manufacturer, forging a powerful collaboration that has delivered a string of world-record efficiencies for industrial TOPCon cells, with 26.7% this year, after earlier records of 24.8% in 2020 and 25.4% in 2021.

Supported by ARENA and ACAP, the partnership is defined by its ability to rapidly translate laboratory breakthroughs into scalable, cost-effective industrial solutions.

Macdonald says the timeline between identifying a loss mechanism and implementing a solution in mass production can be as short as 12 months.

The partnership is made more potent with the collaboration of Associate Professor James Bullock and his team at the University of Melbourne (UoM), bringing unique capabilities including their state-of-the-art soft sputtering system for depositing ultra-thin, low-damage contacts. Combined with ANU’s comprehensive fabrication and advanced characterisation facilities, the collective team can develop and test new materials and structures with unprecedented precision.



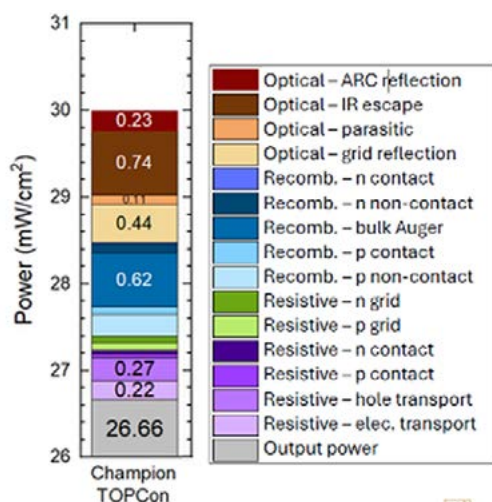
A critical enabler of these achievements is the use of advanced simulation and analysis tools. SunSolve and Quokka, provided via PV Lighthouse, enable detailed optical and electrical modelling of cells, pinpointing exactly where efficiency losses occur – whether from surface recombination, resistive losses, or shading by metal contacts. With support from ARENA, PV Lighthouse makes these tools available at no cost to Australian researchers to accelerate progress across the sector.

“Without access to these tools, we wouldn’t be able to break down different losses in detail or identify the most effective pathway to improving cell performance,” says Macdonald.

Loss analysis of champion 26.7% TOPCon cell

Key loss mechanisms

- Optical losses:
 - IR escape – better light-trapping
 - Poly-Si absorption – thinner poly
 - Front finger reflection – thinner fingers
- Recombination losses:
 - No bulk defect recombination! Auger only
 - Front surface – improve passivation
- Resistive losses:
 - Transport to electron and hole contacts – contact spacing > 5 × cell thickness!
 - » Closer contacts required



Loss analysis of Jinko champion TOPCon cell, showing the primary loss mechanisms, and pathways for improvement.

Picking the low hanging fruit on the path to > 27% efficiencies

Through systematic mapping and mitigation of loss mechanisms, Macdonald’s team has closed the “voltage gap” and identified pathways to approach the theoretical efficiency limit of silicon (~29.5%).

“The big takeaway is that almost no bulk defects remain in the silicon. The last performance challenges are now engineering problems that industry can resolve,” Prof Macdonald explains.

Looking ahead, the opportunities lie in better light management, smarter contact design, and thinner wafers.

- **In the near term (1–3 years)** manufacturers can push standard TOPCon into the 27% range with incremental, scalable improvements.
- **Medium-term (3–7 years)** will see the emergence of back-contact designs, allowing efficiencies above 27.5% – especially valuable for rooftop and space-constrained markets.
- **Long-term** these advances pave the way for silicon-based tandem cells above 30%, which will leverage savings across the value chain. “Every fractional efficiency gain translates into billions of dollars in savings across gigawatts of deployment,” Macdonald emphasises.



Professor Dan Macdonald's PV Silicon research team at ANU.

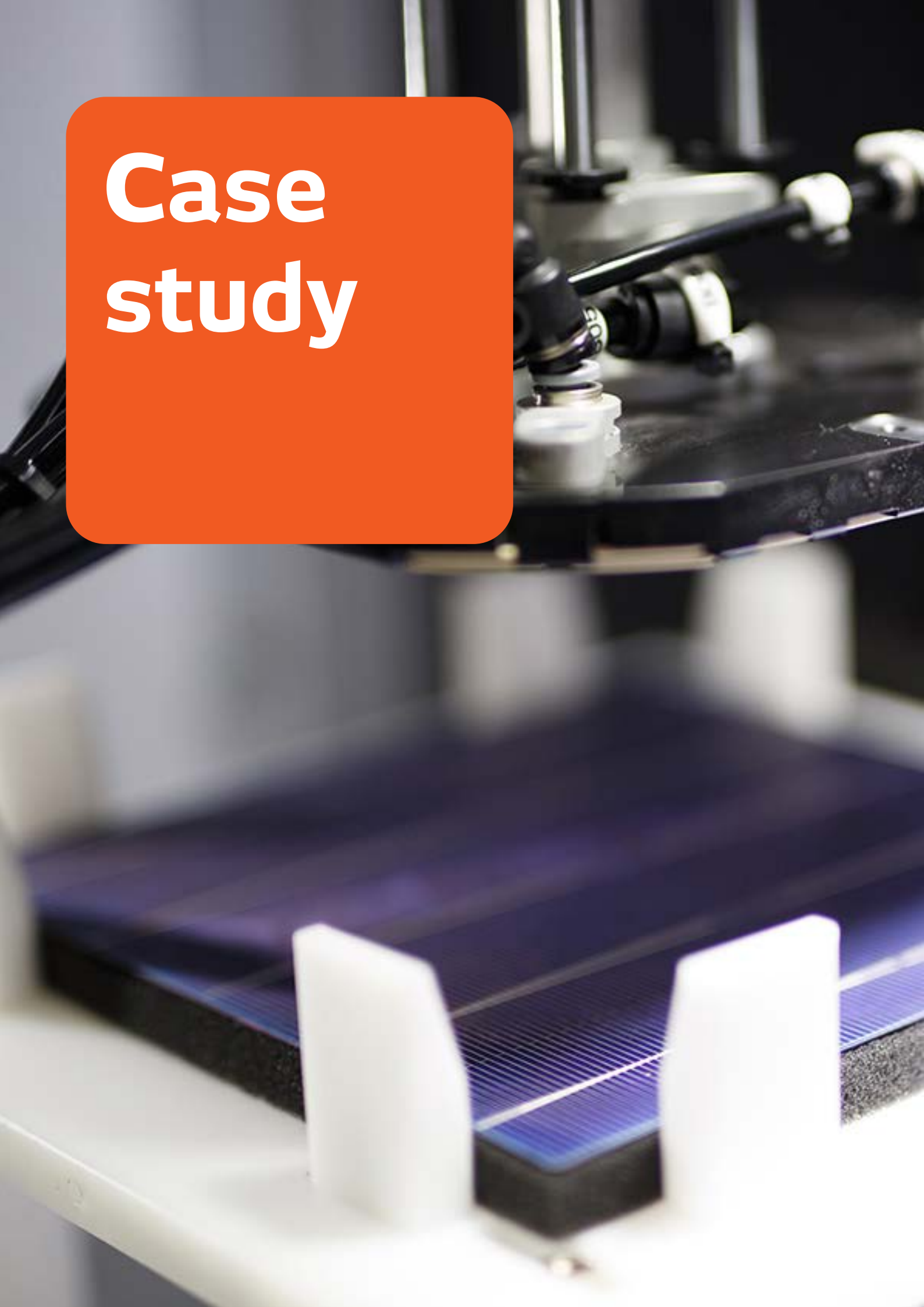
The partnership enjoys deep trust between collaborators. JinkoSolar's Chief Scientist Dr Hao Jin, and Vice President R&D Dr Xinyu Zhang are both ANU alumni, while ACAP fellowships throughout the partnership have trained a new generation of PV leaders. These connections ensure ongoing knowledge transfer and collaboration.

Dr Xinyu Zhang said, "ANU and Jinko have worked together for many years – exploring new materials, innovative cell structures, and breakthrough processing methods. The collaboration has delivered advancement of technologies and products across the entire photovoltaic industry."

“
Every fractional efficiency gain translates into billions of dollars in savings across gigawatts of deployment.
”

With rapid innovation cycles and a clear roadmap, the ANU–Jinko–UoM partnership is set to keep Australia and its partners at the forefront of global solar technology, driving down the cost of clean energy worldwide. ■

Case study

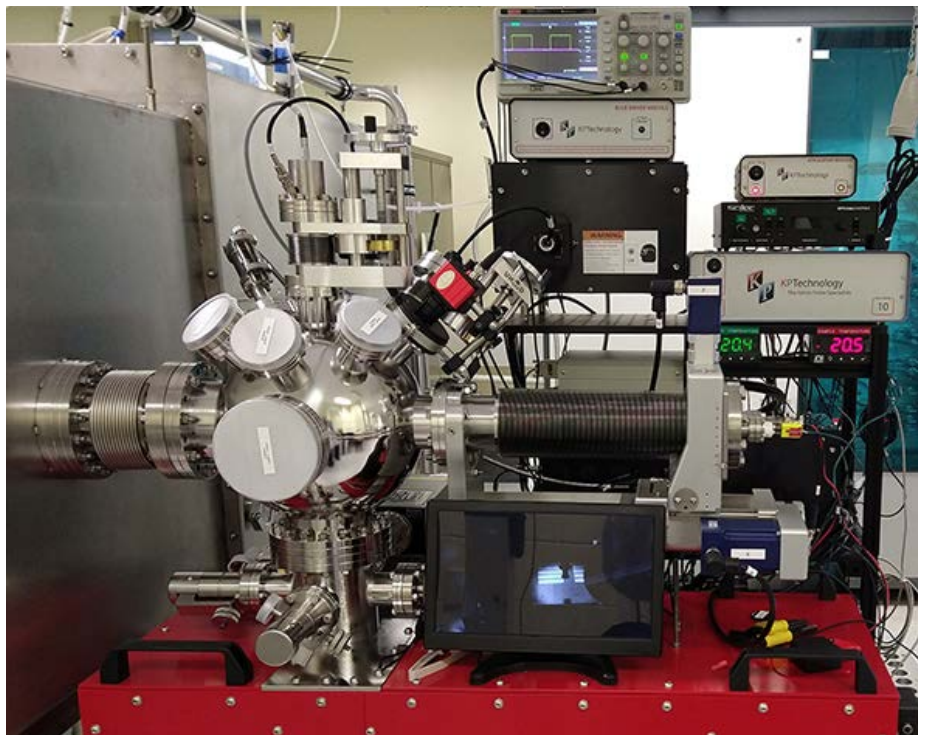


10 years in the pipeline – ACAP collaboration delivers industry ready, high-performance, low-cost passivating contacts for solar cells

For more than a decade, researchers at the Australian National University have been exploring how new kinds of metal oxides can make silicon solar cells more efficient, affordable, and reliable. Working with ACAP colleagues at the University of Melbourne and UNSW Sydney, the team has become a global leader in developing new transparent passivating contacts.

A *passivating contact* is a very thin layer placed between the silicon and the metal contacts. Its job is to reduce defects on the silicon surface (which otherwise cause energy losses) while still letting electrons pass through easily. Most high-efficiency solar cells today rely on amorphous or polycrystalline silicon passivating contacts, but they can slightly block sunlight and require complex, high-temperature processing. Metal oxides, by contrast, are transparent, easy to deposit, and potentially cheaper.

The new Kelvin Probe Ambient-Pressure Photoemission system enables precise study of how materials behave at the atomic level.



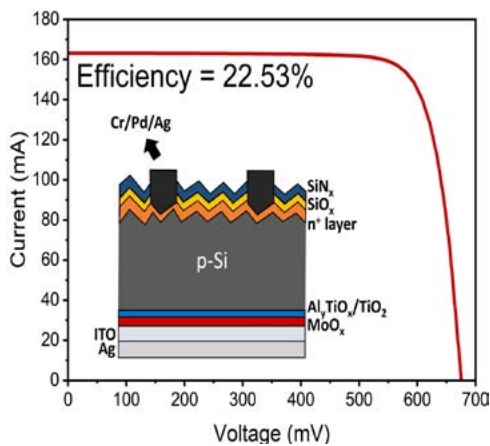
ANU's breakthrough research has shown that the presence of chlorine, when certain oxides – like titanium oxide (TiO_2) and aluminium oxide (Al_2O_3) – are manufactured, can dramatically reduce the number of defects at the silicon surface, and thus energy losses in solar cells.[1]

ANU researchers including Dr Lachlan Black, Dr Gabriel Bartholazzi, Dr Mohamed Shehata, and Professor Daniel Macdonald have demonstrated world-leading results. Their chlorinated aluminium–titanium oxide (Al_yTiO_x) and titanium oxide (TiO_2) stacks have achieved record efficiencies when combined with molybdenum oxide (MoO_x), for transparent hole-selective contacts – up to 22.5% – while showing remarkable stability and even “self-healing” behaviour after exposure to UV light or manufacturing steps.[2]

(l-r) Dr Mohamed Shehata, Dr Gabriel Bartholazzi, and Dr Lachlan Black at PVSEC-35 in Numazu, Japan (2024) after Dr Bartholazzi won best oral presentation and Dr Shehata won best poster presentation for their work relating to metal oxides.

“Our work shows that chlorine-based passivation can deliver outstanding surface quality, transparency and long-term stability,” said Dr Lachlan Black, presenting at the 32nd Workshop on Crystalline Silicon Solar Cells and Modules in Breckenridge, Colorado, in July 2025.[3]





Schematic of the team's best performing cell (the optimised $\text{Al}_y\text{TiO}_x/\text{TiO}_x/\text{MoO}_x$ stack) with an efficiency of 22.53%. This was a new record for cells incorporating transparent hole-selective passivating contacts.

“
These results point to a new generation of contact materials that could outperform existing silicon-based layers, while being simpler and cheaper to manufacture.
 ”

“These results point to a new generation of contact materials that could outperform existing silicon-based layers, while being simpler and cheaper to manufacture.”

The new Kelvin Probe Ambient-Pressure Photoemission system and Next-Generation Silicon and Tandem Hetero-Contact Laboratory at ANU allow precise study of how these materials behave at the atomic level. These facilities have also strengthened national collaboration, enabling UNSW and the University of Melbourne to share samples, data, and expertise across ACAP's research network.

The team's new ACAP-supported project is now taking this research closer to industry, in partnership with Trina Solar, developing metal oxide layers suitable for mass-production environments. The project will address one of the main challenges with transparent metal oxides – their integration on the front side of cells while meeting industrial standards.

Dr Gabriel Bartholazzi said, “This effort is only possible thanks to a decade of leading research by ANU, UNSW and the University of Melbourne.”

“Achieving this goal will be a significant milestone for the PV community, building on years of dedicated work and ensuring our advances remain relevant to industry.” ■

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Case study




ANU and LONGi shape industry direction for manufacturing high-performance silicon wafers

In recent years, with the support of ACAP, Dr Anyao Liu and the Silicon PV Research Group at ANU have delivered a roadmap that charts the path for global industry to cleaner, more efficient, and more stable silicon solar technologies.

Building on decades of pioneering work at both ANU and UNSW in identifying and eliminating bulk defects in silicon, the ANU team – including Professor Dan Macdonald, Dr Anyao Liu, Dr Rabin Basnet, Ms Afsaneh Kashizadeh, Dr Zhongshu Yang and many former colleagues – has sharpened industry's understanding of wafer quality, characterisation methods, and defect-control strategies that are central to next-generation solar manufacturing.

As solar cell efficiency continues to rise, materials are becoming far more sensitive to even tiny traces of contamination. A major step was a comprehensive review in 2021[1] of how manufacturers can remove metal impurities to less harmful regions of the device during solar cell production, a process known as gettering. Dr Liu and the team reviewed all gettering techniques applicable to silicon solar cells, including some pioneered by the ANU team, and provided the first comprehensive map of how manufacturers can optimise these steps as the industry moves towards higher purity requirements. Their findings reinforced ANU as a trusted voice in guiding the production of cleaner, more reliable wafers at scale.

The team's 2024 investigation into the impacts of iron contamination in TOPCon cells provides practical pathways for manufacturers to better manage impurities and stabilise cell performance.[2] They confirmed the robustness of TOPCon and highlighted how advanced gettering helps maintain performance as efficiencies increase.



With ACAP's support, ANU and LONGi have positioned Australia at the forefront of high-performance silicon wafer research that is directly shaping the future of global solar manufacturing.

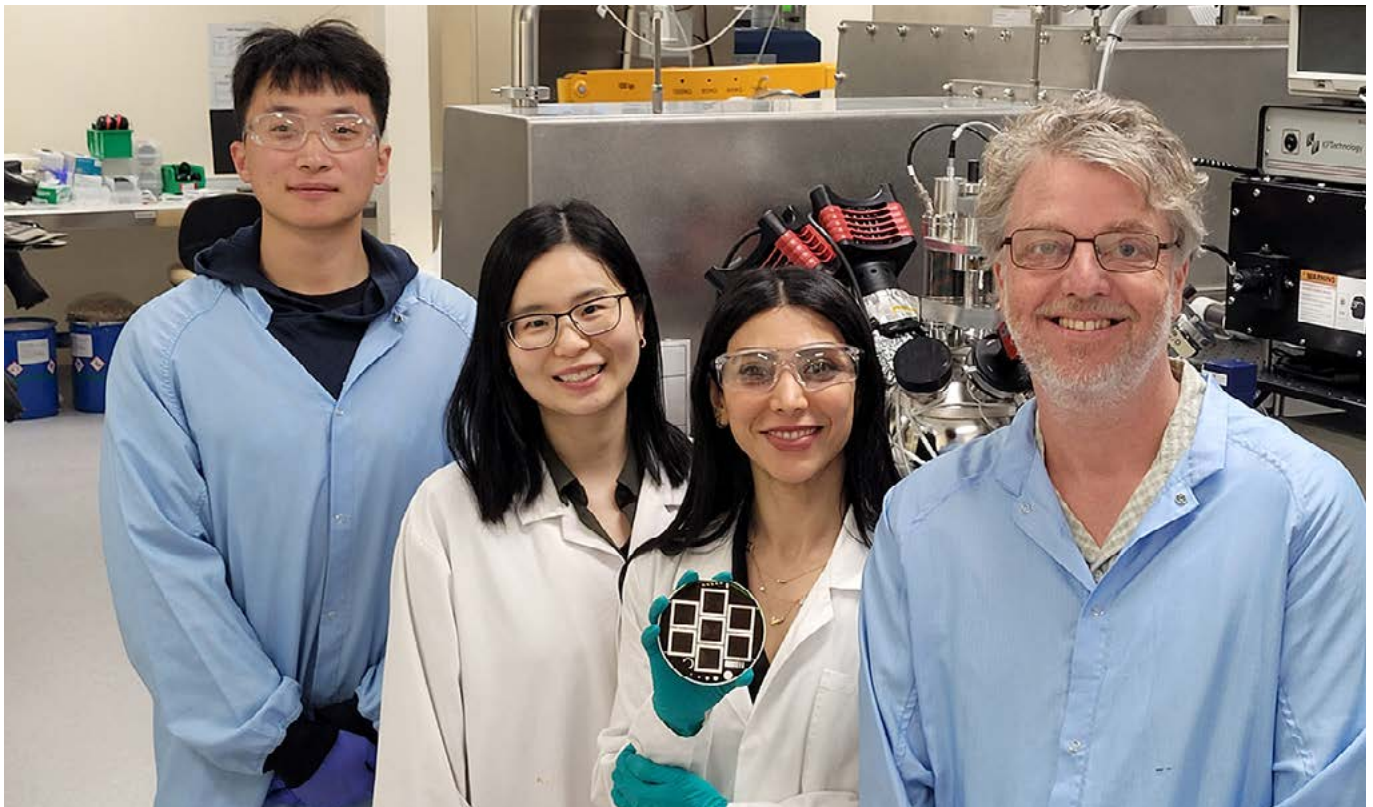


In parallel, the ANU team advanced the understanding of the emerging recharged Czochralski (RCz crystal-growth method (2024)).[3] This work showed that RCz silicon can achieve exceptional purity and consistency, even after multiple reuses of the melt, providing confidence that high-volume, energy-efficient production can still deliver world-class material quality.

In 2025 the ANU team delivered cutting-edge investigations focused on the emerging antimony-doped (Sb-doped) n-type silicon.[4][5] The researchers demonstrated that Sb-doped wafers show more uniform electrical behaviour along the ingot and exhibit excellent quality that is mostly at the intrinsic limit.

These breakthroughs were made possible through ANU's long standing and close collaboration with LONGi, one of the world's largest producers of silicon wafers for solar PV. As Dr Liu explains, "LONGi is able to grow the new silicon materials, and we have the expertise to provide in-depth characterisation and analysis. Together we are making valuable progress."

(l-r) ACAP and ANU's Dr Zhongshu Yang, Dr Anyao Liu, Ms Afsaneh Kashizadeh, Dr Rabin Basnet (not pictured) and Professor Dan Macdonald have sharpened industry's understanding of silicon wafer quality, characterisation methods, and defect-control strategies that are central to next-generation solar manufacturing.



Taken together, ANU's program of work provides the industry with a clear pathway towards cleaner, and more consistent n-type wafers, delivering higher efficiencies. As Dr Basnet concludes, "These findings indicate that Sb-doped n-type Cz wafers are considered a strong candidate to become the industry standard for the next generation of n-type wafers."

Dr Liu reflects, "It's exciting to think our work can have a direct impact on the solar industry, driving real world progress in renewable energy, and shaping the future of solar technology."

With ACAP's support, ANU and LONGi have positioned Australia at the forefront of high-performance silicon wafer research that is directly shaping the future of global solar manufacturing. ■

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Case study

Professor Martin Green compared tiny pyramids on silicon's surface for improved sunlight absorption – and big performance gains

In 2025, at the world's largest solar exhibition and conference in Shanghai, ACAP founder and UNSW Scientia Professor Martin Green unveiled new insights showing that silicon still has room for big performance gains. His plenary talk focused on a promising frontier in photovoltaic innovation: reducing reflection and boosting light capture using ultra-fine, sub-micron surface structures.

For decades, researchers have worked to extract every additional fraction of a percent in efficiency from silicon. A key barrier has always been reflection – sunlight bouncing off the surface instead of being absorbed and converted into electricity. Traditional pyramid texturing has helped, but Professor Green's latest work shows that much more is possible.

Using nanoscale surface features – pyramids smaller than a micrometre across – his team has demonstrated that silicon can support special “resonances”, or miniature echo chambers for light. These resonances dramatically reduce reflection and keep photons inside the cell for longer, increasing the likelihood they'll be harvested for energy.

Professor Green and Dr Zhou calculated an efficiency of 30.1% is achievable in principle.



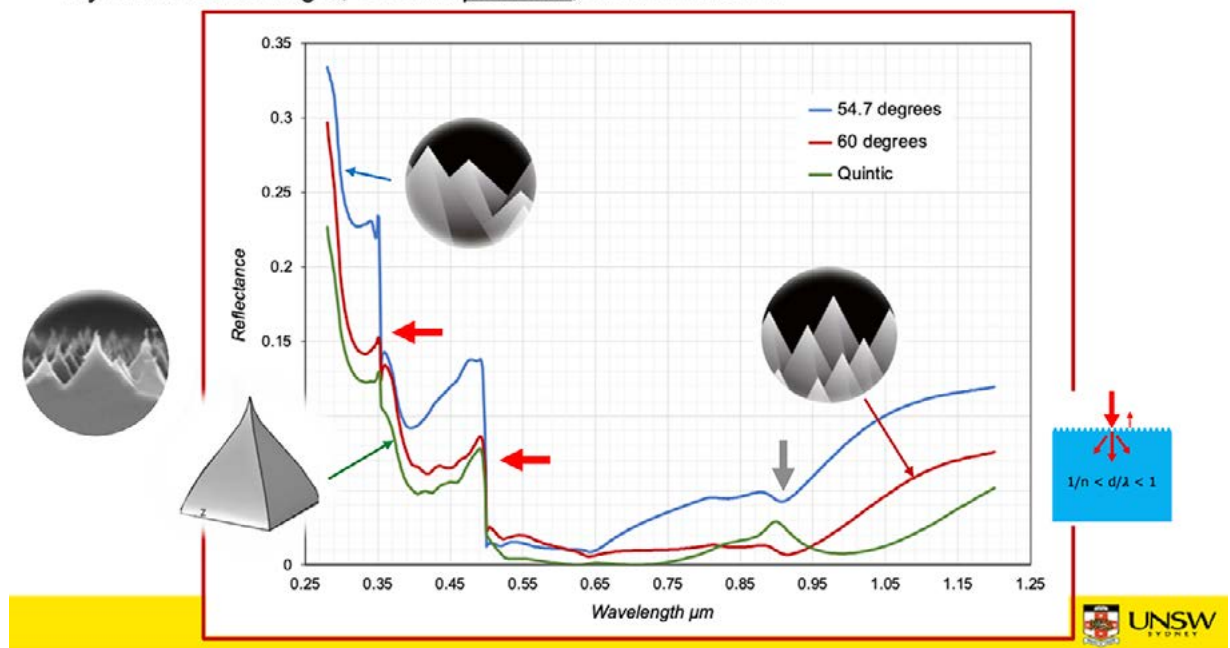
Scientia Professor Martin Green delivering his plenary talk at SNEC 2025.

By refining the geometry and spacing of these pyramids, the researchers propose that the long-assumed theoretical efficiency limit for silicon, around 29.4%, is actually conservative.

Professor Green and co-author Dr Zibo Zhou calculated an efficiency of 30.1% is achievable in principle, with one of the schemes analysed, “Although we may obtain even better results in the future,” said Professor Green.

Crucially, the team is now exploring whether these benefits require perfectly periodic patterns or whether more irregular, lower-cost surfaces could achieve the same effect. If so, manufacturers could incorporate these advanced textures using scalable, industry-friendly processes – leading to cheaper modules with higher performance.

Pyramid base angle, 500nm periodic, actual index n



A slide from Professor Green’s SNEC PV 2025 presentation.[1]

The graph above shows how the different microscopic pyramid shapes, etched onto a silicon solar cell’s surface, affect how much sunlight is reflected, across the wavelengths of the solar spectrum. Lower values mean less light is being reflected and more can be converted into electricity.

The blue line is a pyramid with a base angle of 54.7° – similar to the angle used in the ancient pyramids at Giza – and already reduces reflection quite effectively. The red line is a slightly steeper pyramid with a 60° base angle



Professor Martin Green giving a plenary presentation at SNEC PV 2025, in Shanghai, on a promising frontier in photovoltaic innovation: reducing reflection and boosting light capture using ultra-fine, sub-micron surface structures.

and performs even better. The green line is for a more complex, smoothly curved “quintic” shape, like that in the microscopic picture, and is the most effective at reducing reflection.

The sharp drops in reflection around 500 nanometres arise from optical resonances, where light becomes temporarily trapped by the tiny surface structures instead of being reflected away. “Past work suggested that silicon cells needed to be over 100 microns thick for optimal performance, however, our work shows that a thickness around 60 microns may be the actual optimum,” said Professor Green, “with the additional advantage of reducing silicon wafer costs.”

While still in development, this research highlights a powerful message: silicon, already the most successful energy technology in history, still has untapped potential. ■

Reference

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Case study



UNSW collaboration delivers revolutionary, faster, cheaper and more powerful solar-cell testing technology

“
Our new technology offers lower-cost, higher-throughput testing and, importantly, new insights that will make solar cells more efficient and reliable.
”

A collaboration between UNSW’s ACDC Photovoltaic Research Group and ACAP industry partner BT Imaging, a UNSW spin-out, has delivered a breakthrough solar-cell inspection system set to transform manufacturing efficiency worldwide.

“While solar cells have advanced dramatically in recent years, the main quality inspection tool has remained largely unchanged for over a decade,” says Professor Ziv Hameiri, head of the ACDC Research Group.

“Our new technology offers lower-cost, higher-throughput testing and, importantly, new insights that will make solar cells more efficient and reliable. It is also compatible with next-generation solar materials and designs, including perovskites and tandems.”

Conventional current-voltage (I-V) testing requires contact with the fragile surface of a solar cell and can only measure performance after metal contacts are added, making it difficult to detect issues early in production. It cannot pinpoint the exact location or type of defects in the cell, and it struggles with the complex architectures of emerging cell types.

(l-r) Dr Shubham Duttgupta (BT Imaging) and Professor Ziv Hameiri (UNSW and ACDC Research Group).
Photo by Anastasia Bruniaux, TRaCE.



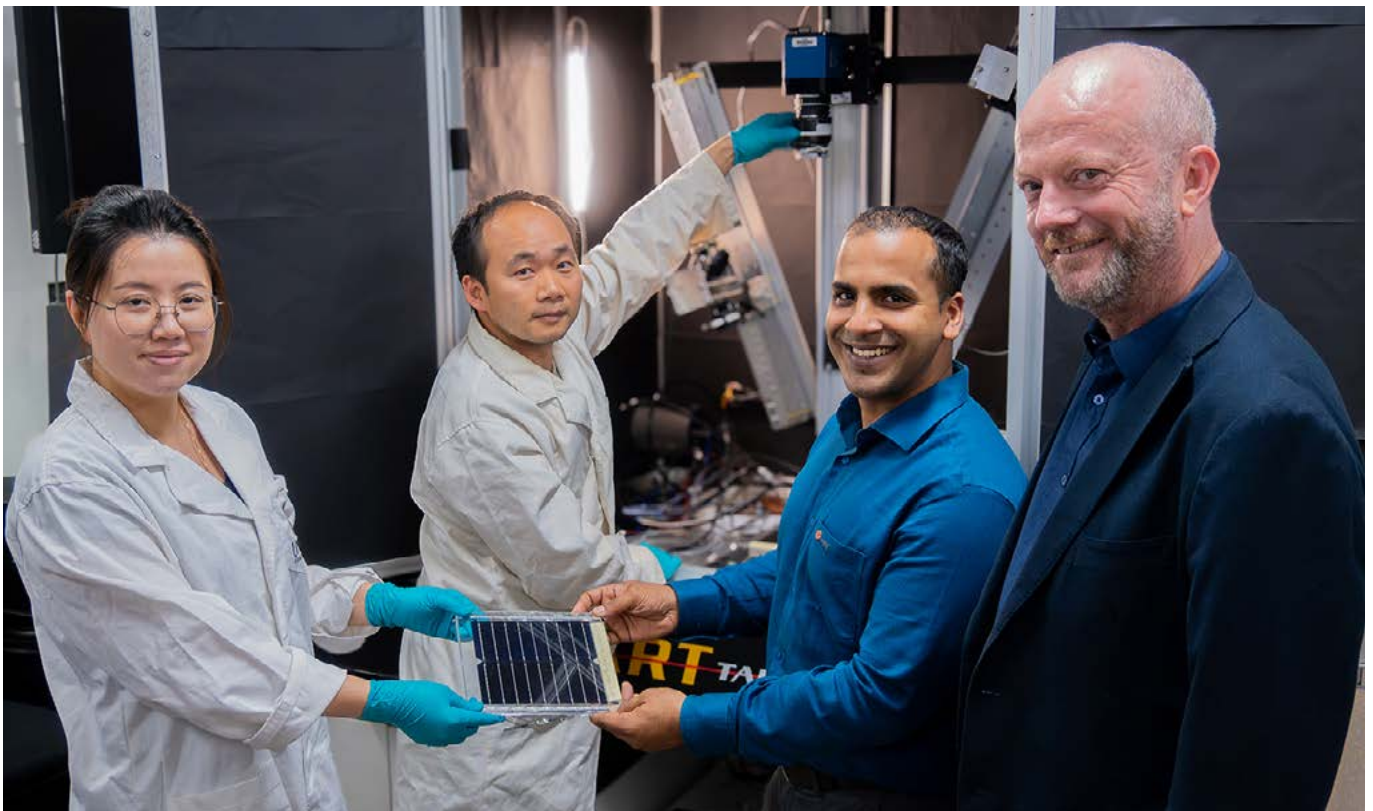
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We have three of the largest solar manufacturers in the world testing our system. They can see that this approach is vital.
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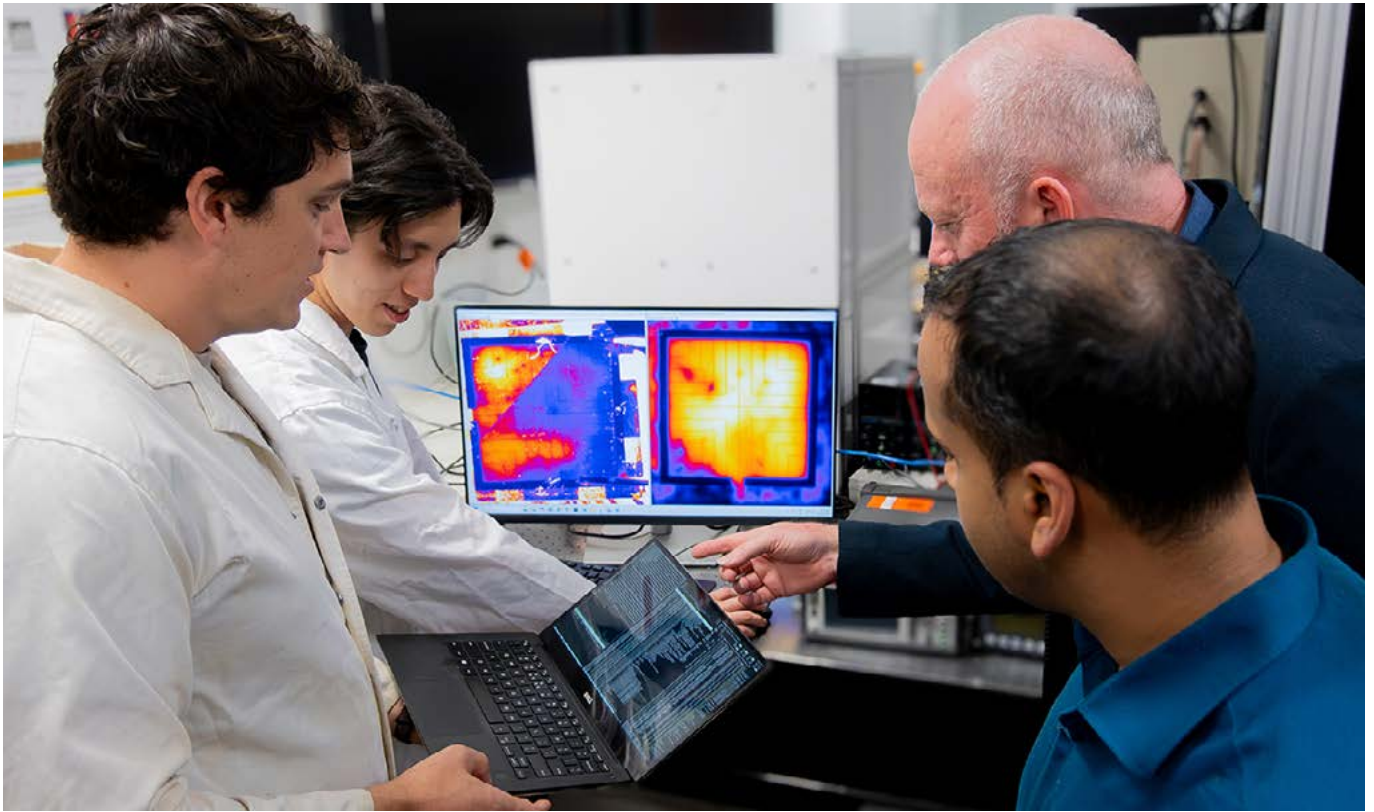
By contrast, the new UNSW–BT Imaging system is completely contactless, combining photoluminescence (PL) and artificial intelligence (AI) to analyse cell quality. When light is shone onto a cell it gives off a small amount of its own light, as luminescence. In the system design, this photoluminescence is captured and interpreted by AI software to identify microscopic defects and predict performance in real-world conditions. This allows manufacturers to pinpoint and understand problems much earlier, improving quality and reducing waste.

The innovation is already attracting international attention. “We have three of the largest solar manufacturers in the world testing our system, and we’re in discussions with several others,” Professor Hameiri says. “They can see that this approach is vital.”

Today’s AI-enhanced, contactless system builds on decades of research at UNSW, where Professor Thorsten Trupke and colleagues pioneered practical applications of PL imaging for PV wafers and solar cells, eventually leading to the 2007 commercial spin-out BT Imaging, which developed the first industrially scalable PL inspection systems.

(l-r) Dr Shuai Nie (UNSW), Dr Yan Zhu (UNSW), Dr Nitin Nampalli (BT Imaging), and Dr Timothy Walsh (BT Imaging) . Photo by Anastasia Bruniaux, TRaCE.





Dr Brendan Wright (UNSW), Dr Zubair Abdullah-Vetter (UNSW), and Dr Timothy Walsh and Dr Nitin Nampalli (BT Imaging). Photo by Anastasia Bruniaux, TRaCE.

For many years, ACAP has supported Prof Hameiri's ACDC Research Group, including undergraduate and PhD scholarships, travel support, and valuable connections with leading PV companies. Professor Hameiri says, "This ongoing support makes progress much easier."

Commercialisation of the technology by UNSW-BT Imaging has been supported by Lab to Market Funding under the Federal Government UNSW Trailblazer project TRaCE, with a \$400,000 grant, to turn these ACAP-supported breakthroughs into practical, factory-ready systems for both silicon and next-generation solar cells.

Dr Shubham Duttgupta, Managing Director of BT Imaging, says, "Partnerships like this allow us to keep pushing innovation into the marketplace. By combining UNSW's cutting-edge methods with our commercialisation expertise, we're creating inspection systems that manufacturers can rely on, that are faster, more accurate, and future-proofed for the next generation of solar cells." ■

BENCHMARK CELLS



ACAP's 2025 benchmark solar cell efficiencies

27.3%

**PEROVSKITE
CELL 0.1 CM²**
(WITH SOOCHOW, BAIMALAKE)

27.06%

**PEROVSKITE-PEROVSKITE-SI
TRIPLE JUNCTION
CELL 1CM²**

23.3%

**PEROVSKITE-PEROVSKITE-SI
TRIPLE JUNCTION
CELL 16 CM²**

15.95%

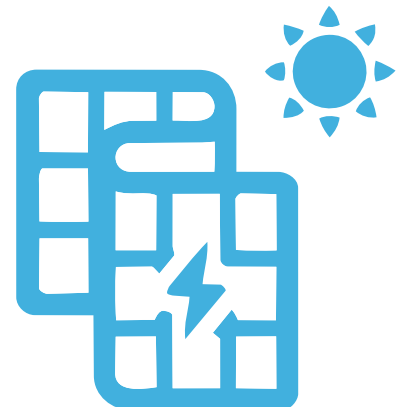
**CD FREE CIGS
0.2 CM²**

10.1%

**SB₂(S,SE)₃ CELL
0.06CM²**

13.2%

**CZTS CELL
RECORD 0.1 CM²**





Emerging Materials

Program Package 2



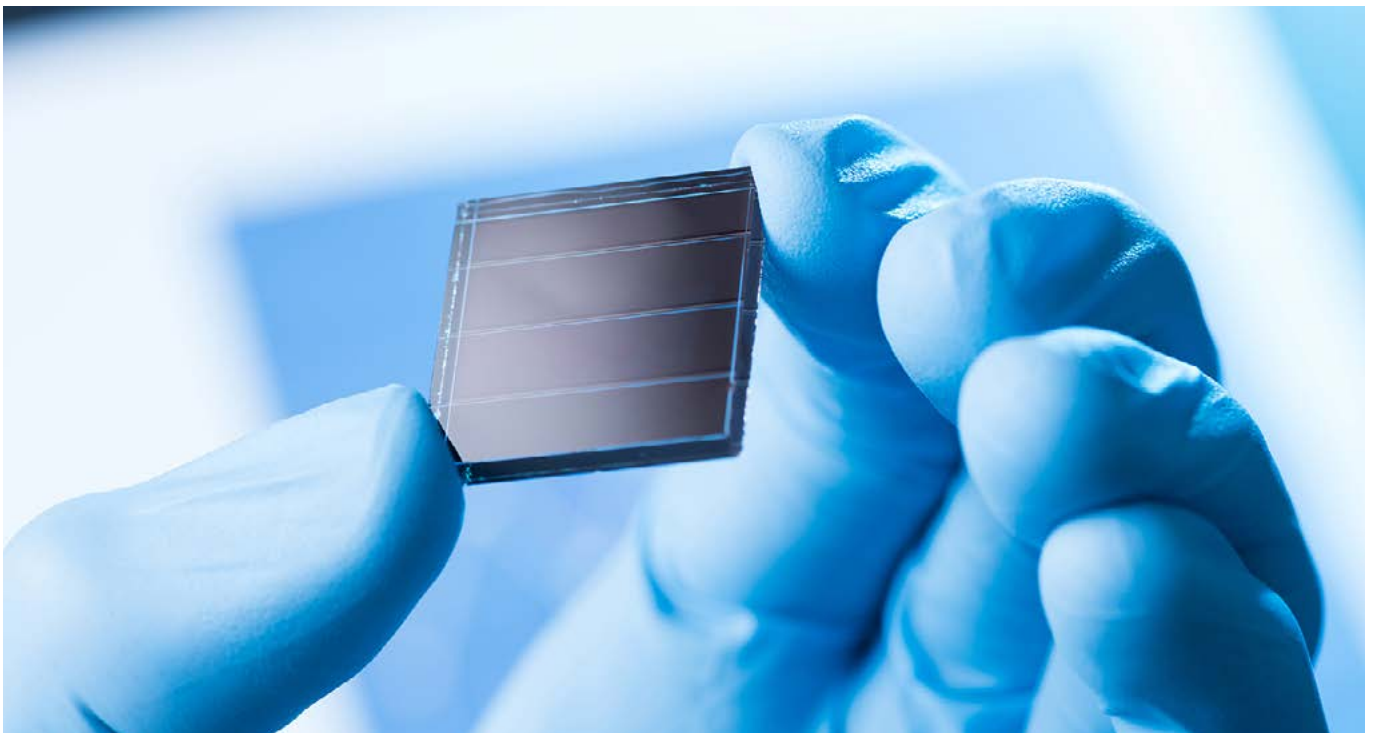
Technical Program Lead
Dr Anthony Chesman
CSIRO Manufacturing

Single-junction silicon solar cells are approaching their practical efficiency limits, which constrains further performance improvements using conventional device architectures.

The Emerging Materials Program explores emerging materials and device strategies to achieve solar cell efficiencies beyond 30%. This includes their application in tandem solar cell architectures and spectral-conversion approaches, such as in down-conversion layers integrated with silicon solar cells, to achieve higher efficiency while maintaining high stability and compatibility with industrial manufacturing.

Research activities across ACAP include materials discovery, materials synthesis and characterisation incorporation into devices and their optimisation for efficiency and durability, and scale-up using industrially relevant production methods.

The key challenges are to develop photoabsorber materials and associated device structures that (1) are efficient and stable, (2) can be fabricated at scale, and (3) comprise earth-abundant and affordable materials, to deliver new solar materials that can be added to silicon or integrated into tandem devices to improve performance.



Solution pathways

1. **Perovskites:** Improve the efficiency and stability of high-bandgap perovskite photoabsorbers to act as the top cell in perovskite-silicon modules.
2. **Novel photoabsorbers:** Explore fabrication of other emerging photoabsorber materials, such as earth-abundant kesterites and organics, which demonstrate higher stability than perovskites, but have lower efficiency and have been harder to produce at scale. High-throughput fabrication facilities will be used to rapidly explore large material parameter spaces.
3. **At-scale production:** Improve methods and equipment for the economical production of solar cells incorporating emerging materials at industrially relevant scales.
4. **Artificial intelligence (AI) and machine learning (ML):** Develop AI models that will predict novel materials with ideal optoelectronic properties and fabrication potential, and the ML models that will accelerate their large-scale production.

Key progress

Laser processing for perovskite single junctions

This project, led by the University of Sydney, aims to demonstrate the laser-annealed fabrication process for a variety of mid- and wide-bandgap perovskite solar cells (PSCs) under ambient conditions with short annealing time, reducing the temperature experienced by substrates.

The project achieved the first demonstration of mid-infrared CO₂ laser annealing of FAPbI₃ films. A CO₂ laser was employed due to its long wavelength (10.6 μm), and therefore low photon energy (0.12 eV), making it compatible with Pb–I bonds. FAPbI₃ films fabricated by this laser annealing process produce large grains of the photoactive perovskite black-phase with minimal PbI₂ defects. The champion FAPbI₃ cell achieved an efficiency of 21.8%. [1] This scalable, additive-free method outperformed thermal hot-plate-based annealing and offers a promising route for high-efficiency perovskite solar cell manufacturing.

The project then progressed to the (first) demonstration of CO₂ laser annealing in ambient conditions for both a wide-bandgap 1.80 eV FA_{0.8}Cs_{0.2}PbI_{1.8}Br_{1.2} perovskite layer and a Me-4PACz hole transport layer. This process reduced the annealing time from 20 minutes to two minutes and lowered substrate temperatures from 100 °C to ~65 °C. The laser-annealed films exhibited improved crystallinity, larger grain sizes, and longer carrier lifetimes, resulting in reduced non-radiative recombination and suppressed halide segregation. A 3D thermal model validated localised heating and effective cooling. The champion device achieved a record 1.35 V open-circuit voltage and 19.8% power conversion efficiency for 1.80 eV perovskite cells. [2]

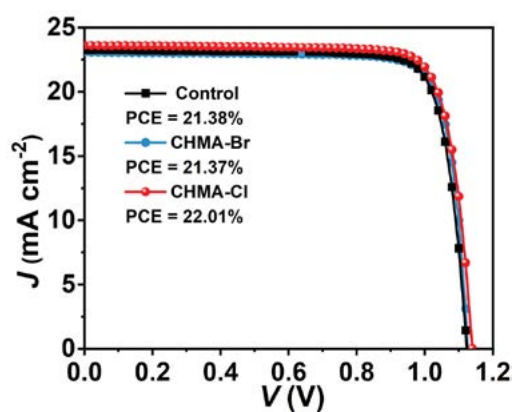
Surface modification materials and processing additives

Interfaces at surfaces and grain boundaries are a key bottleneck for both efficiency and stability improvement in PSCs. Processing additives play a crucial role in passivating defects such as surface traps and grain boundaries, while self-assembled monolayers (SAMs) improve the interface between the perovskite layer and the transparent conducting oxide (TCO) layers. SAMs are used to enhance energy level alignment and promote the formation of dense, smooth, pinhole-free perovskite films.

This project aims to design new additive and SAM molecules to further optimise interfacial properties. By enhancing charge extraction and minimising recombination losses, the project seeks to improve both the efficiency and long-term stability of PSCs, building on recent advancements that have pushed efficiencies close to 27%.

In 2025, researchers from the University of Queensland synthesised a series of additives featuring cyclohexyl, carbazolyl, and perfluoro-1,4-phenylene ammonium salt structures. Among these, the cyclohexyl ammonium additives were evaluated in wide-bandgap PSCs. The highest power conversion efficiency achieved was 22.01%, and the average was 21.07 ± 0.55 , using the cyclohexyl ammonium chloride (CHMA-Cl) additive.

The team also synthesised a series of SAM molecules based on two distinct head groups, indole and thien-indole, which are anticipated to offer improved energy alignment compared to reported carbazole head group-based SAMs. Additionally, two types of anchoring groups were incorporated: phosphonic acid and cyanophosphonic acid. The cyanophosphonic acid is specifically designed to enhance the wettability of the TCO substrate for uniform deposition of the perovskite layer, further optimising interface quality. Preliminary wettability tests using MAPbI_3 indicate that the new fluorinated-SAM-2 forms a more uniform perovskite layer compared to the control SAM, carbazole-based 2PACz.



Current density-voltage curves for wide band-gap perovskite devices with the cyclohexyl ammonium salt additives.

Blade coating for large-area processing


The aim of the large-area PSC activity is to develop scalable, high-quality perovskite films suitable for large-area device fabrication using cost-effective blade coating methods. By optimising deposition parameters such as coating speed, temperature, solvent system, and nitrogen-assisted drying, the goal is to achieve high-efficiency, stable, and reproducible large-area PSCs. Ultimately, the project supports the transition toward scalable, low-cost, and energy-efficient manufacturing for next-generation solar technologies.

In 2025, the University of Queensland team made substantial progress in advancing large-area PSCs by successfully fabricating high-efficiency 25 cm^2 MAPbI₃-based monolithic devices using an optimised nitrogen knife-assisted blade-coating technique, described in the case study [“UQ successfully scales \$25 \text{ cm}^2\$ 15% efficient perovskite solar cell”](#).


The study demonstrated that perovskite films with excellent uniformity and optoelectronic properties can be achieved over large areas through careful control of coating parameters, solvent systems, and nitrogen flow dynamics. While blade coating itself is a laboratory-scale technique, it serves as a critical proof-of-concept tool to demonstrate that perovskite devices can be processed using scalable methods compatible with industrial production.

At-scale production using industrial production methods

This project, led by CSIRO and Monash University, aims to demonstrate upscaled perovskite cell fabrication using low-cost techniques, such as industrial roll-to-roll printing. Advances in the efficiency and lifetime of solar cells that incorporate emerging materials must be accompanied by the development of large-scale, industrially relevant production methods to enable their translation to the PV market. Furthermore, cost-prohibitive materials – such as silver or gold electrodes – need to be replaced with affordable alternatives to achieve the ULCS goal. Accordingly, this project also seeks to identify low-cost materials to substitute high-cost components, such as vacuum-processed electrodes.



The team developed machine learning models capable of generating current density–voltage curves and predicting device performance.



In 2025, a new pilot-scale PV fabrication facility was brought online to enable the reliable production of perovskite solar cells. To accelerate lab-to-fab translation, the team has developed a high-throughput research-scale printer that allows experiments to be conducted under the same humidity-controlled conditions as those used in pilot-scale production. This new capability significantly enhances the speed of technology translation and is covered in the case study [“ACAP and CSIRO lead global progress in printed photovoltaics”](#).

The research team has also developed machine learning (ML) models capable of generating current density–voltage curves from fabrication parameters and accurately predicting device performance. Building on the ML models, the team established an expandable training dataset designed to incorporate future materials and has begun collecting data from the pilot-scale printer to enable the application of ML technology in solar PV manufacturing.

In 2024, the CSIRO and Monash team reported the world’s first fully roll-to-roll fabricated perovskite PV module. To demonstrate its operational stability, the team conducted long-term testing after encapsulation with commercial barrier films in 2025. The modules exhibited excellent durability, retaining over 85% of their initial efficiency after 6,000 hours of continuous illumination under 1-sun conditions.

The team is now developing next-generation modules with higher output using the new pilot-scale printer and conducting further stability assessments of the fully roll-to-roll printed modules, including outdoor performance tracking. See more in the case study in this chapter, [“ACAP collaborators pioneer predictive data-driven design for high performance organic solar cells”](#).

Wide-bandgap (>1.8 eV) materials in top cells for tandems

This project, led by ANU and the University of Melbourne, aims to establish theoretical and practical evidence for the viability of non-current matched tandems that couple wide-bandgap top cell absorbers ~1.8-2.5 eV with state-of-the-art silicon. This will vastly expand the range of top cell material candidates and offer stability advantages by maximally exploiting the well-established performance and reliability of silicon PV.

Investigators completed a first-principles assessment of the efficiency potential of non-current matched tandems pairing wide-bandgap top cells > 1.8 eV with state-of-the-art silicon. They identified the key advantages of this architecture. Specifically, a wide-bandgap top cell shifts more of the photocurrent generation to the silicon bottom cell, which reduces performance requirements of the top cell to achieve a given power conversion efficiency. Conversely, the architecture depends more on the stability of the silicon bottom cell and relaxes the stability demands on the top cell. Silicon has well-proven its real-world stability, and the team has shown how this architecture can make the most of Si PV's performance, without undermining it.

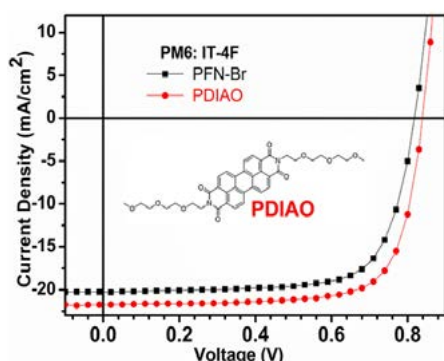
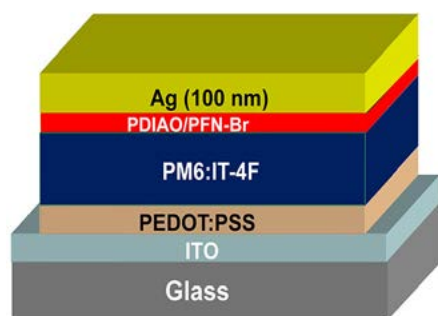
This work demonstrates that this architecture enables improved stability while remaining compatible with the deployment of relatively immature top-cell technologies. This exciting work is covered in the case study in the Tandem Solar Cells program chapter, ["ACAP/ANU researchers' radical design transforms stability of perovskite-silicon tandem solar cell"](#).

Hybrid interface layer materials for high-performance organic solar cells

The University of Melbourne, the University of Queensland, and CSIRO are collaborating on the development of electron-deficient molecular materials as an additive for modulating bulk heterojunction morphology for efficient organic photovoltaic devices and to achieve control of nanoscale morphology through additive engineering.

To explore the effect of electron-deficient additives on the morphology control and device performance of the bulk heterojunction active layer, researchers used two molecular materials: 2-bis-[bis(pentafluorophenyl)phosphino] ethane (BPFPE) and tetrafluoroterephthalonitrile (TFCN). In all cases, the effect on device performance for standard device architectures using PM6-Y6-BO was a 10% improvement through active morphology modification. These additives are volatile and do not remain in the active layer after processing, however, they affect morphology development.

In additional work, researchers replaced the electron transport layer with an organic molecule Tri(oxyethylene)-functionalised perylene diimide (PDIAO) in conjunction with a standard ZnO nanoparticle layer. The addition of the organic electron transport layer modifier increased the device efficiency by up to 17%, for a standard conventional device architecture with a PCE of 17.1%, and significantly enhanced device performance using ZnO nanoparticles.[3]



Organic solar cells fabricated with a new electron transport interlayer PDIAO showed increased efficiency.

$\text{Sb}_2(\text{S,Se})_3/\text{Si}$ – from record single-junctions to scalable tandem solar cells

In a new collaboration, UNSW and ANU are working together to advance $\text{Sb}_2(\text{S,Se})_3$ as a practical and scalable high-bandgap top cell for silicon tandems. Building on their world-record 10.7 % single-junction performance [4] and the first demonstrated $\text{Sb}_2(\text{S,Se})_3/\text{Si}$ tandem [5], this work targets significant absorber-quality improvement, semi-transparent device architectures, and efficient tandem integration with customised Si bottom cells. The outcome will be reproducible $\text{Sb}_2(\text{S,Se})_3/\text{Si}$ tandem devices approaching 30% efficiency, validated for durability and

UNSW and ANU are working together to advance $\text{Sb}_2(\text{S,Se})_3$ as a scalable high-bandgap top cell for silicon tandems.

scalability, thereby contributing to ACAP's Ultra-Low-Cost Solar (ULCS) mission through high-efficiency, earth-abundant, and non-toxic technologies.

During 2025, major progress was made in material quality and device demonstration. Absorber-quality uplift was achieved via additive-assisted composition control and post-deposition treatments, suppressing deep-level defects. Device architectures were improved with the development of a stable all-inorganic MnS hole-transport layer and sputter-compatible TCOs, enabling semi-transparent $\text{Sb}_2(\text{S,Se})_3$ top cells. Furthermore, researchers fabricated and characterised functional $\text{Sb}_2(\text{S,Se})_3/\text{Si}$ tandems, confirming the working concept.

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Case study



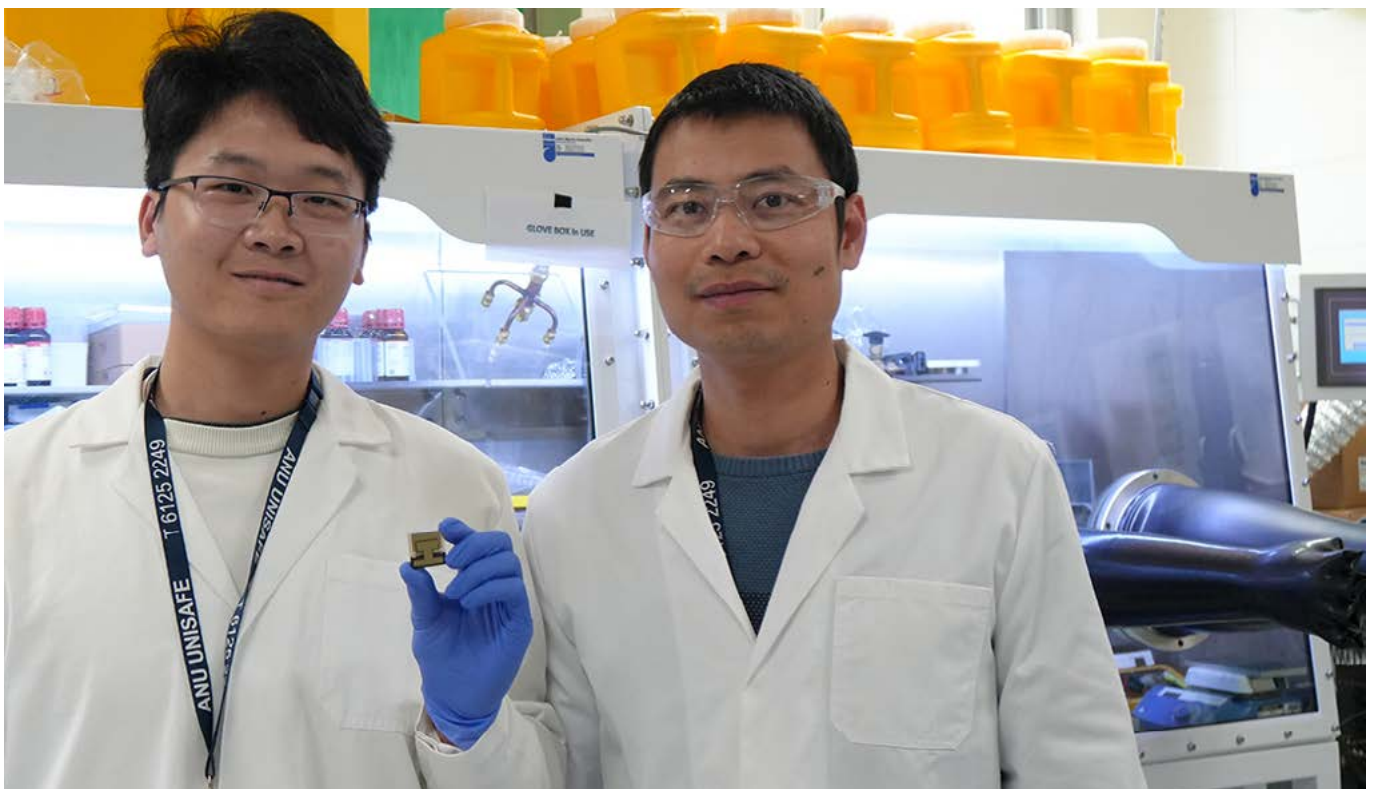
ACAP-ANU's record 26.29% efficiency single junction PSC – with excellent stability

ACAP supported researchers at ANU have achieved a major advance in both the efficiency and stability of n-i-p single-junction perovskite solar cells (PSC), one of the most commercially promising architectures in next-generation, low-cost solar technologies.

The ANU team's outstanding device reached a certified 26.29% efficiency (by an internationally recognised certification centre) – the highest reported for n-i-p perovskites using SnO_2 – and showed strong stability, with $T_{80} > 500$ hours under continuous illumination, and 94% of initial performance retained after more than 10,000 hours in dry air.

Single-junction PSCs have just one active perovskite absorber layer tuned to capture a broad portion of the solar spectrum. In comparison to multijunction/tandem devices, they combine simplicity, high efficiency, lower cost, faster manufacturability, and cleaner scientific optimisation, while providing foundational advances that feed directly into tandem solar technologies.

ANU's Dr Keqing Huang (left) and Dr The Duong with their record-breaking perovskite solar cell.
Photo: Rittwick Visen/ANU



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A solar cell’s lifetime is often determined by a single weak interface.
”

Single junction perovskites now exceed 26% efficiency, but champion devices often degrade quickly. Microscopic chemical defects and mobile ions that accumulate at key internal interfaces create electrical ‘leakage points’ that reduce efficiency and accelerate ageing. In the study, the researchers (Dr The Duong, Dr Keqing Huang, Associate Professor Heping Shen and Professor Klaus Weber) tackled one of the most unstable regions in the device: the interface between the perovskite absorber and the SnO₂ electron-transport layer.

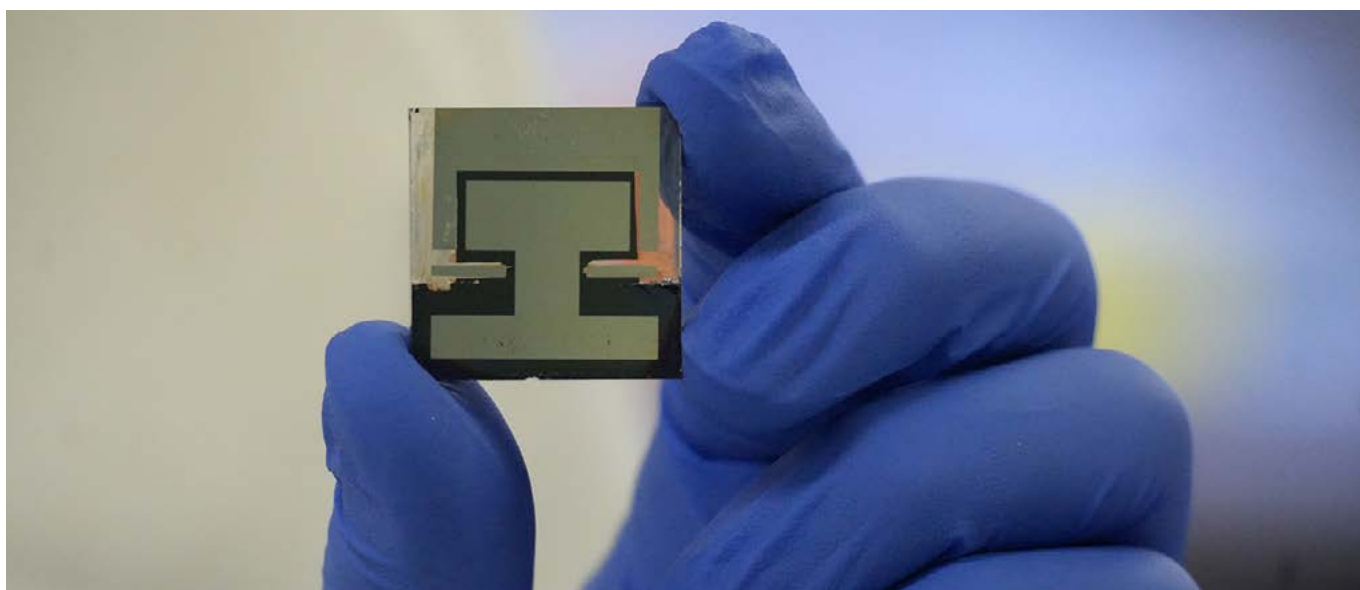
Lead researcher Dr Duong explains, “A solar cell’s lifetime is often determined by a single weak interface. By strengthening that junction, we improved efficiency and stability in one step.”

Their simple solution

The innovation was simple and multifunctional. An aluminium chloride (AlCl₃) surface treatment was applied to SnO₂ before perovskite deposition. This step:

- removed potassium ions and hydroxyl groups that contribute to chemical instability
- naturally converted into an ultra-thin stabilising Al₂O₃ layer during processing
- passivated defects and improved energy-level alignment between layers.

The ANU team’s record-breaking n-i-p single junction perovskite solar cell demonstrated exceptional robustness and efficiency. Photo: Rittwick Visen/ANU.



Their novel interface engineering dramatically reduced recombination losses – unlocking the record efficiency – and hindered ion migration, boosting operational stability.

“The AlCl₃ treatment works like a deep clean and a protective coat in one,” said first author Dr Keqing Huang. “It creates a much calmer interface, which is exactly what perovskites need to perform well over time.”

“
Improving stability without compromising efficiency is the core challenge.
”

Putting the stability result in context

T₈₀ is the time it takes for a device to fall to 80% of its initial performance under defined operational stress conditions. Silicon modules have T₈₀ lifetimes measured in years, not hours, but for lab-scale perovskite cells in 2025, achieving T₈₀ above 500 hours shows unusually strong stability, signalling that degradation pathways at the interfaces have been significantly suppressed. This, combined with 94% efficiency retention after more than 10,000 hours in dry air demonstrates a level of robustness that very few high-efficiency SnO₂-based n-i-p perovskites have shown.

“Improving stability without compromising efficiency is the core challenge,” said lead researcher Dr The Duong. “This work shows we can advance both, together.” Further work is needed to demonstrate long-term durability under real-world outdoor conditions, but this breakthrough illustrates the globally significant progress being made by ACAP researchers in moving perovskite technologies towards commercial viability. ■

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Case study



A new tandem candidate – antimony chalcogenide cells

As silicon solar cells approach their practical efficiency limits, the global photovoltaic community faces a defining challenge: identifying the optimal 'top cell' material for next-generation tandem solar technologies that combine high performance, long-term stability, scalable manufacturing and low cost.

Supported by ACAP, UNSW researchers are advancing antimony chalcogenide as a serious tandem top cell candidate. The material offers a compelling combination of properties, including strong light absorption, inorganic stability and compatibility with low-temperature processing. However, global progress had stalled, with efficiencies plateauing below 10% for several years.

In a major breakthrough, a UNSW research team led by Scientia Professor Xiaojing Hao has overcome this bottleneck, achieving a world-record certified efficiency of 10.7% for antimony chalcogenide solar cells. The result, published in *Nature Energy*[1], represents the highest independently verified performance for this material worldwide and secured its first-ever inclusion in the international *Solar Cell Efficiency Tables* (Version 65).[2]

Professor Hao says, "There is no single perfect top cell material yet for tandem solar technologies. What we need is a broader and stronger set of candidates that can partner with silicon, and antimony chalcogenide is showing very positive potential."

Beyond the headline efficiency, the research delivered a critical scientific insight – uneven distribution of sulphur and selenium during hydrothermal deposition created an internal energy barrier that restricted charge transport. Dr Chen Qian, Research Fellow and first author of the study, demonstrated that introducing a small amount of sodium sulphide stabilises the chemical reactions, producing a more uniform absorber layer and significantly improving device performance.

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**We need a broader
and stronger set of
candidates that can
partner with silicon.**
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Antimony chalcogenide solar cells fabricated at UNSW reached 11.02% efficiency, with an independently certified value of 10.7% provided by CSIRO.

Solar cells fabricated at UNSW reached 11.02% efficiency, with an independently certified value of 10.7% provided by CSIRO, one of only nine internationally recognised photovoltaic measurement centres. The broader research team also included Dr Jialiang Huang, contributing to materials optimisation and device analysis.

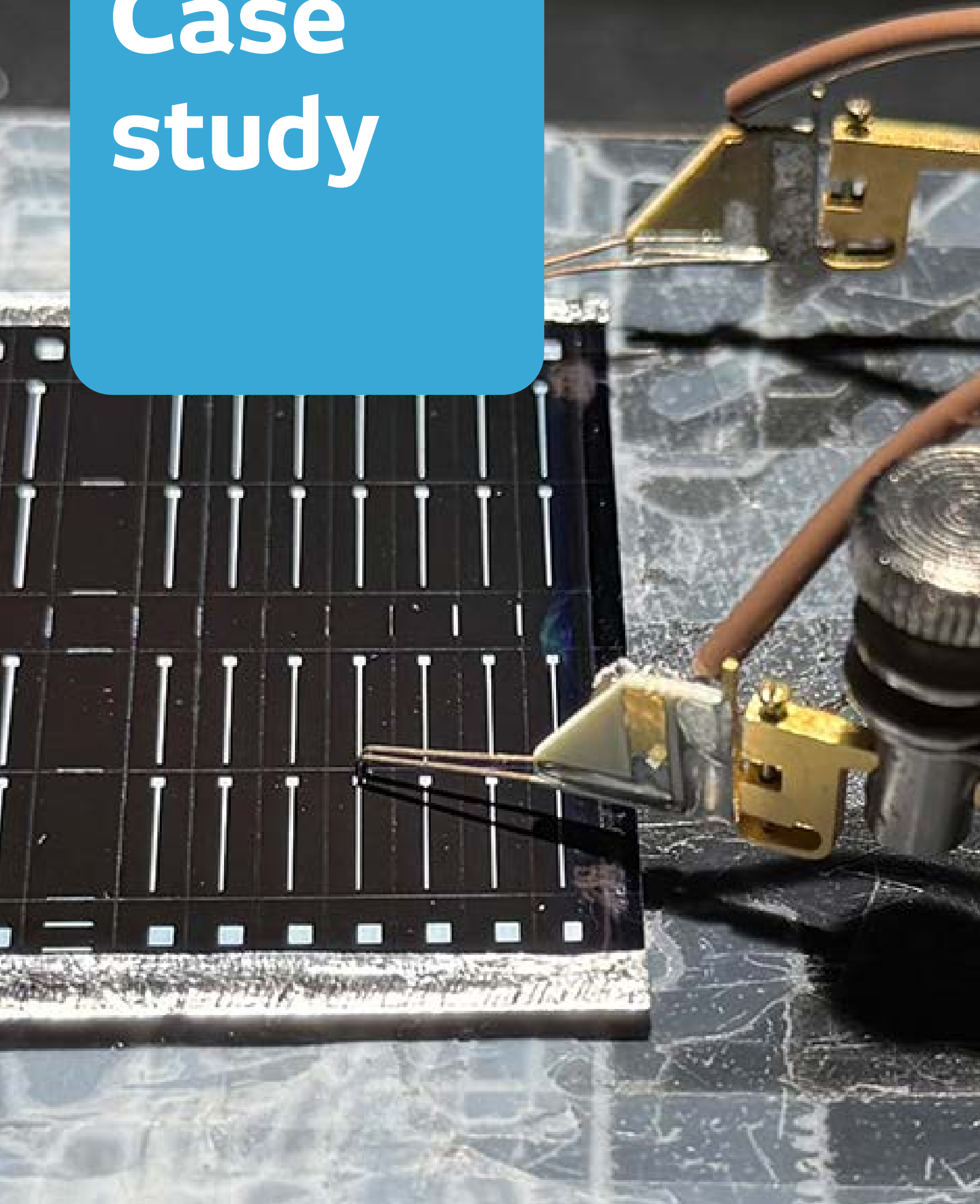
Antimony chalcogenide's suitability extends beyond tandems. Its ultra-thin structure (≈ 300 nm), semi-transparency and high bifaciality (0.86) enable applications such as solar windows, while its bandgap is well matched to indoor lighting conditions. These opportunities are already moving towards commercialisation through UNSW spinout Sydney Solar.

The team is now targeting efficiencies approaching the next milestone efficiency of 15% through strategies such as defect passivation. Their work exemplifies ACAP's role strengthening Australia's leadership in advanced photovoltaic materials through world-class research, national measurement capability and clear pathways to impact. ■

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Case study



Solving kesterite's efficiency challenge

They're non-toxic, earth-abundant, and compatible with low-cost manufacturing.

For more than two decades, kesterite solar cells (made from copper, zinc, tin and sulphur/selenium) have promised a sustainable alternative to other emerging thin-film photovoltaics. They're non-toxic, earth-abundant, and compatible with low-cost manufacturing. Yet despite their strong theoretical potential, kesterite devices remained stalled below 13% efficiency for many years.

Kesterite's complex chemical structure, $\text{Cu}_2\text{ZnSn}(\text{S,Se})_4$ (CZTSSe), makes it versatile but also prone to defect formation during material fabrication. Overcoming this efficiency bottleneck has been one of the most persistent challenges in emerging photovoltaic research.

A major breakthrough is now reported in *Nature Energy* (2026) in the Review article "Formation pathway of high-efficiency kesterite solar cells fabricated through molecular ink chemistry"[1], authored by an international team including Scientia Professor Xiaojing Hao (UNSW) (corresponding author) and Dr Kaiwen Sun, alongside collaborators from leading research institutes in Europe and Asia. The work synthesises more than a decade of experimental insight and establishes a unifying framework that directly links precursor chemistry, reaction pathways and defect formation to device performance.

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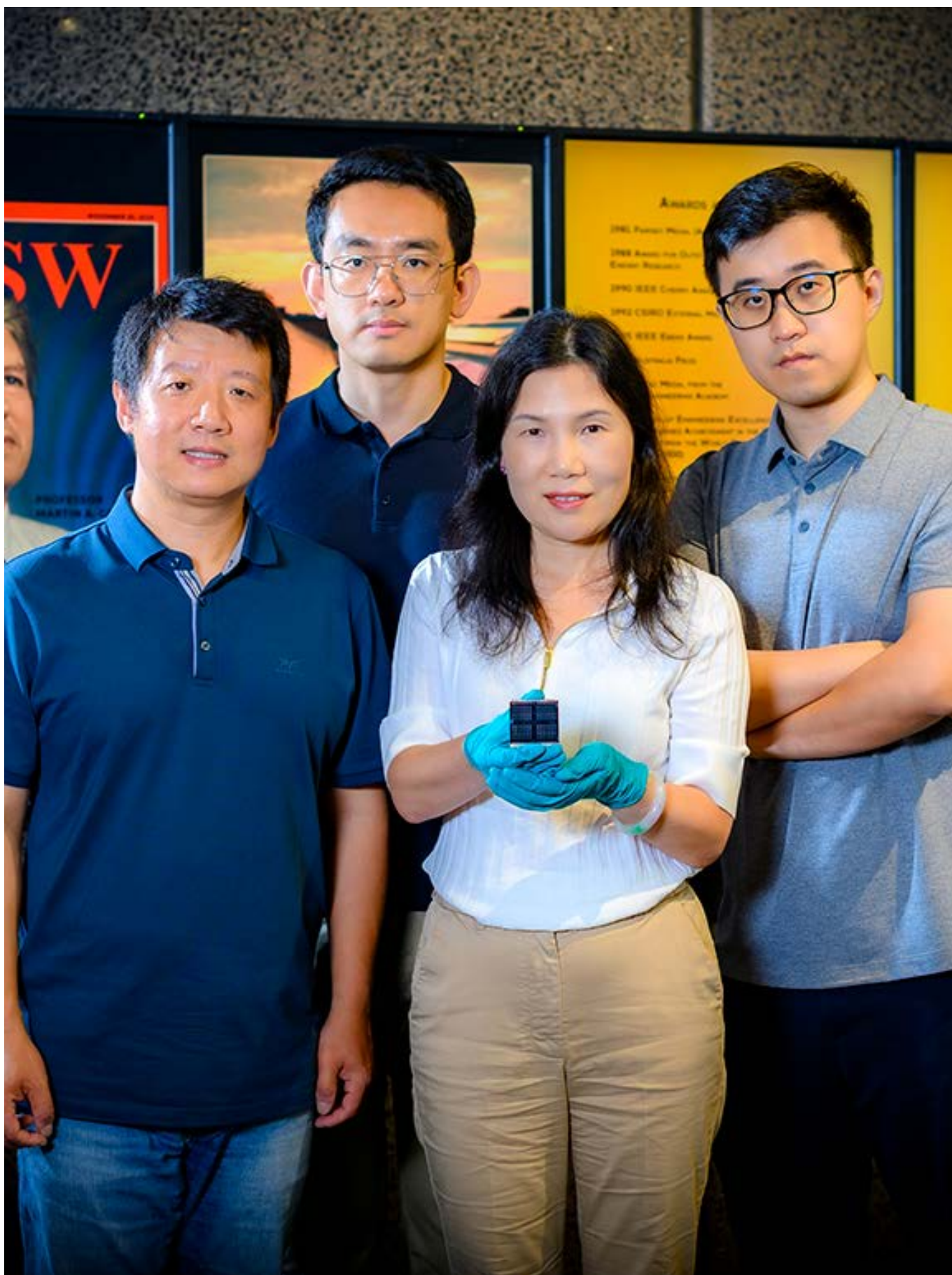
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Review Article | Published: 12 January 2026


Formation pathway of high-efficiency kesterite solar cells fabricated through molecular ink chemistry

[Alex Jimenez-Arguijo](#) ✉, [Yuancai Gong](#) ✉, [Ivan Caño](#), [Outman El Khouja](#), [Jianjun Li](#), [Kaiwen Sun](#), [Zacharie Jehl Li-Kao](#), [Sergio Giraldo](#), [Hao Xin](#), [Alejandro Perez-Rodriguez](#), [Xiaojing Hao](#) ✉ & [Edgardo Saucedo](#) ✉


The *Nature Energy* review article by Scientia Professor Xiaojing Hao, Dr Kaiwen Sun and international collaborators.



Professor Xiaojing Hao's team have lead development of the affordable, non-toxic solar PV material kesterite. (l-r) Dr Jialiang Huang, Dr Kaiwen Sun, Scientia Professor Xiaojing Hao and Dr Ao Wang.



Kesterite solar cells have now surpassed 15% power conversion efficiency.



At the heart of this advance is precise control of the kesterite formation pathway using molecular ink chemistry, instead of relying on traditional vacuum-based fabrication methods. The review demonstrates that managing oxidation states, molecular coordination and phase evolution during synthesis prevents kinetically trapped defects that previously limited performance.

By engineering these pathways, kesterite solar cells have now surpassed 15% power conversion efficiency, a milestone that repositions the technology as a credible, scalable alternative to less sustainable thin-film options.

Professor Hao and her team at UNSW have played a leading role in this progress, building sustained expertise in kesterite materials, defect physics and solution-processed photovoltaics. This leadership has been strongly supported by ACAP and its collaborative model that enables close integration between materials science, device engineering and advanced characterisation. ACAP-supported research has helped translate fundamental chemistry insights into reproducible, high-performance devices, while fostering international collaboration across academia and industry.

Beyond kesterites, the framework outlined in this *Nature Energy* publication provides a roadmap for other complex semiconductors, reinforcing Australia's role in shaping the future of sustainable solar technologies. ■

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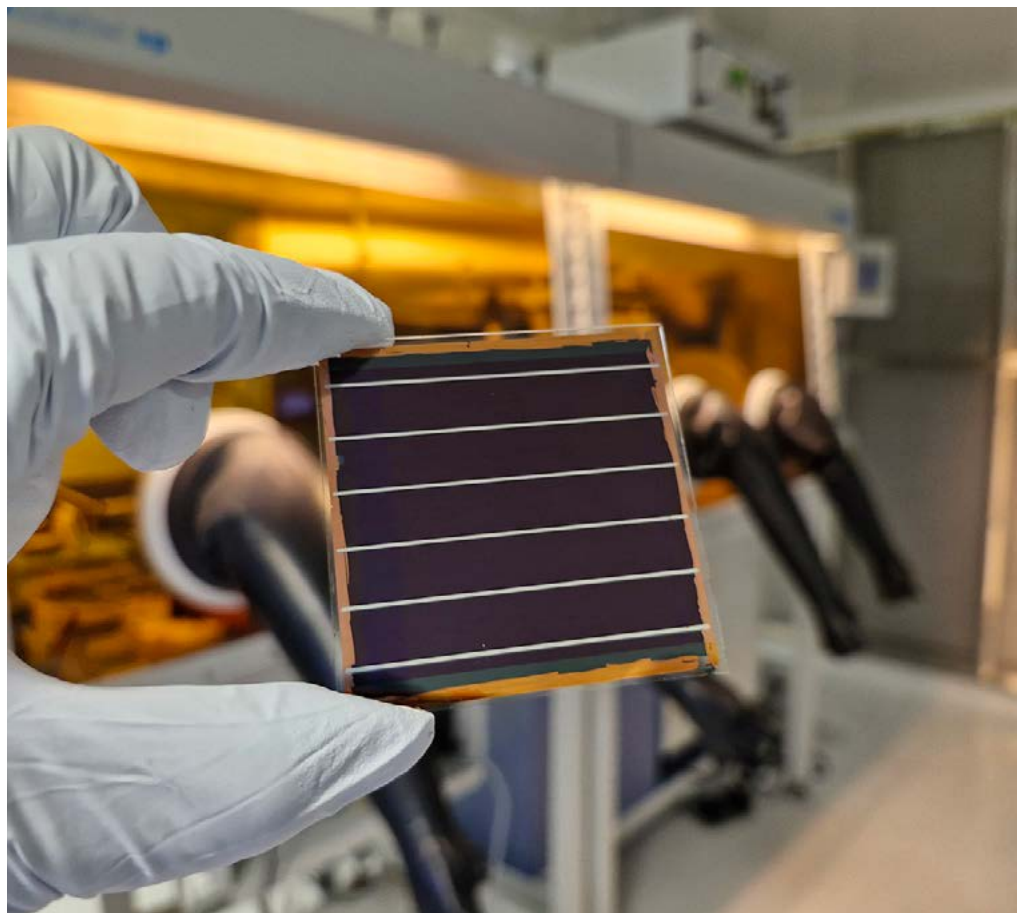
Case study




UQ successfully scales 25 cm² 15% efficient perovskite solar cell

One of the biggest challenges facing next-generation solar technologies is scale. Perovskite solar cells often perform exceptionally well in the lab, but their efficiency tends to drop sharply when researchers try to make them larger. Many approaches rely on complex designs to manage this problem, which adds cost and makes large-scale manufacturing more complex.


ACAP researchers at the University of Queensland (UQ) have made a major step forward by showing that large-area perovskite solar cells can deliver high performance using simpler, more scalable designs. The team has demonstrated 25 cm² solution-processed, monolithic perovskite solar cells with an efficiency of 15% – the highest reported result for this type of device based on the widely studied perovskite material MAPI₃, and close to the technology's theoretical 17% performance limit.



Researchers at the University of Queensland have demonstrated large-area (25 cm²) solution-processed perovskite solar cells with 15% efficiency – the highest reported for MAPI₃ devices of this type and approaching the material's 17% theoretical limit. Photo credit: Hellen Jin.



Instead of using many narrow strips, the team produced a single continuous sub-module solar cell.



The work was led by Associate Professor Paul Shaw and Emeritus Professor Paul Burn at UQ, with key contributions from PhD student Yaomiao Feng. Modelling and design optimisation were carried out in collaboration with James Cook University (JCU).

Instead of using many narrow (width ≤ 1 cm²), interconnected strips, a common but complex approach for fabricating larger perovskite devices, the team produced a single, continuous sub-module solar cell. They used an industry-relevant coating technique (nitrogen-knife assisted blade-coating), supported by carefully chosen material additives, to boost performance and stability.

The advanced modelling helped the researchers design the device so that electrical losses were minimised as the cell size increased.

This result provides confidence that large-area perovskite solar cells, and ultimately perovskite-silicon tandem devices with efficiencies of 30% or more, can be manufactured using simpler processes. Supported by ACAP funding, this work strengthens Australia's position at the forefront of scalable, high-efficiency solar technology. ■



Case study



ACAP collaborators pioneer data-driven design for high performance organic solar cells


A collaborative research team has demonstrated a step change in how organic photovoltaic (OPV) research can be conducted – moving the field from slow, trial-and-error experimentation to a predictive, data-driven paradigm.

By combining high-throughput manufacturing-style experimentation with machine learning (ML), researchers from CSIRO and Monash University have achieved both unprecedented data scale and record device performance, as published in *Energy & Environmental Science*.^[1] The project's first author Na Gyeong (Korean Research Foundation, hosted by Monash University) was overseen by Professor Udo Bach (Monash University) and worked closely with Dr Doojin Vak and researchers at CSIRO operating ACAP's high-throughput roll-to-roll OPV MicroFactory platform.


A long-standing barrier to applying artificial intelligence in experimental energy research is the lack of large, consistent, high-quality datasets. In OPVs, this problem is particularly acute: device fabrication is typically manual, low-throughput, and highly researcher-dependent. Through ACAP's industrially relevant MicroFactory infrastructure, the team overcame this bottleneck by mimicking real manufacturing conditions inside the lab.

"Machine learning in photovoltaics has been talked about for years, but without the right kind of data it simply can't deliver," said Dr Vak.

"ACAP's high-throughput roll-to-roll platform allowed us to generate manufacturing-grade data at a scale that changes what's possible. Instead of guessing what might work, we can now predict performance before a device is even made."



“
We can now predict performance before a device is even made.
”



Using this approach, more than 26,000 unique OPV devices were fabricated and characterised in just four days – two to three orders of magnitude faster than conventional research methods. ML models trained on this dataset successfully predicted full current–voltage behaviour and guided optimisation of materials and processing conditions.

The result was a record 11.8% power-conversion efficiency for fully roll-to-roll-fabricated organic solar cells, the highest reported globally.

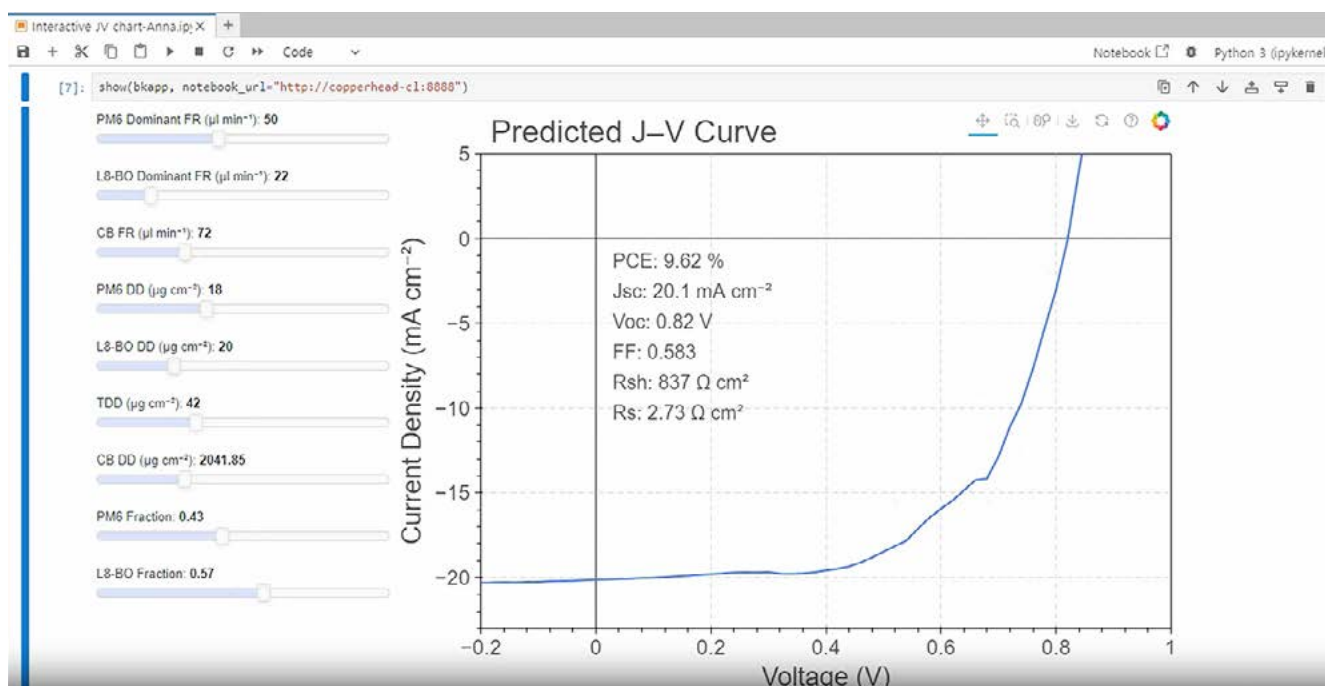
The interactive J–V prediction ML model provides a whole new method of device optimisation. The team can browse experimental parameters with the ML tool, instantly showing J–V curves of virtually planned experiments.

“We can now conduct experiments with predictive guidance, where decisions about materials and processing are informed by data-driven models before fabrication,” said Dr Vak.

“Seeing machine learning move from post-analysis to an active part of the experimental workflow is particularly exciting.”

The high-throughput roll-to-roll coater is part of ACAP’s MicroFactory platform at CSIRO and is enabling data driven design of organic photovoltaic solar cells.





The interactive J-V prediction ML tool lets the team browse experimental parameters, instantly showing J-V curves of virtually planned experiments.

The result was a record 11.8% efficiency ... the highest reported globally.

The project exemplifies the strength of ACAP's collaborative model. The combination of roll-to-roll-compatible fabrication, automated characterisation, and large-scale data production in a laboratory setting is still rare internationally.

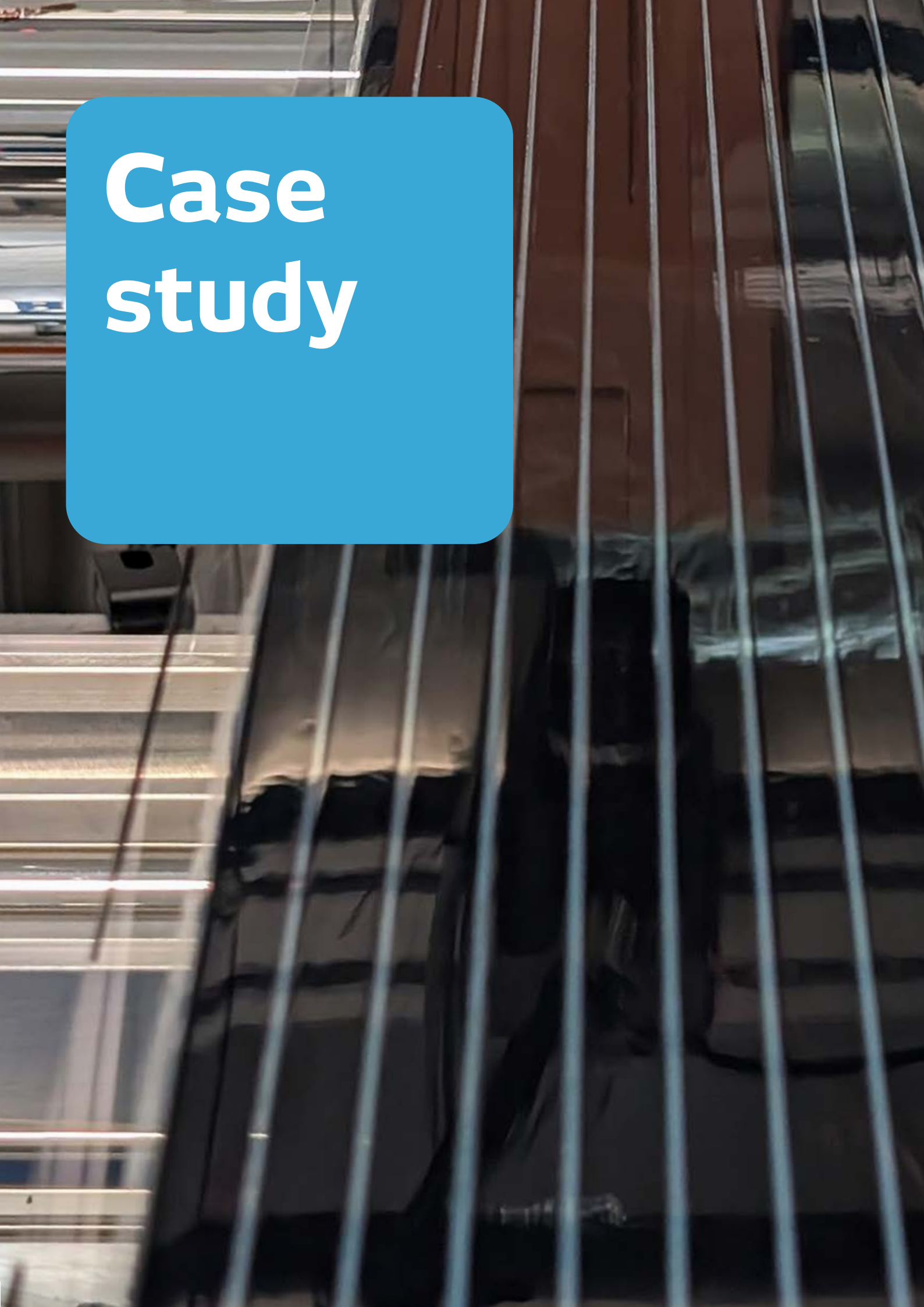
By demonstrating not only accurate ML prediction but also ML-guided experimental optimisation, this work moves beyond proof-of-concept studies and establishes a practical framework that few groups worldwide currently possess. It positions ACAP firmly at the international leading edge and lays the groundwork for future data-rich solar manufacturing innovations.

"We've shown that large, high-quality experimental datasets – once a major bottleneck – can be generated routinely, allowing machine learning to become a reliable tool rather than an exploratory add-on," said Dr Vak.

"This fundamentally changes how device research and optimisation can be approached." ■

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Case study

ACAP and CSIRO lead global progress in printed photovoltaics

In 2025, CSIRO and ACAP achieved some of the world's highest efficiencies for fully roll-to-roll printed perovskite solar modules produced on a commercial-scale printing facility.

Using the ACAP-supported commercial-scale printer, Dr Mei Gao, Dr Anthony Chesman, and Dr Doojin Vak and the rest of the Printable Photovoltaics Team at CSIRO successfully fabricated fully printed 100 cm² perovskite modules with efficiencies of 11-12%, matching the performance previously achieved only on research-scale printing equipment. This combination of high efficiency, large area, and pilot-scale manufacturing places CSIRO at the global forefront of printable photovoltaics.

Equally significant is the demonstrated reproducibility and consistency of these modules – an essential requirement for any pathway to mass production. By optimising solution concentrations and processing parameters on the pilot line, the team has shown that high-performance printed perovskite modules can be produced reliably, not just as isolated laboratory results.

CSIRO's ACAP-supported Printable Photovoltaics Team: (l-r) Dr Jueng-Eun Kim, Ms Régine Chantler, Dr Mei Gao, Dr Luke Sutherland, Dr Doojin Vak, Dr Andrew Scully, Dr Dechan Angmo, and Dr Anthony Chesman.



Extensive experience delivers major technical achievement

Scaling printed photovoltaics from lab-scale tools to industrial equipment is notoriously challenging. Following commissioning of the Printed Photovoltaics Facility (PPVF) in 2024, the CSIRO team undertook the complex task of translating established research processes to a much larger, industrial printer operating under controlled humidity and temperature.

This required systematic re-optimisation across materials, printing and post-processing, as well as the rapid adoption of new technologies such as rotary screen printing for high-quality and smooth electrode and interconnection patterns. More than a decade of experience in printed photovoltaics enabled the team to overcome these challenges efficiently.

What's next?

With this milestone achieved, the focus now shifts to what the PPVF makes possible next: higher-throughput operation, longer print trials and larger module formats, with widths of up to 30 cm planned. The facility is also enabling meaningful engagement with industry by producing printed solar modules at a scale suitable for real-world prototypes.

In parallel, collaborations with other ACAP nodes will support advanced characterisation and stability testing.

This world-leading progress has been underpinned by sustained ACAP support, which has been critical to establishing, operating and evolving the PPVF – positioning Australia as a global leader in printed solar manufacturing. ■



Tandem Solar Cells

Program Package 3



Technical Program Lead
Professor Klaus Weber


Australian National
University

Silicon solar cells and modules that dominate today's market face a practical conversion efficiency limit below 30%. One approach to achieve efficiencies beyond the single-junction silicon limit requires tandem architectures, where two or more solar cells based on different materials and with different optical properties are stacked on top of one another. Each solar cell absorbs a specific part of the solar spectrum and efficiently converts it into electrical power.


Program Package 3 aims to develop innovative high-efficiency tandem solar cells and modules and to look beyond to triple junction tandems and new materials that enhance the efficiency of silicon solar cells.

Key challenges

Efficiencies beyond 30% have been achieved and demonstrate what is possible, but challenges remain in cell and module durability, in scaling up from research to manufacturing, and in test and certification of the more complex structures in tandem solar cells. The key research challenges addressed in 2025 include: (1) diverse material pathways, (2) access to an adequate supply of suitable silicon bottom cells fabricated for tandem integration, (3) characterisation of tandem cells, requiring greater care, deeper skills and a different toolset due to the more complex and diverse architecture, and (4) the lack of standardisation of processes and structures between research institutions making it more difficult to replicate research results and learn from each other.



Tandem cells are more complex than single-junction cells, requiring greater skill and an understanding of the material history.



Solution pathways

1. **Perovskite tandems:** Perovskite-based solar cells have demonstrated high conversion efficiencies and are promising candidates for tandem cells. They offer many possibilities such as perovskite-perovskite, perovskite-silicon or perovskite-chalcogenide tandem cells. The ability to tune the optical and electronic properties is a particular advantage.
2. **III-V on silicon tandems:** 'III-V' materials such as gallium arsenide have demonstrated high conversion efficiencies but are expensive. Tandem cells using III-V materials were designed to operate under concentrated sunlight to achieve low-cost solar technology.
3. **Chalcogenide on silicon tandems:** Chalcogenide materials such as copper-zinc-tin-sulphide (CZTS) use earth-abundant elements and have good stability. Improvements in their conversion efficiency can enable high-efficiency tandems when combined with silicon.
4. **Tuned bottom silicon devices:** Silicon cells are used as the bottom cells in many tandem structures. For maximum tandem performance and lowest cost, their structure should be modified or 'tuned' compared to that used in single-junction silicon modules.
5. **Characterisation:** Tandem cells are more complex than single-junction cells, with the interpretation of even simple I-V curves requiring greater skill, and an understanding of the material history. ACAP has led the development of specific characterisation techniques to understand the factors limiting their performance.
6. **Laboratory cell and module performance testing:** Tandem cells make greater demands on the equipment and processes used to determine their performance. Suitable equipment must be developed and tested, and measurement procedures refined to ensure reliability and consistency.

Key progress

Perovskite tandems

With cell efficiencies over 30% achieved for perovskite-silicon tandems, ACAP has shifted focus to challenges of stability and manufacturability as well as material and device alternatives.

In a stability-first design philosophy, ACAP researchers at ANU have led a fundamental shift in thinking. Rather than chasing maximum peak performance, the research demonstrates how strategic engineering can unlock the commercial potential of ultra-high-efficiency tandem cells. See case study, [“ACAP ANU researchers’ radical design transforms stability of perovskite-silicon tandem solar cell”](#).

Perovskite tandems fabricated by ACAP partners have demonstrated promising stability when exposed to key stress tests such as IEC 61215 standard damp heat and thermal cycling tests, as well as testing under illumination using the ISOS protocol.[1]

Outdoor testing of tandem cells has commenced. After three months of outdoor testing, the best encapsulated cell showed no clear degradation (see Figure PP3. 1). Challenges in determining actual performance due to varying outdoor conditions require post-measurement data processing, which still leaves significant noise in the obtained data. Future work will include refining the methods to extract efficiency.

In parallel with stability studies, significant progress has been achieved in improving device efficiency. The properties of the transport layers – the materials on either side of the perovskite which facilitate the extraction of electrons and holes – as well as the interfaces they form with the perovskite, play a crucial role in determining device performance. Through modification of the bottom transport layer on which the perovskite is deposited, the ANU team was able to achieve a very high fill factor of 86.8% and certified efficiency of 23.4% for a solar cell with an area of 0.16 cm², the highest fill factor for this type of cell reported to date.[2] The team then combined the perovskite cell with a silicon bottom cell in a mechanically

ACAP researchers have shown that a stability-first design philosophy is key to unlocking the commercial potential of tandem cells.

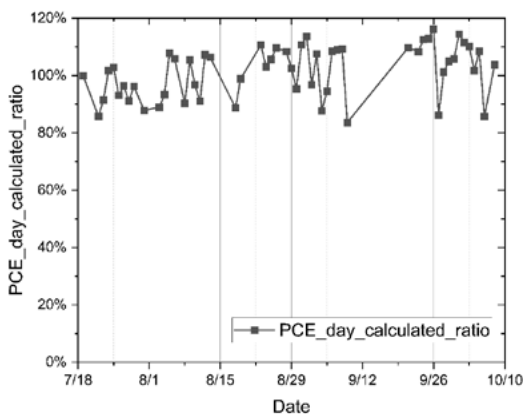


Figure PP3. 1 The calculated normalised tandem cell efficiency (with an initial efficiency of 28.5% and a size of 1 cm²) over three months of outdoor exposure.



Monolithic perovskite–silicon tandems are widely seen as the leading candidate for large-scale commercialisation.



stacked, four-terminal tandem and achieved an efficiency of 30.97% for a solar cell with the same size (0.16 cm²).[2]

In a collaboration led by Sydney University, triple-junction tandems demonstrated record-setting size, performance, and durability, achieving independently certified efficiencies of 27.06% (1 cm²) and 23.3% (16 cm²) with perovskite–perovskite–silicon triple-junction solar cells. The team also delivered the first triple-junction device of its kind to pass the IEC 61215 Thermal Cycling test. See case study, [“Global record for triple-junction tandem solar cell reported by University of Sydney/ACAP-led team”](#).

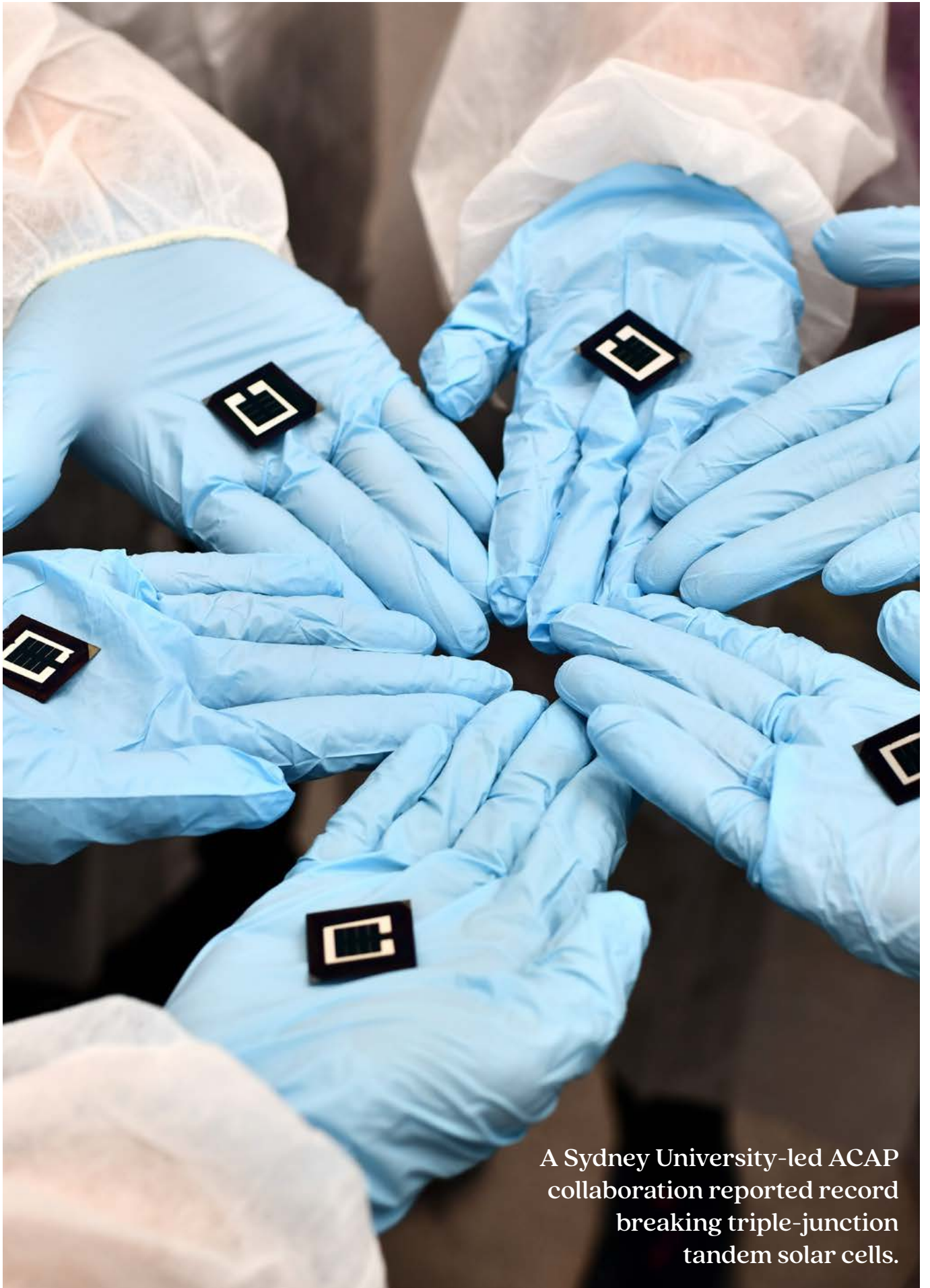
Alongside performance improvements, efforts are also focused on developing fabrication processes that are compatible with commercial tandem technologies. One of the major challenges arises when aiming to fabricate monolithic perovskite–silicon tandem cells.

This type of tandem, where the perovskite cell is deposited directly on top of the silicon cell and electrically connected with it, is considered the best candidate for commercialisation of tandems. For optimum performance, the silicon bottom cell should be textured as this will increase light absorption in both sub cells. However, the deposition of perovskite layers and transport layers on a textured (and therefore rough) silicon substrate is more difficult than deposition on planar substrates.

Researchers at ANU developed an innovative two-step solution deposition process specifically designed for wide-bandgap perovskites making it suitable for monolithic tandem cells. The goal is to create a technique that is seamlessly compatible with textured silicon substrates.

The first step of the process involves the preparation and deposition of a precursor solution containing the necessary metal halides such as lead iodide (PbI₂). In the second step, a controlled deposition of the organic parts is employed to promote the conversion of the metal halide template into a stable perovskite phase.

In 2025, the team optimised the composition and fabrication conditions of the metal halides. As a result, they achieved a record performance for wide-bandgap perovskite single-junction solar cells, with a champion efficiency of 21.6% and a certified efficiency of 21.24% (0.16 cm²), the highest reported to date for wide-bandgap



A Sydney University-led ACAP collaboration reported record breaking triple-junction tandem solar cells.

perovskite fabricated by a two-step solution process. Integration with TOPCon silicon cells delivered 29.98% efficiency (1 cm²).[3] Read more in the case study [“ACAP-ANU team develop industry-friendly large area deposition method for perovskite-silicon tandems”](#).

In addition to solution-based fabrication, alternative deposition approaches are also being explored to enable scalable manufacturing. Most perovskite film deposition methods involve the crystallisation of the perovskite from a solution through the removal of organic solvent. One disadvantage with this approach is the need to deal with a significant solvent waste stream. An alternative is to deposit perovskite films from the vapour phase.

A team at CSIRO are working towards automated vapour phase deposition of perovskite films. Vapour phase deposition may also reduce batch-to-batch variation in film quality and is compatible with deposition of textured silicon substrates. In 2025, an automated deposition system was developed, optimised and validated, producing large area (30 mm x 30 mm), ultra uniform, reproducible perovskite films that are pin-hole free. The team developed and validated a new method for practically eliminating batch-to-batch variability in perovskite deposition.

Tuned bottom silicon devices

TOPCon-based bottom cells, either conventional or bi-poly TOPCon structures incorporating both p⁺ and n⁺ poly-Si contacts, are increasingly being adopted as silicon bottom cells in tandem solar architectures. TOPCon structures are generally considered thermally stable up to 600–800 °C, particularly when capped with hydrogen-rich dielectric layers, as in fire-through metallisation of single-junction TOPCon cells. This intrinsic robustness under high-temperature conditions broadens the range of compatible materials and processes for efficiency enhancement, enabling the potential integration of inorganic perovskites and high-temperature-processed transport layers.



Atomic layer deposition of ultra thin passivating contacts for high efficiency TOPCon-based tandem devices, at ANU.

Once the hydrogen-rich capping layers are removed, however, both n^+ and p^+ hydrogenated poly-Si contacts become thermally unstable, leading to significant surface passivation losses during post-annealing. This dehydrogenation challenge poses a key compatibility issue for achieving high-efficiency TOPCon-based tandem devices.

To mitigate these challenges, researchers from ANU are exploring two complementary strategies for surface passivation recovery:

1. Ultrathin AlO_x interlayers, designed to act as localised hydrogen sources during post-annealing while maintaining suitable contact resistivity.
2. Hydrogen plasma treatments at controlled temperatures, aimed at reintroducing hydrogen to the Si/SiO_x/poly-Si interface.

The preliminary observations indicate that hydrogen plasma treatment effectively recovers the V_{oc} of bottom cells following thermal degradation. These efforts will help establish the potential of TOPCon-based bottom cells as a viable and scalable alternative to silicon heterojunction-based bottom cells in high-efficiency tandem architectures.

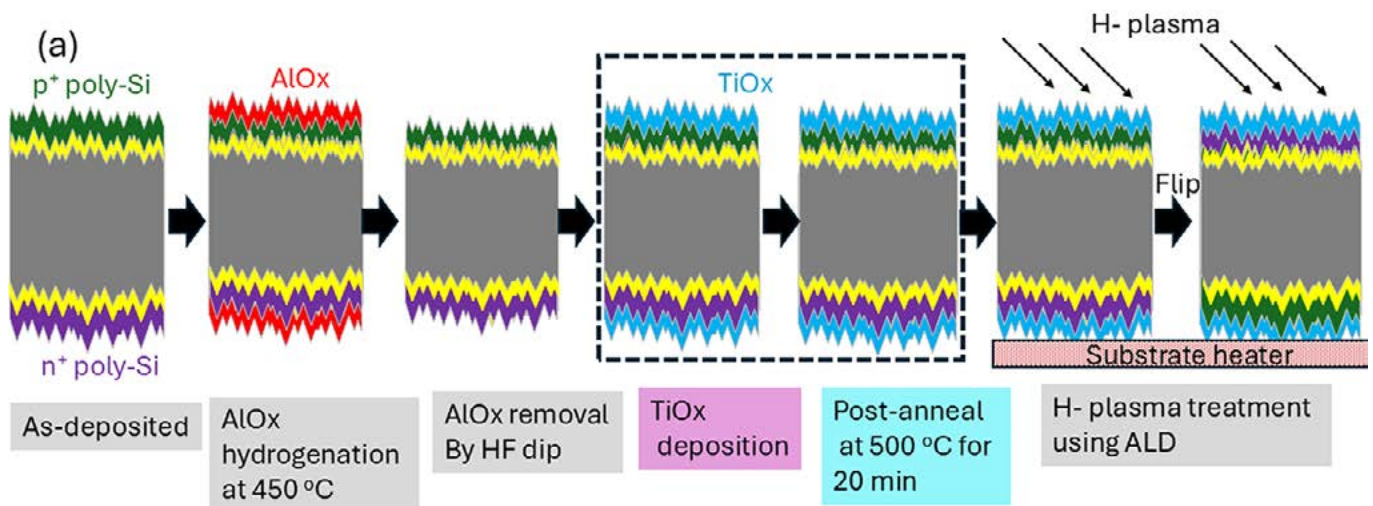


Figure PP3.2 Schematic capturing the process of de-hydrogenation and subsequent recovery by hydrogen-plasma treatment, as studied by ANU researchers.

Characterisation


Achieving high performance and long-term stability in perovskite/silicon tandem solar cells requires a deep understanding of the underlying limitations to voltage, current, and fill factor. To address this, several advanced characterisation methods were developed to accurately identify the origins of performance loss and degradation.

Using Kelvin probe measurements, ANU and UNSW researchers can extract the surface photovoltage (SPV) of individual sub cells, which corresponds to their internal voltages. Comparing these values provides direct insight into voltage losses and guides strategies for band alignment and interface optimisation. In parallel, they have established a method to quantify sub cell current density-voltage (J-V) characteristics in monolithic tandem devices under monochromatic illumination, enabling identification of which sub cell limits overall performance.


Furthermore, the team implemented voltage-dependent luminescence imaging to spatially resolve series resistance distributions in tandem cells. This technique offers valuable guidance for improving fill factor and overall power conversion efficiency. Results demonstrate the robustness of the method under a range of realistic conditions, including current mismatch, low shunt resistance, and luminescence coupling effects.

The researchers demonstrated that even for a relative high-performance tandem cell, with efficiency of ~29%, reducing series resistance by just $1 \Omega\text{-cm}^2$ can increase the total efficiency by ~0.2%, providing a concrete quantitative target for further improvement.[4]

Current efforts focus on expanding these approaches to image additional optoelectronic parameters to better correlate material properties with device performance. Leveraging the contactless nature of luminescence and SPV techniques, we are also developing methods to replace traditional contact-based measurements with fully non-invasive diagnostics suitable for high-throughput characterisation and process feedback.



We are developing methods to replace contact-based measurements with non-invasive, high-throughput diagnostics.



Laboratory cell and module performance testing

CSIRO works with researchers across ACAP to improve test and measurement techniques for tandem cells, developing the capabilities as the technology develops. In 2025, CSIRO completed the re-accreditation audit assessment needed for certified measurement of tandem cells, described in detail in the case study, "[CSIRO's PVPL test lab leads international perovskite standards](#)".

The facilities and accreditation are important for all ACAP partners as CSIRO fulfils an essential role in independently testing cells produced by ACAP researchers and other parties. CSIRO completed measurements for 144 devices for six clients over 2025.

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Case study



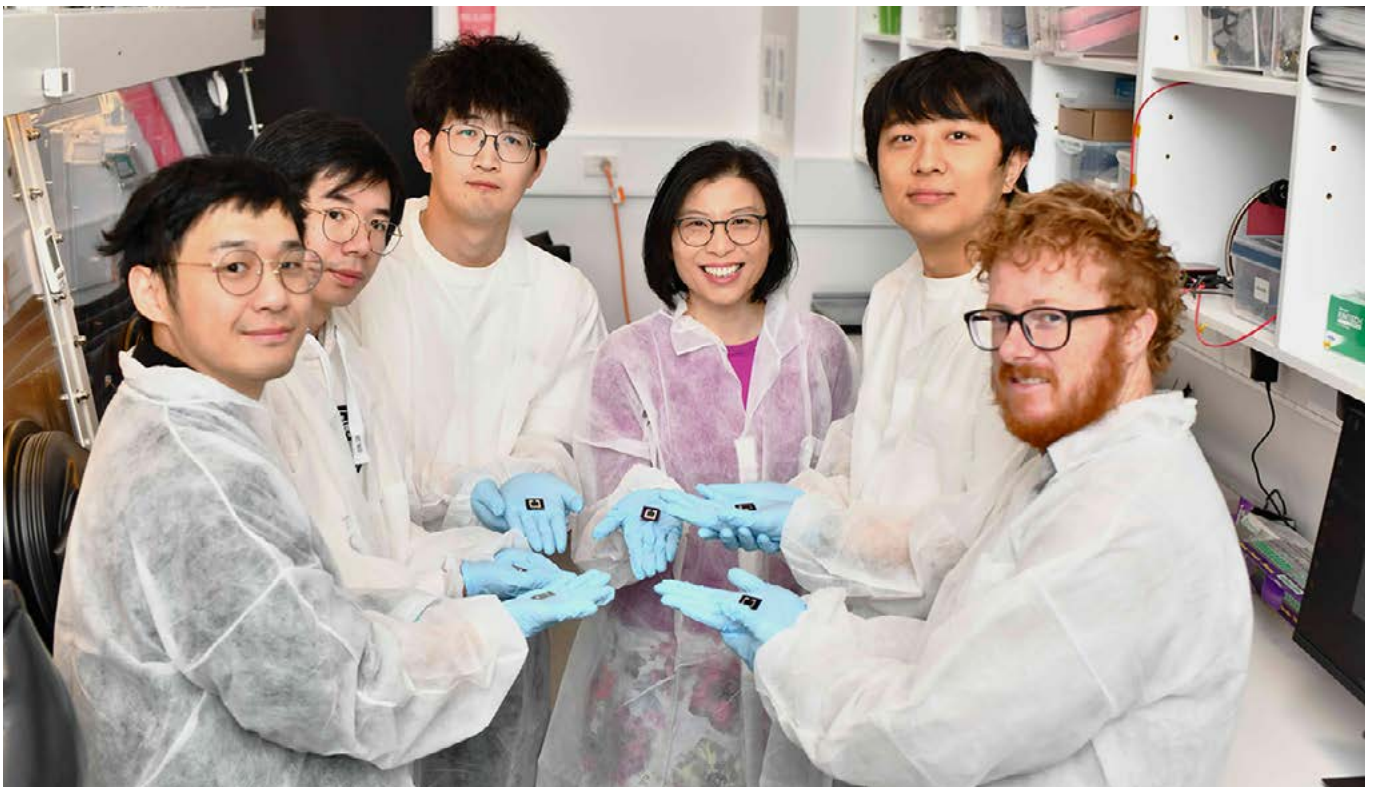
Global record for triple-junction tandem solar cell reported by USYD/ACAP-led team


A collaborative team of multi-disciplinary researchers, led by the University of Sydney, demonstrated record-setting size, performance and durability for perovskite–perovskite–silicon triple-junction solar cells.

The work, published in *Nature Nanotechnology* (October 2025), achieved independently certified efficiencies of 27.06% (1 cm²) and 23.3% (16 cm²) – the latter representing the most efficient large area perovskite–perovskite–silicon triple-junction solar cell reported to date.


The team also delivered the first triple-junction device of its kind to pass the IEC 61215 Thermal Cycling test, establishing new standards for durability in perovskite-based solar technology.

The University of Sydney team and their record-setting perovskite–perovskite–silicon triple-junction solar cells.





Stacking three subcells with different bandgaps is promising because they can harness a broader portion of the solar spectrum more efficiently.



The work was supervised by Professor Anita Ho-Baillie (University of Sydney, ACAP Node Lead) and co-led by Dr Jianghui Zheng and Dr Guoliang Wang from the University of Sydney. Dr Zheng, a former ACAP Fellow at UNSW Sydney and Research Fellow at the University of Sydney, is now an Associate Professor at Xiamen University in China.

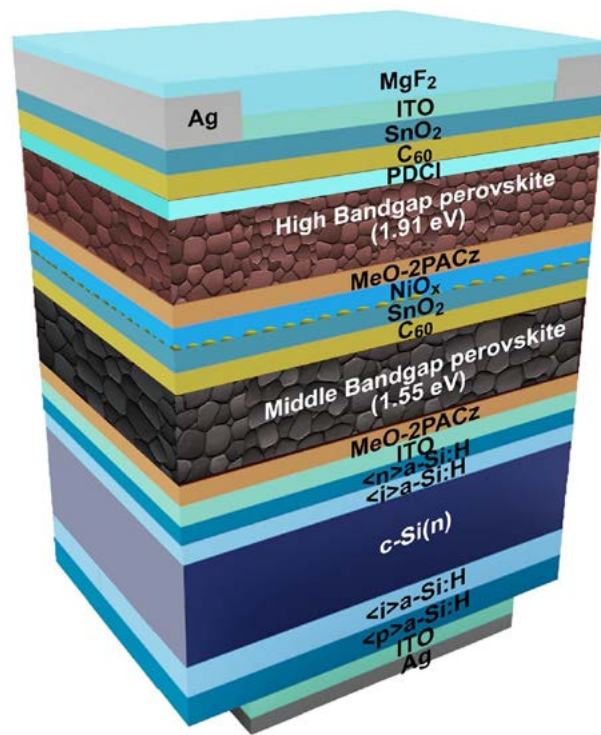
The study also brought together researchers from the University of Sydney, UNSW and the Australian National University, working with international partners at Forschungszentrum Jülich, Shenzhen Hiking PV Technology, Wuhan University of Technology (China), and the University of Ljubljana (Slovenia) – a powerful example of the global and interdisciplinary strength of the ACAP network.

Triple-junction solar cells (stacking three subcells with different bandgaps) are promising because they can harness a broader portion of the solar spectrum more efficiently. In particular, perovskite–perovskite–silicon architectures are attractive because perovskites offer tuneable bandgaps, high absorption, and potentially low-cost fabrication; while silicon is mature, stable and widely used.

However, real devices of this kind have not reached theoretical limits because of voltage losses, stability issues (particularly under heat, moisture, and light exposure) and challenges integrating the perovskite–perovskite and perovskite–silicon junctions.

The success in improving the top perovskite cell stability came from the replacement of the less stable methylammonium with rubidium, creating a layer that is less prone to defects and degradation. A new surface treatment for the top perovskite cell was also developed using piperazine-1,4-dium chloride (PDCI) improving the cell's light stability.

To precisely engineer the interface between the perovskite cells, gold in the form of nanoparticles was used in favour of a continuous film. The coverage of the nanoparticles was engineered to maximise the flow of electric charge and light absorption by the solar cell.



Schematic of the record-breaking perovskite-perovskite-silicon triple junction tandem cell.

Achieving high efficiency and durability with larger cell areas represents a major milestone. Professor Ho-Baillie emphasised that the findings illustrate both the promise and the remaining challenges of perovskite on silicon tandem solar cells.

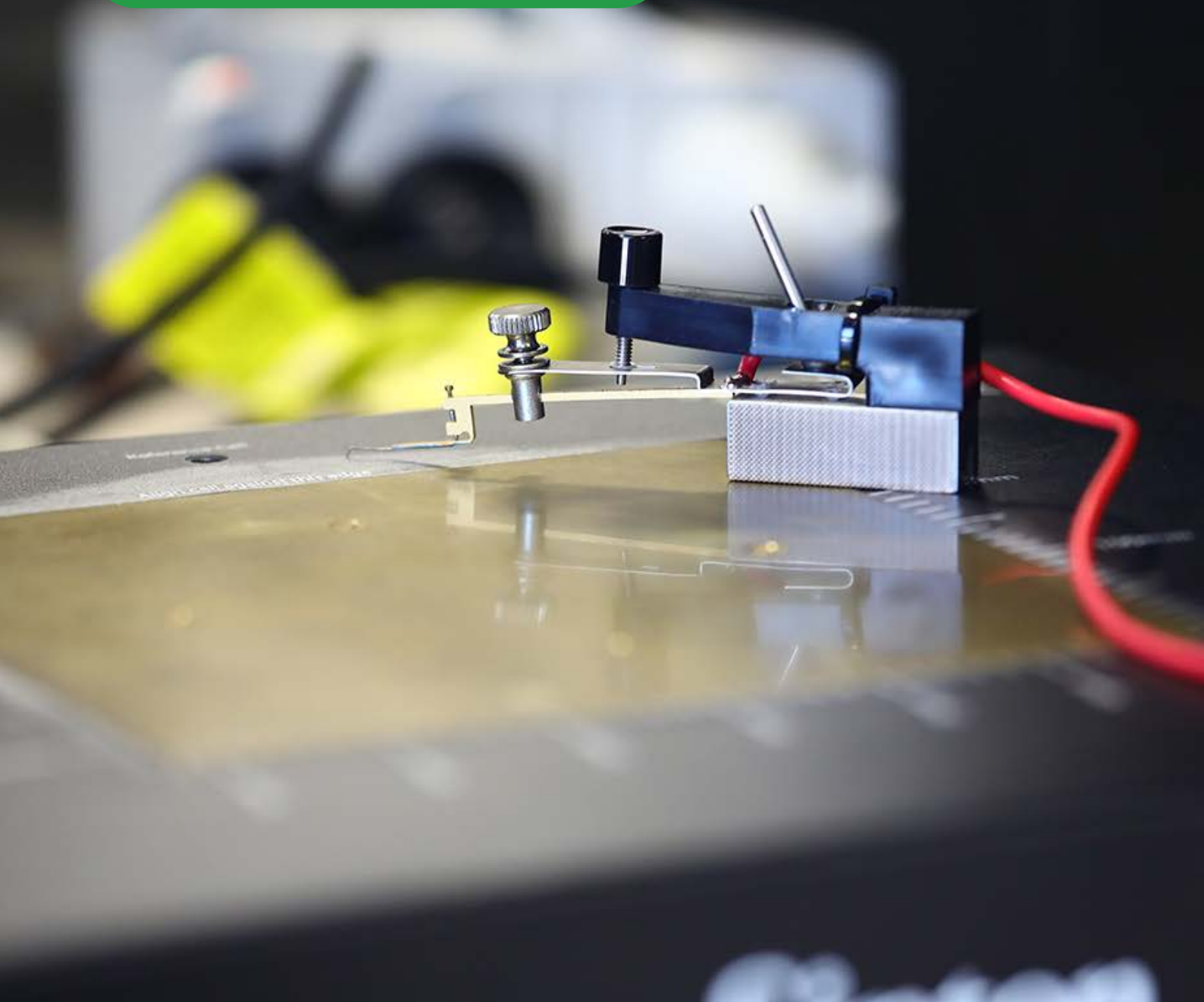
“The results strengthen confidence in the potential of triple-junction perovskite devices. We’re moving closer to real-world application, which is very exciting. Long-term stability and large-scale manufacturability remain as challenges to be tackled,” Professor Ho-Baillie said.

This world record achievement reinforces Australia’s global leadership and ACAP’s pivotal role in advanced solar research. ■

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Case study



ACAP ANU researchers' radical design transforms stability of perovskite–silicon tandem solar cell

Creative thinking by ANU's Dr Daniel Walter and Kunlin Chen led to a counterintuitive approach of deliberately not optimising for peak efficiency to achieve better real-world performance in perovskite–silicon tandem solar cells.

Perovskite–silicon tandem solar cells can look stable in the lab, but struggle in the real world. In real operation, a solar module never sits at a perfectly fixed voltage. Grid interactions, inverters, shading, clouds, temperature swings, and maximum power point tracking (MPPT) all cause the voltage across the cell to constantly change.

For perovskite tandems, these voltage swings are especially problematic. Perovskites suffer from hysteresis, an instability where the cell's performance fluctuates unpredictably depending on recent voltage changes. Charged particles within the perovskite material migrate in response to voltage fluctuations that are common in real-world conditions. This migration not only makes reliable performance measurement nearly impossible, but also accelerates long-term degradation, threatening the technology's commercial viability.

Rather than fighting to eliminate this instability – which is the approach most researchers have pursued – ACAP-supported scientists at ANU took a radically different path.

Most tandem researchers will design the stacked subcells so they generate the same electrical current, allowing the device to operate efficiently without one layer limiting the overall power output. This is called 'current matching'.

Led by Dr Daniel Walter, the team discovered that by deliberately running tandem cells in a slightly 'mismatched' mode, where the silicon layer limits the overall current rather than seeking the ideal balance between the two materials, they could dramatically suppress the problematic voltage fluctuations in the perovskite layer.

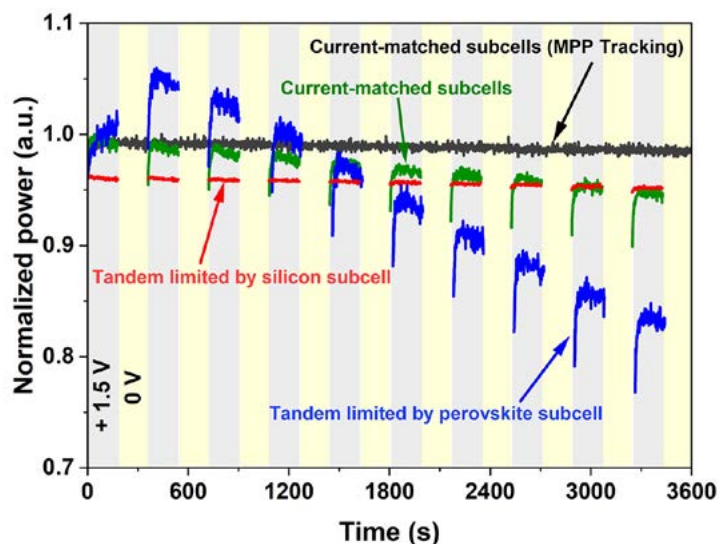
“
If we configure the tandem in a specific way, we can shift some critical stresses to the silicon cell, away from the perovskite cell,” explains Dr Walter.

“Our work shows that if we configure the tandem in a specific way, we can shift some critical stresses to the silicon cell, away from the perovskite cell,” explains Dr Walter.

“Because state-of-the-art silicon solar cells are highly robust and well-adapted to handle the stress, this is a way we can extend the lifetime and performance of silicon-perovskite tandem solar cells by maximally exploiting the robustness of silicon solar cells.”

The approach requires accepting a modest efficiency reduction – by as little as 5% – but delivers transformative improvements in stability, measurement reliability, and total energy production over the device’s lifetime. By letting the robust silicon layer shoulder more operational stress, the fragile perovskite remains stable far longer.

When Walter and Chen engineered the tandem so that the robust silicon cell limits the current (red) and shoulders more operational stress, voltage cycling is much less damaging to the perovskite, and the tandem’s stability closely matches fixed-bias laboratory conditions (dark grey).



This stability-first design philosophy represents a fundamental shift in thinking. Rather than chasing maximum peak performance, the research demonstrates how strategic engineering can unlock the commercial potential of ultra-high-efficiency tandem cells, accelerating ACAP’s mission to deliver sustainable, affordable solar technology for net zero economies worldwide. ■



Photo credit: Rob Largent / UNSW

Case study



ACAP ANU team develop industry-friendly large area deposition method for perovskite-silicon tandems

Working with Jinko Solar, researchers at ANU have bridged the gap between perovskite lab breakthroughs and solar manufacturing.

Perovskite-silicon tandem solar cells promise a step-change in solar efficiency, but one stubborn problem has slowed their path to market: how to coat perovskite materials uniformly over the large, textured silicon wafers used in real factories. In 2025, researchers at the Australian National University (ANU), led by Dr The Duong, delivered a major breakthrough by solving this scalability challenge.

The team developed and refined a two-step hybrid deposition method that combines evaporation of an inorganic metal-halide template with blade coating of the organic components. Crucially, this approach enables uniform perovskite films on large-area, textured silicon substrates – up to 150 mm × 110 mm – using processes compatible with industrial manufacturing.

Perovskite film deposited by the 2-step hybrid evaporation/blade coating method on 150 mm x 110 mm textured silicon substrates.



“This work moves the field beyond asking whether perovskite–silicon tandems can work at scale, to how fast they can be manufactured,” said Dr Duong.

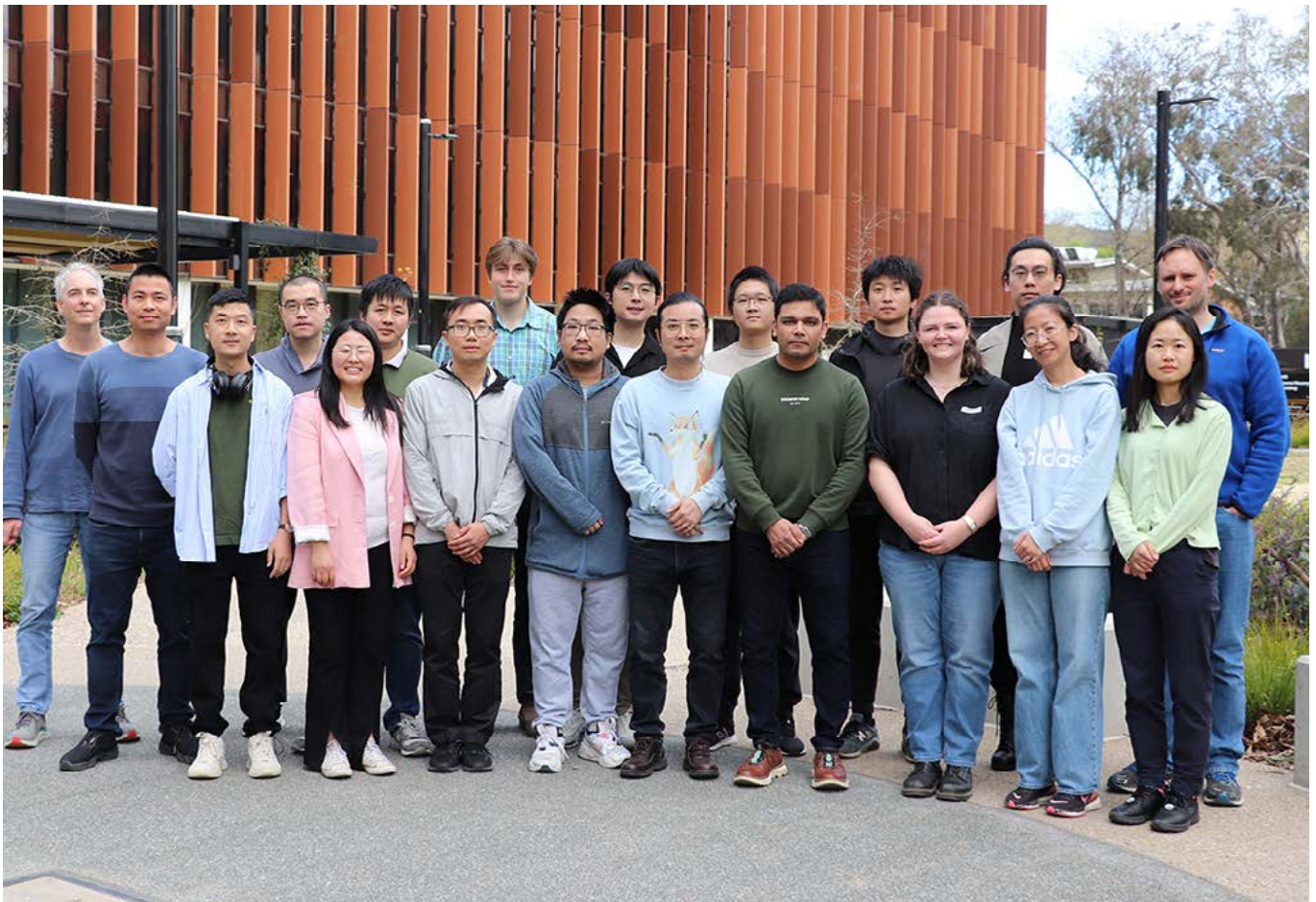
“That shift is essential for real-world deployment.”

“
We now have much better control over perovskite thickness at scale, which opens new pathways for further efficiency gains.
”

Key contributors include Dr Viqar Ahmad, Ms Qian Cui, Associate Professor Heping Shen, and Professor Klaus Weber, with ACAP providing critical infrastructure and coordination. The project also benefits from collaboration with UNSW, the University of Melbourne, and industry partner JinkoSolar, ensuring the research remains tightly aligned with manufacturing realities and commercial pathways.

Using their large area deposition method for perovskite–silicon tandems, the ANU team achieved over 28% efficiency on 1 cm² devices, while maintaining performance during upscaling. Their medium-term targets include 30% efficiency at small scale and at least 27%

The ACAP supported ANU Perovskite Research Group. Group leader Professor Klaus Weber at far left; Dr The Duong second from the left; Associate Professor Heping Shen is fifth from the left in pink jacket; Dr Viqar Ahmad is sixth from the right in green; Ms Qian Cui is front row, second from the right.



efficiency on devices larger than 20 cm², benchmarks that would place tandem solar cells firmly within commercial reach.

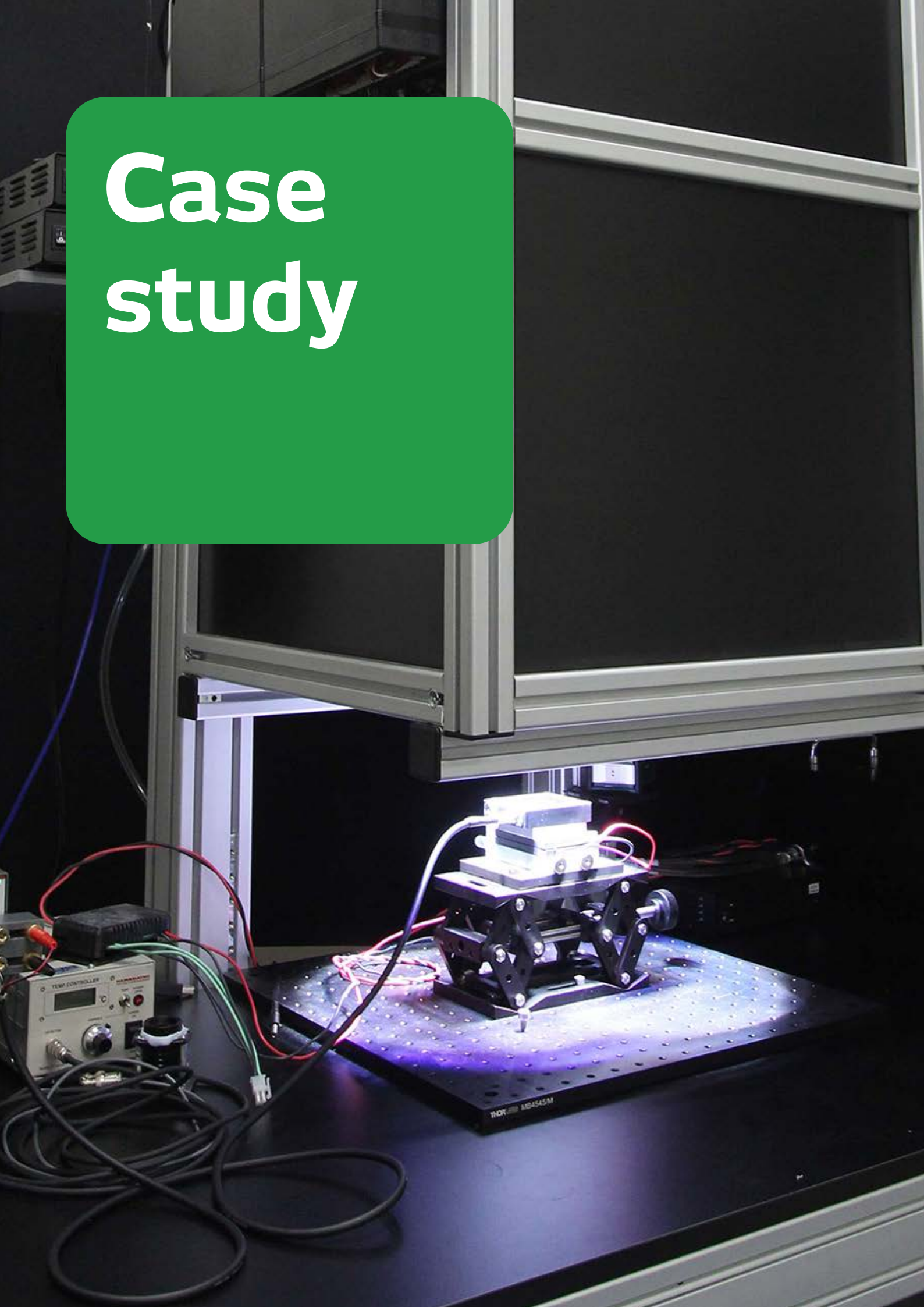
Stability has been a central focus alongside efficiency. The researchers are advancing encapsulation strategies and undertaking both accelerated and outdoor testing to ensure long-term reliability – an essential requirement for bankable solar technologies.

“What excites us most is the ability to extend this approach to full industrial wafer sizes, including M10 wafers,” Dr Duong noted.

“We now have much better control over perovskite thickness at scale, which opens new pathways for further efficiency gains.”

Together, this work marks a decisive step towards making high-efficiency tandem solar cells manufacturable, reliable, and ready for global deployment. ■

Case study



CSIRO's PVPL test lab leads international perovskite standards


CSIRO's globally accredited PV testing lab is leading the development of international standards for perovskite solar cell measurement.

Perovskite solar cells are notoriously challenging to characterise due to their time- and history-dependent behaviour. Australia's only NATA accredited PV testing lab is working with a handful of similar labs around the world to develop effective perovskite performance verification protocols – utilising high performing cells supplied by ACAP research teams.


As next-generation solar technologies such as perovskites move from laboratory research towards commercial deployment, measuring their performance accurately, repeatably and credibly is a challenge. Without trusted, standardised measurement protocols, research results cannot be compared, efficiencies cannot be independently verified, and investors lack the confidence required to support emerging technologies at scale.

Addressing this challenge is a core capability of the Photovoltaic Performance Laboratory (PVPL) at CSIRO Newcastle, one of the ACAP nodes. PVPL is the only laboratory in Australia operating under ISO/IEC 17025 and the PV specific IEC 60904 accreditation for photovoltaic performance measurement, spanning both established silicon technologies and emerging devices such as perovskite solar cells.

In 2025, as perovskite efficiencies continued to advance across the ACAP research network, CSIRO undertook an external technical assessment as part of its ongoing accreditation. In July, CSIRO's PVPL test lab hosted a senior researcher from Renewable Energy Systems (UAE) to independently review its measurement procedures, with a particular focus on metastable photovoltaic devices.



PVPL has verified three world-record photovoltaic device performances reported by ACAP teams.



CSIRO's custom 40-LED solar simulator allows extremely precise control of the light spectrum for accurate measurements of tandem solar cells, at CSIRO Newcastle, Australia's only NATA accredited Photovoltaic Performance Laboratory.



ACAP researchers are leading the development of a new international standard for perovskite measurement.



During the year, the majority of advanced measurements undertaken by PVPL focused on high-performing perovskite solar cells supplied by ACAP partners, directly linking national research excellence with accredited measurement capability. PVPL's role in the verification of three world-record photovoltaic device performances reported by Australian (ACAP) research teams reinforces its position as a trusted authority in photovoltaic measurement.

This capability is critical not only for research integrity, but for commercial readiness: accredited, standardised testing underpins bankability, investor confidence, and market entry for next-generation solar technologies.

Building on this valuable experience, ACAP supported CSIRO researchers are leading the development of a new international standard for perovskite measurement, IEC 60904-1-4. This will remove a major barrier to commercialisation of perovskite solar cells, helping ensure global consistency as the technology matures.

The standard is not yet finalised, but ACAP Technical Lead Dr Chris Fell (CSIRO) says, "The barrier removal really is significant because, until this standard is available, it's impossible for anyone to perform the globally mandated IEC standard stress testing."

"So there really can't be a product without the work we're doing."

Looking ahead, CSIRO is expanding PVPL's capabilities to include module-scale and tandem device measurements, ensuring Australia remains at the forefront of validating the photovoltaic technologies that will shape the next phase of the global energy transition. ■



Case study




An Outstanding Thesis Award for two solar device designs that improve tandem cell stability

Dr Guoliang Wang received the University of Sydney Faculty of Science Outstanding PhD Thesis award for developing two device design strategies that improve the efficiency and stability of perovskite–silicon tandem solar cells. One of the new materials Dr Wang reported for this purpose is already in commercial use.




Dr Guoliang Wang (R) and his award, with ACAP Node Lead for the University of Sydney, Professor Anita Ho-Baillie (L), who supervised Dr Wang's PhD. Photo credit: Jayne Ion.

For the novel device design, Dr Wang developed two new interlayers between the perovskite and the surrounding materials that improved voltage output, stability, and cost-effectiveness. These act like freeway on-ramps. When designed well, cars (charges) can flow without slowing or losing energy; when poorly designed, traffic jams build up, and energy is lost.



Wang's first breakthrough was the design of a new molecular layer that improved voltage output and stability in high-bandgap perovskite cells.



Better “positive charge” layer (Ph-2PACz)

Wang's first breakthrough was the design of a new molecular layer, Ph-2PACz, that improved voltage output and stability in high-bandgap perovskite cells.

When integrated into a perovskite–silicon tandem, it delivered an efficiency of 28.9%, surpassing the best silicon solar cells at the time, and crucially, passing the IEC 61215 Thermal Cycling Test, a key international reliability standard. This work was published in *Joule*[1] and highlighted by *PV Magazine*, reflecting its global significance.

Wang said, “We were one of the three research groups in the world that could demonstrate tandems that pass this test at that time.”

Notably, Ph-2PACz is now sold commercially, allowing other researchers and companies to build on this innovation.

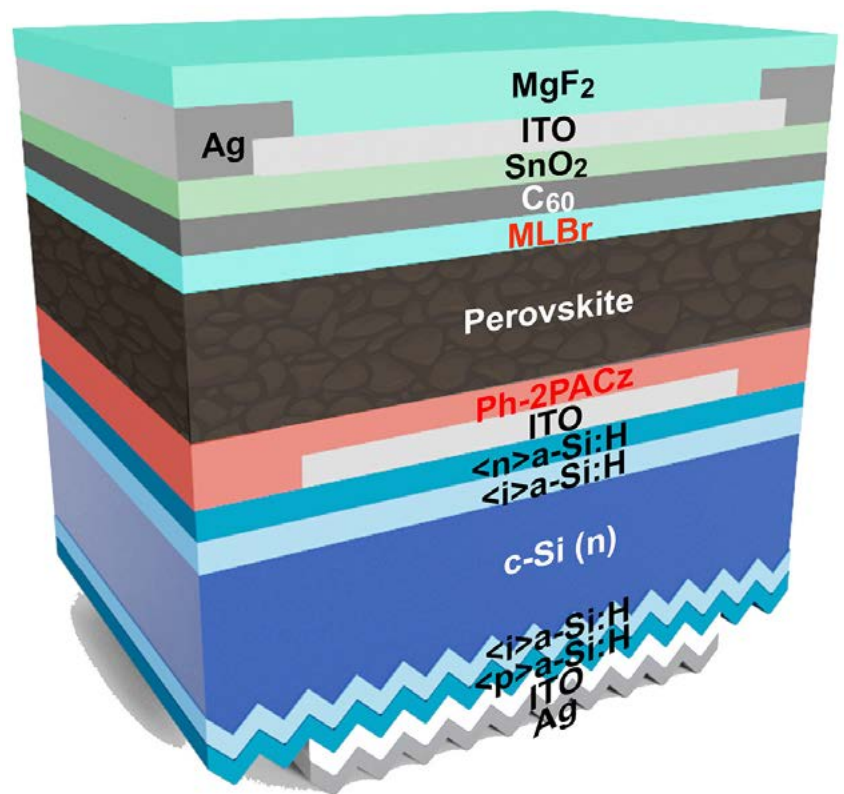
Better “negative charge” layer

Building on this, Dr Wang turned to the other side of the cell interface, replacing the commonly used but unstable lithium fluoride with a new interlayer, morpholinium bromide. This more durable and affordable material improved electron extraction and enabled tandems to pass the Thermal Cycling test not just once, but twice – a rare achievement shared by only a handful of groups across the world.

This second breakthrough was published in *Advanced Energy Materials*. [2]

Together, these push perovskite–silicon tandems closer to commercial viability.

“By improving voltage output, stability, and cost-effectiveness, they help accelerate the trajectory toward ultra-low-cost, high-efficiency solar technologies.” says Guoliang.



A tandem device structure with the two new interlayers, Ph-2PACz and morpholinium bromide (MLBr), between the perovskite and the surrounding materials that improved voltage output, stability, and cost-effectiveness.

There is still work to be done before tandem solar cells become a mainstream technology. Challenges remain in scaling up fabrication, ensuring long-term durability in outdoor conditions, and reducing manufacturing costs to levels that can compete with that of silicon. However, progress like this demonstrates how scientific innovation is overcoming barriers. ■

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Case study



Australia's first tandem fabrication platform delivers world record efficiencies

In 2025, UNSW successfully completed commissioning of ACAP's new Tandem Cluster, a major research infrastructure and the first of its kind in Australia.

The final component – the broadband antireflection coating (ARC) deposition system – was commissioned in December 2025, completing a staged installation of tools delivered between 2023 and 2025.

Led by Scientia Professor Xiaojing Hao, Professor Nicholas J. Ekins Daukes, Professor Bram Hoex, and Professor Ziv Hameiri, the project has established Australia's first virtual tandem fabrication cluster. This integrated suite of sputtering, evaporation, ALD and in situ characterisation systems now provides ACAP researchers with a unified platform for fabricating next generation tandem solar cells.

Throughout 2024–2025, the cluster directly supported multiple UNSW thin film top cell projects, including kesterite and chalcogenide (CZTS and CIGS) and wide bandgap perovskite programs. These projects have already delivered certified world record efficiencies: 13.2% for CZTS, 14.9% for CIGS, and 21.8% for wide bandgap perovskite top cells.

The tandem cluster directly supported multiple UNSW thin film top cell projects ... which have already delivered certified world record efficiencies: 13.2% for CZTS, 14.9% for CIGS, and 21.8% for wide bandgap perovskite top cells.



Part of the tandem fabrication cluster: multi-chamber sputters for functional layers.

Atomic Layer Deposition (ALD) for sulphide and oxide function layer materials.



Dual-source e-beam evaporator for anti-reflection coating (ARC) materials.



Multi-source evaporator for high bandgap adamantine absorber.



Evaporator for selective transport materials integrated with glovebox.



Professor Xiaojing Hao said, “These achievements highlight the impact of the new infrastructure in accelerating device development and improving interface quality, uniformity, and contamination control across fabrication steps.”

Beyond individual records, the cluster is enabling more reproducible, scalable tandem cell fabrication and paving the way for future technology transfer at high TRLs. By integrating UNSW’s Si cell manufacturing capabilities with high bandgap thin film expertise, the facility positions Australia at the forefront of tandem PV innovation and strengthens national capacity for next generation, high efficiency photovoltaic technologies. ■

Device to Module

Program
Package 4



Technical Program Lead
Professor Bram Hoex

UNSW

The Device to Module Program focuses on translating advances in photovoltaic cell technology into reliable, durable, and commercially viable module solutions. Its activities address ARENA's Ultra Low-Cost Solar (ULCS) mission by developing metallisation schemes with drastically reduced silver use, exploring copper-based contacts, engineering lightweight and low-cost modules, and strengthening understanding of degradation and reliability mechanisms through advanced indoor and outdoor testing.

The Device to Module Program focuses on translating advances in photovoltaic cell technology into reliable, durable, and commercially viable module solutions.

Device-to-module research can deliver benefits at the cell-design level, reducing the use of materials such as silver, enabling larger wafers and module sizes, new cell interconnection technologies, light trapping and manufacturing process improvements.

The learnings from the growing maturity of the silicon PV industry can be applied to support a faster transition of new, emerging materials and devices from the research phase to pilot scale production, with relevance to tandem solar devices.

Key challenges

Key challenges include (1) sustainable metallisation, (2) copper contact reliability, (3) lightweight module design, and (4) the lack of predictive links between laboratory degradation studies and field performance.



Solution pathways



A national network of indoor and outdoor testing facilities enables validation of laboratory insights against real-world performance.



- 1. Ultra-low silver and copper metallisation:**
Development of silver-lean (<5 mg/W) and silver-free copper-based metallisation schemes compatible with existing industrial infrastructure enables sustainable, terawatt-scale manufacturing without loss of efficiency.
- 2. Module degradation and reliability physics**
Advanced physical models of UV-induced degradation, corrosion, and mechanically driven failure mechanisms provide fundamental insights into reliability limits and inform improved material selection and module designs.
- 3. Mechanical stress and contact reliability modelling**
Statistical and physics-based modelling of copper-plated contacts links processing conditions to fracture strength and long-term durability, enabling optimisation of copper metallisation for bankable module deployment.
- 4. Lightweight and low-cost module architectures**
Novel lightweight silicon module designs reduce material use and balance-of-system costs while maintaining mechanical robustness, opening new markets such as off-grid, mining, and transport-limited installations.
- 5. Integrated indoor-outdoor testing infrastructure**
A national, harmonised network of indoor and outdoor testing facilities enables validation of laboratory insights against real-world performance, supporting predictive lifetime modelling and future standards development.

Key progress

Advanced screen printing and metallisation

The UNSW-led “Advanced screen printing” project made major progress towards sustainable metallisation for silicon solar cells. Pilot production at partner facilities demonstrated silver-lean TOPCon cells consuming only 7 mg of silver per watt (down from the industry standard 12 mg/W), with efficiencies on par with current industrial standards.

Five new silver-lean and silver-free paste formulations were developed in collaboration with materials partners, spanning high-temperature aluminium, silver-coated copper, and pure copper pastes. These achieved bulk resistivities between 4 – 7 $\mu\Omega\cdot\text{cm}$, well below the 50 $\mu\Omega\cdot\text{cm}$ target.

A bifacial mini-module fabricated from four silver-lean TOPCon cells demonstrated 3 mg/W silver consumption at the module level and exhibited mechanical robustness and minimal (<1%) light-induced degradation. For silicon heterojunction (SHJ) devices, completely silver-free large-area cells (210 × 105 mm²) achieved 23% efficiency using pure copper contacts.

Collectively, these achievements confirm the technical feasibility of sub-5 mg/W metallisation compatible with existing production infrastructure, directly advancing terawatt-scale sustainable manufacturing. Read the case study, [“Solving solar’s looming silver supply constraint”](#).

Module degradation and reliability physics

The “Module degradation” project led by UNSW achieved an advanced fundamental understanding of module reliability mechanisms. The team developed a new physical model for ultraviolet-induced degradation (UVID) that captures metastable behaviour observed in laboratory testing. See case study, [“Shaping industry standards for UV-induced degradation in TOPCon”](#).

Parallel work on corrosion-related degradation analysed the effects of soldering flux, bill-of-materials (BoM) interactions, and unintentional contamination. Studies demonstrated that atomic-layer-deposited (ALD) barrier layers can effectively protect solar cells against metal and dielectric corrosion. See more in the case study, "[Guiding industry to prevent corrosion in TOPCon solar cells](#)".

The UVID mechanism work was selected for a plenary presentation at EU PVSEC 2025, recognised as one of the conference's highlights. Furthermore, collaboration with Tindo Solar led to a \$540,000 industry project directly leveraging ACAP findings. Across the year, the team published ten peer-reviewed papers covering degradation mechanisms and mitigation strategies.



The UVID mechanism work was selected for a plenary presentation at EU PVSEC 2025, recognised as one of the conference's highlights.



Stress modelling of copper-plated contacts

UNSW, in collaboration with Sydney based cell technology developer SunDrive Solar, performed a detailed statistical analysis of fracture strength in copper-plated heterojunction (HJT) cells, which revealed clear correlations between annealing conditions and mechanical performance.

The analysis showed that fast annealing increased the microstrain in both copper (Cu) and indium tin oxide (ITO) layers and introduced localised high stress (~60 MPa) in silicon, while self-annealed Cu exhibited higher fracture strength and lower dislocation density in the dominant Cu (111) orientation. These insights link processing conditions to long-term module reliability and provide essential data for optimising copper metallisation schemes. [1][2]

Lightweight and low-cost silicon modules

The Monash-led project focuses on addressing structural and cost barriers in traditional glass-glass modules. The team demonstrated mechanically robust lightweight silicon module architectures, built in-house testing systems to perform IEC 61215 durability tests, and identified the key design parameters governing mechanical and environmental stability.

The project secured \$200,000 funding through the Australian Economic Accelerator (Ignite) program, enabling prototype scaling. Lightweight silicon modules were showcased as a potential solution for off-grid and mining applications at the Asia-Pacific International Mining Expo (AIMEX 2025) and featured in the SXSW Sydney Innovation Showcase, underlining their economic and deployment advantages.

Advanced outdoor testing infrastructure

CSIRO's advanced Outdoor Module Testing Facility continued to expand its role as Australia's premier outdoor performance characterisation platform. In 2025, the system's control architecture was fully upgraded, introducing standardised daily "data packs" that are automatically compressed and distributed to researchers.

A total of 29 PV modules from multiple ACAP projects were installed and monitored to benchmark the real-world durability and yield of commercial high-efficiency modules under Australia's diverse climates, with 21 slots remaining for upcoming collaborative activities. These outdoor results will be complemented with indoor characterisation results from ANU, UNSW, and ACAP partner PV Lab Australia. The system's electrical capability was doubled (14 A → 28 A) to accommodate large-format modules, and a maximum power point (MPP) tracking upgrade was completed for R&D device measurements. These enhancements enable higher-precision outdoor data and accelerate research on degradation and yield modelling. Read more in the case study, ["Expanding Australia's outdoor solar testing facilities"](#).

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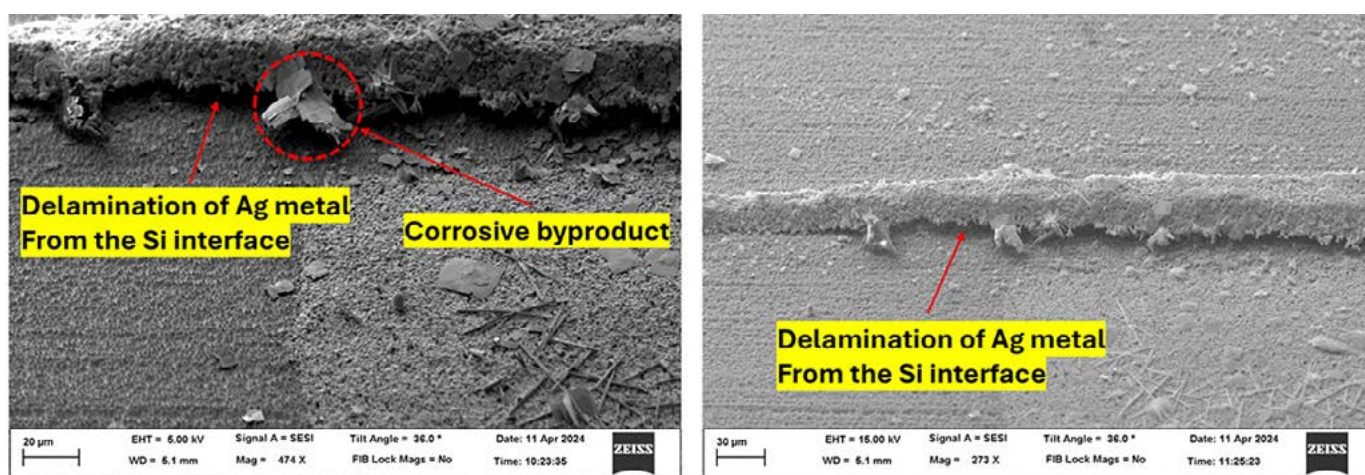
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Case study



Guiding industry to prevent corrosion in TOPCon solar cells

In 2025, researchers led by Professor Bram Hoex (UNSW) tackled one of the most serious and least visible threats to next-generation solar technology: corrosion and chemical degradation in high-efficiency silicon solar cells. As the global industry rapidly shifts to tunnel oxide passivated contact (TOPCon) and heterojunction (HJT) technologies, understanding and controlling these degradation pathways has become essential to ensuring long-term performance, bankability, and investor confidence.



Scanning electron microscopy images showing moisture-assisted corrosion and peeling (delamination) of the front silver contact in a TOPCon solar cell after exposure to residual soldering flux. Corrosion by-products are visible.

“
To ensure TOPCon’s success we must understand its unique sensitivities.
”

Supported by ACAP-funded infrastructure and collaborative projects, this research addressed corrosion as a system-level challenge – spanning cell architecture, materials chemistry, manufacturing processes, handling, and module assembly. Small, often invisible changes at any stage can quietly undermine the lifetime of high-efficiency solar modules once deployed in the field.

“TOPCon presents an exciting leap in efficiency, but to ensure its long-term success, we must understand its unique sensitivities to environmental stresses and manufacturing choices,” said Professor Bram Hoex.

“The manufacturing process is evolving rapidly, and small adjustments can either strengthen or weaken long-term stability. Identifying these vulnerabilities is essential for designing solar modules that perform reliably in Australia’s climate, and at scale globally.”

Working closely with industry partners, including Canadian Solar, Jolywood, and Tindo Solar, the Hoex Group combined fundamental degradation science with solutions implementable in modern production lines.

Australia's only solar module manufacturer, Tindo Solar, produces panels designed to withstand intense sunlight, coastal salt spray, wide temperature fluctuations, high humidity and hailstorms – conditions that can otherwise lead to delamination, corrosion, condensation, and long-term power loss.

"Tindo and UNSW are optimising TOPCon technology to deliver high power output across diverse climatic conditions," said Richard Petterson, CEO of Tindo Solar.


"Tindo has strong in-house design and engineering capability, but partnering with a leading research organisation such as UNSW is critical. It's this blend of industry and research that will deliver the next generation of solar technology."

A laser-assisted firing process for industrial TOPCon cells delivered an efficiency gain of ~0.6% (absolute) while improving resistance to corrosion and damp-heat exposure.[1][2] By reducing losses at the metal-silicon interface, the process enables manufacturers to use lower-aluminium pastes, cutting costs and improving production yield.


The team also showed that copper plating of cell contacts can dramatically slow corrosion. In accelerated damp-heat tests, conventional TOPCon cells rapidly lost performance, while copper-plated cells retained the majority of their efficiency.[3] This approach reduces silver use, improving sustainability while maintaining electrical performance.

Beyond device engineering, ACAP researchers uncovered how trace contamination from gloves, packaging, or handling equipment can drive significant power losses under humid conditions.[4][5]

"Reliability is as much about process discipline as it is about materials," said Dr Chandany Sen (UNSW), lead author on several of the studies.



Researchers found that trace contamination from gloves, packaging, or handling equipment can drive significant power losses.



“Small choices in handling or assembly can have large consequences years later.”

Complementary studies demonstrated that certain soldering fluxes can chemically attack sensitive layers in advanced cells, particularly HJT devices[6], highlighting risks even in sealed modules.

Dr Xinyuan Wu (UNSW), a lead author on several of the studies, noted, “By identifying and understanding how corrosion initiates at contacts, we can design protection strategies that are scalable and immediately relevant to manufacturers.”

Their work has attracted substantial industry and media attention, including coverage in the international and Australian editions of *PV Magazine*. Results were presented at major international and regional forums, including the European Photovoltaic Solar Energy Conference (EU PVSEC 2025) and the Asia-Pacific Solar Research Conference (APSRC 2025), as well as invited industry-focused seminars and webinars.

(l-r) UNSW's Dr Umair Khan, Professor Bram Hoex, and Dr Chandany Sen. With Dr Xinyuan Wu (UNSW), the ACAP-supported team have led efforts to identify and understand how corrosion initiates at contacts, and to design protection strategies that are scalable and immediately relevant to manufacturers. Photo credit: Isabella Moore

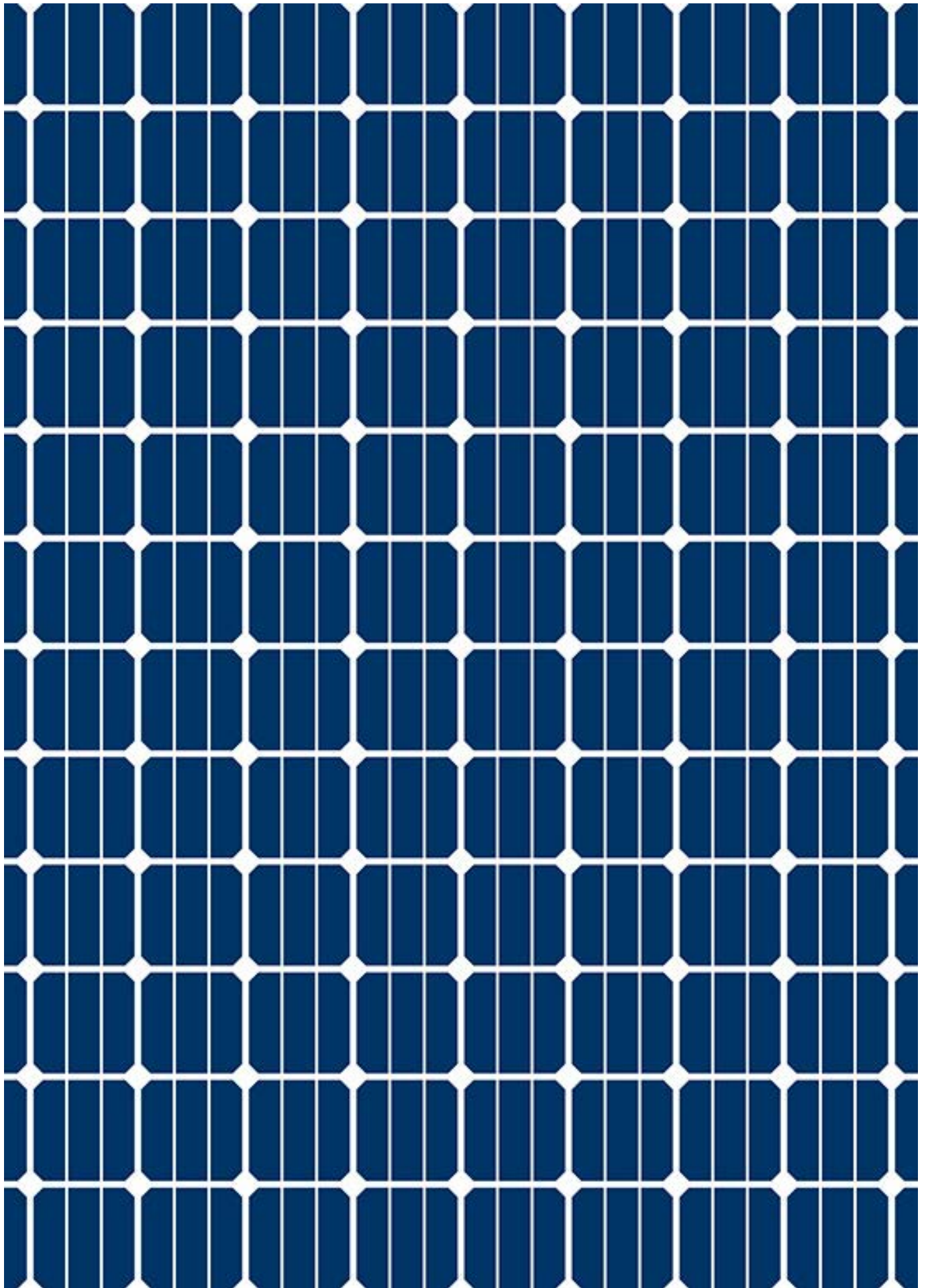


By linking fundamental science with scalable solutions – from laser-assisted firing to copper-plated contacts and atomic layer deposition barriers (ALD)[4] – this research provides practical, bankable strategies for producing TOPCon and HJT modules that are more reliable, lower cost, and better suited to diverse climates.

The Hoex team’s work sets a benchmark for comprehensive, system-level PV reliability research, reinforcing Australia’s position as a global leader in solar materials and manufacturing science. ■

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Case study



Expanding Australia's outdoor solar testing facilities

Understanding how solar technologies behave in outdoor conditions is essential for improving performance, reliability, and long-term value. Real-world testing is a necessary complement to indoor laboratory tests, which cannot fully reproduce the complexity of actual operating environments, including temperature swings, wind, humidity, and daily solar and thermal cycling.

"If Australia wants to stay at the forefront of solar innovation, we must expand and consolidate our outdoor testing capabilities," says Dr Chris Fell, ACAP Technical Lead and Principal Research Scientist at CSIRO Energy.

"We need facilities that can test performance and durability under real Australian conditions, evaluate advanced diagnostic tools, and make high-quality data broadly available. This is essential for translating lab breakthroughs into reliable, bankable technologies."

“
We need facilities that can test performance and durability under real Australian conditions.
”

Against this backdrop ANU, UNSW, and CSIRO are developing plans to build an ecosystem of outdoor testing facilities for all ACAP researchers across sites with different climate zones. ANU has progressed its outdoor testing facility to support emerging technologies, while UNSW is working hard to create an outdoor testing site in Manly, funded internally and through an ACAP collaborative project, and another at the Desert Knowledge Centre in Alice Springs, with initial funding from ARENA.

However, the most significant expansion in 2025 of outdoor testing capacity was a substantial upgrade of CSIRO's PV Outdoor Module Testing Facility in Newcastle, making it accessible to all ACAP researchers.

The facility hosts 60 module test beds and more than 20 research-device stations, co-located with a world-class solar ground station that records detailed sunlight characteristics, spectral content, weather, and device temperature data.



CSIRO's newly upgraded PV Outdoor Research Facility in Newcastle can test performance and durability under real Australian conditions and will make high-quality data available to ACAP Nodes.

CSIRO's PV Outdoor Research Facility upgrades include:

- A fully re-engineered control system for greater reliability and continuous operation.
- A new data architecture and standardised nightly "data packs" for seamless sharing across ACAP.
- Expanded electrical capacity for modern high-power modules, with further upgrades scheduled throughout 2025.
- New maximum power point tracking hardware for small R&D devices.
- Two ACAP Collaborative Projects are preparing to use the system, and several more are lined up.

"By giving researchers high-quality field data – sunlight, weather and device behaviour captured together – we can boost energy yield, improve durability and lower project risk," says Dr Fell.

"This upgraded facility will accelerate the innovations that reduce the cost of solar."



Part of the CSIRO Photovoltaics Outdoor Module Testing Facility, the ground station continuously monitors around twenty different solar and weather parameters that can influence the behaviour of solar panels being tested at the facility.

With further enhancements planned through 2026 and 2027, the PV Outdoor Module Testing Facility is becoming a national cornerstone for device-to-module research – strengthening collaboration, supporting education and helping Australia’s next-generation solar technologies succeed where it counts: outdoors.

CSIRO’s module-testing infrastructure also includes the recently commissioned Sinus-3000 Advanced solar simulator. One of only three in the world, it delivers near-perfect spectral accuracy for controlled indoor experiments and analysis of large commercial solar panels, and new technologies like perovskite and multi-junction modules.

Together, these assets, along with those of ANU and UNSW, are the foundation of what is hoped to become a powerful national testing ecosystem. ■

“
With high quality field data we can boost energy yield, improve durability and lower project risk.
”

Case study



Shaping industry standards for UV-induced degradation in TOPCon


As TOPCon silicon solar cells become the dominant technology in global photovoltaic manufacturing, long-term stability has become as critical as peak efficiency. One increasingly important stress factor is ultraviolet (UV) radiation, which can trigger performance losses over time. At UNSW, Professor Bram Hoex and his research group are leading the international effort to understand, quantify and standardise how UV-induced degradation (UVID) should be tested and mitigated in modern silicon solar cells.[1][2]

Supported by ACAP-funded infrastructure and a 2025 ACAP Collaborative Project, the Hoex group has carried out one of the most comprehensive investigations of UVID in TOPCon devices worldwide. Experimental work is led at UNSW, with close industrial collaboration with Canadian Solar. Together, this partnership has developed a practical UV cell-testing protocol that is now informing the emerging IEC standard for UVID testing.


From observation to mechanism and then guidance for industry

In the first study, the team compared exposure to UV-A and UV-B radiation under controlled conditions. Both wavelength ranges produced the same degradation mechanism, but UV-B acted much faster.[1] This finding shows that UV-B can be used to accelerate reliability testing without introducing artificial failure modes. This also highlights that areas with high UV-B, such as the Australian outback, are at greater risk for this degradation.


The work also demonstrated that the current rear side of TOPCon cells is inherently stable, as the doped polysilicon layer blocks short-wavelength UV from reaching the sensitive tunnel oxide, making them suitable for bifacial applications.



Areas with high UV-B, such as the Australian outback, are at greater risk for UV induced degradation.



“
We can finally design UV tests that reflect how TOPCon cells really behave in the field.
”



In a second, complementary study, the group developed a comprehensive model describing how UVID develops and recovers.[2] Ultraviolet photons break silicon-hydrogen bonds near the front surface, releasing mobile hydrogen that accumulates at the interface and increases recombination losses. At the same time, UV exposure temporarily traps negative charge in the aluminium oxide layer, masking some of the damage. After illumination stops, performance can continue to drift during dark storage as these charges are released. A brief low temperature anneal restores electrical performance, even though spectroscopy reveals a permanent rearrangement within the dielectric stack.

As Professor Bram Hoex explains, “By separating what is reversible from what is permanent, we can finally design UV tests that reflect how TOPCon cells really behave in the field – and avoid both under- and over-testing.”

The work has gained strong international visibility. Prof Bram Hoex, on behalf of Dr Muhammed Umair Khan (who was unable to travel), presented this work in a plenary session at EU PVSEC 2025 in Bilbao[3], and the findings have been widely reported by PV Magazine and PV Tech.

Reflecting on the impact, Dr Khan notes, “Our results show that UV-induced degradation is not a single effect, but a coupled chemical and electrical process – once you understand that, you can design cells and tests that are far more resilient.”

Key contributors include Muhammad Umair Khan, Chandany Sen, Alison Ciesla, Aeron Johns, Michael Pollard, Ting Huang, Munan Gao, Ruirui Lv, Yuanjie Yu, Xinyuan Wu, Haoran Wang, and Xutao Wang, under the leadership of Professor Hoex.

Together, this body of research positions UNSW as a global reference point for UV reliability in TOPCon technology and directly shapes how the next generation of silicon solar cells will be tested and deployed. ■

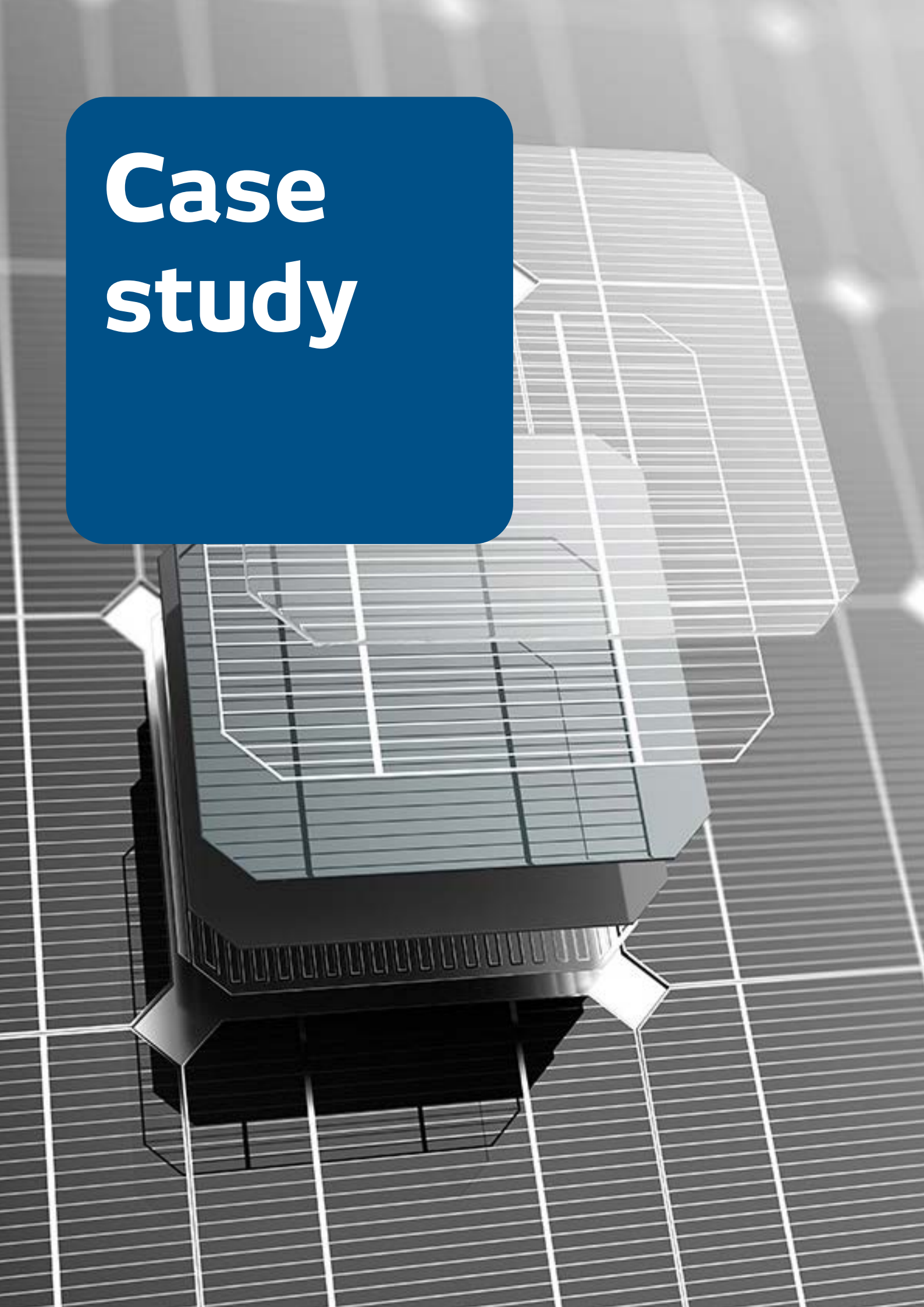


(l-r) Dr Alison Ciesla, Dr Chandany Sen, Haoran Wang, Dr Muhammad Umair Khan, Prof Bram Hoex, Xutao Wang, Jiexi Fu, Dr Xinyuan Wu. Image: Rob Largent / UNSW

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Case study



Solving solar's looming silver supply constraint

As the global solar industry accelerates toward terawatt-scale manufacturing, it faces a critical bottleneck: silver. Today's high-efficiency silicon solar cells rely on screen-printed silver contacts and, in 2025 alone, photovoltaic manufacturing consumed roughly 25% of global silver supply, highlighting the material risk of scaling solar without redesigning how critical resources are used.

In 2025 alone, photovoltaic manufacturing consumed roughly 25% of global silver supply.

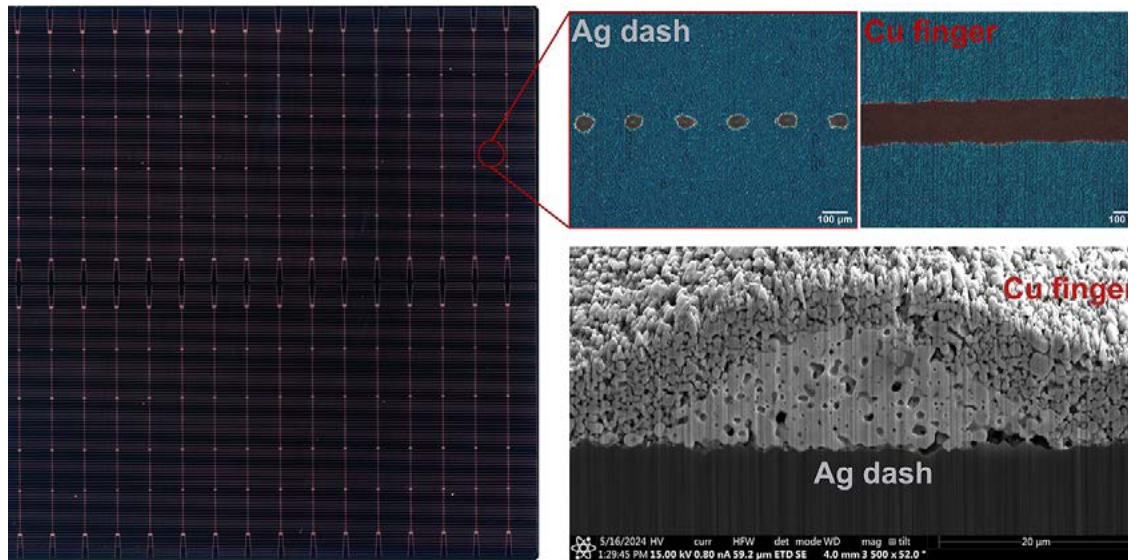
At UNSW Sydney, Associate Professor Brett Hallam and his metallisation team, including Dr Li Wang, Dr Yuchao Zhang, Dr Yuan-Chih Chang, Dr Sisi Wang and colleagues, have developed a practical, industry-ready solution. Their silver-lean screen-printing technology dramatically reduces silver use in high-efficiency TOPCon solar cells while remaining fully compatible with existing industry production lines.

Rather than printing continuous silver fingers and busbars, the team uses silver only where it is electrically essential – as microscopic 'dashes' at the silicon interface. The bulk of the conductive structure is then formed using silver-lean or silver-free pastes such as silver-coated copper, pure copper or aluminium. The result: up to 85% reduction in rear-side silver consumption without sacrificing cell efficiency[1][2], and a path to overall silver consumption as low as 2 mg/W.

The approach builds on a multi-year research arc defining the material intensity limits required for sustainable terawatt-scale manufacturing.[3]

At SiliconPV 2025 in Oxford, Dr Li Wang delivered the presentation with the highest-ranked abstract of the conference, Ultra-Lean Silver Screen-Printing for Sustainable Terawatt-Scale PV.[1]

"If photovoltaics is to scale sustainably to the terawatt level, we must reduce silver consumption to less than 2 milligrams per watt – our approach opens more opportunities for adopting alternative materials to achieve this goal," said Dr Wang.



ACAP-supported research at UNSW shows a silver-lean “dash” contact design can cut silver use to around 2 mg/W – with up to 85% reduction – without sacrificing efficiency.

A complementary 2025 study in *Solar Energy Materials & Solar Cells* demonstrated 25%-efficient industrial TOPCon cells with ultra-low silver consumption under industry-relevant conditions.[2]

“This is not just a laboratory concept,” said Associate Prof Hallam. “We are showing a manufacturable pathway that removes a key materials constraint for global PV deployment at the terawatt scale.”

The work has attracted significant international media attention, including coverage in *PV Magazine* (international and Australian editions), reflecting growing industry recognition that material intensity – not just efficiency – will define the next phase of solar competitiveness.

There is growing industry recognition that material intensity – not just efficiency – will define the next phase of solar competitiveness.

Critically, the technology has been developed in close collaboration with industry partners Toyo Aluminium, Fusion New Materials and Copprint (leading paste formulation development), while UNSW defined performance specifications, conducted integration and validated reliability. Initial pilot production batches have confirmed compatibility with existing flatbed screen-printing lines and soldered interconnection processes.

Sustained investment delivers industry ready results

The progression of this breakthrough reflects coordinated national investment. Early-stage modelling and

development were supported by ACAP, enabling the team to propose a roadmap towards 5 mg/W and 2 mg/W silver consumption for industrial screen-printed silicon solar cells, and to investigate a hybrid plating/printing approach which achieved up to 40% relative reduction in finger silver consumption (although this was not the main approach to achieve ultra-low silver consumption targets).[3]

Later, work focusing on silver reduction using a screen-printing approach was supported by an ARENA Transformative Research Accelerating Commercialisation (TRAC) grant, enabling the team to realise up to 85% reduction in rear-side silver consumption, without sacrificing cell efficiency and a path to overall silver consumption as low as 2 mg/W, which is required for sustainable multi-terawatt manufacturing.[1][2]

Together, this layered funding model demonstrates how strategic public investment can anticipate a global supply constraint and deliver an industry-ready solution before it limits deployment.

The next phase (2026–2027) focuses on industrial optimisation, Tier-1 pilot production and commercial licensing – positioning silver-lean metallisation as a pathway to cost-competitive, resource-efficient solar manufacturing at global scale. ■

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Manufacturing and Sustainability

Program
Package 5



Technical Program Lead
Dr Chris Fell
CSIRO Energy

Global PV manufacturing continues to expand year-on-year, with close to 1 TW of production expected in 2026.

However, its reliance on critical and finite materials, energy-intensive production processes, and complex international supply chains poses increasing risks to both cost and resilience to achieve the 3 TW annual production needed by 2050. At the same time, the industry must prepare for the wave of end-of-life modules emerging from the first generation of large-scale PV installations.

Program Package 5 (PP5) focuses on these critical aspects and aims to develop solutions that enable terawatt-scale manufacturing and deployment that are both sustainable and affordable. PP5 therefore spans the full PV lifecycle for a TW scale industry; from input material supply and module fabrication through to system design, reuse, recycling, and techno-economic analysis.

Key challenges

The key challenges include (1) material availability, (2) manufacturing sustainability, (3) supply chain security, and (4) circularity, all of which must be addressed to achieve ultra low-cost, low-impact solar power at the scale required for Australia's and the world's clean-energy transition.

Dr Michelle Vaqueiro Contreras co-led a study into polysilicon production in Australia.



Solution pathways

1. **Sustainable manufacturing:** Identifying critical material bottlenecks and developing technology roadmaps to enable terawatt-scale production. Research targets metallisation, interconnection, and framing approaches that reduce reliance on scarce elements such as silver, indium and bismuth, and on energy-intensive materials such as aluminium and glass.
2. **Techno-economic and life-cycle analysis:** Providing a quantitative basis for decision-making across ACAP, linking laboratory innovation to real-world cost, energy, and environmental impacts.
3. **Local manufacturing and supply-chain analysis:** Evaluating opportunities and risks for domestic manufacturing, including economic, social, and ethical dimensions.
4. **Performance analysis and optimisation:** Measuring and modelling in-field performance of modules in Australian conditions to maximise lifetime yield and reliability.
5. **End-of-life management:** Diagnostics, logistics, and technology development to reduce barriers to reuse, repair, and recycling.
6. **Novel characterisation:** Developing advanced diagnostic tools to assess manufacturing quality and system performance, feeding data back into design and optimisation loops.

Key progress

Low-emissions manufacturing pathways

Reducing embodied carbon in PV systems remains one of the most effective routes to lower lifecycle cost and environmental impact. In 2025, PP5 teams analysed the effects of decarbonising key inputs such as electricity supply, aluminium and steel production, and silver consumption. Modelling showed that using low-emission metals and renewable electricity throughout the supply chain could halve total manufacturing emissions.

This research was presented internationally, highlighting how upstream material choices influence both emissions and system performance. Ongoing collaborations with industry partners are extending the work towards practical measures such as aluminium-lean module frames and reduced-copper interconnects.

These outcomes underpin ACAP's broader objectives for lowering module and system cost through smarter, cleaner manufacturing. By demonstrating tangible pathways to reduce emissions intensity without compromising performance, the work advances Australia's ability to deliver sustainable, ultra-low-cost PV manufacturing.

Techno-economic and life-cycle modelling

Sound policy and investment decisions rely on robust models of cost and environmental performance. During 2025, PP5 researchers refined a suite of techno-economic and life-cycle analysis tools to evaluate both emerging and established PV technologies.

A collaboration between UNSW and ANU produced updated assessments of metallurgical-grade silicon production in Australia, identifying how local manufacturing could compete globally while cutting embodied emissions.

Complementary analyses examined silicon–perovskite tandem architectures to determine the cost and durability thresholds needed for commercial viability. In parallel, detailed life-cycle studies of waste-glass recycling compared multiple recovery routes, from mechanical re-melting to chemical purification.

Together, these efforts enhance ACAP’s analytical foundation for guiding R&D and policy towards the lowest-cost, lowest-impact solar energy. They support the program’s commitment to improved yield and performance modelling, and to techno-economic frameworks that accelerate innovation across the sector.

Building Australia’s solar supply chain

Australia’s future solar economy depends on secure, efficient supply chains. In 2025, PP5 partners contributed to major national and international studies that assessed opportunities for local production of key PV materials.


Through participation in the Energus – Australian Silicon Study (ARENA Sunshot), ACAP researchers helped evaluate the feasibility of a 50,000 tonne per year polysilicon plant in NSW (see case study [“Examining feasibility of green polysilicon production in Australia”](#)).

In parallel, collaboration on a confidential initiative explored routes for “green polysilicon” production with lower carbon intensity. Further engagement with the European-based Becquerel Institute provided comparative insights into how policy and cost structures influence PV manufacturing competitiveness overseas.


These collaborations position Australia to engage strategically in upstream manufacturing while sharing global knowledge on sustainable industrialisation. They contribute to ACAP’s goal of strengthening domestic capability, fostering industry partnerships, and reducing the capital and operating costs associated with PV supply chains.

Sustainable interconnection technologies

At the device level, PP5 achieved significant progress toward reducing material intensity in module interconnections. Laboratory experiments confirmed reliable tin–bismuth alloy formation at low temperatures using less than 10 milligrams of bismuth per watt of module output – over 90 percent less than conventional solders. The process proved compatible with advanced cell architectures, including HJT, TOPCon, and perovskite–silicon tandems.



Module design and materials innovation can simultaneously cut costs and environmental footprint.




By lowering both temperature and material demand, the approach offers a scalable path to greener, high-efficiency module assembly. It demonstrates how design and materials innovation can simultaneously cut costs and environmental footprint.

This work advances ACAP’s aims in sustainable manufacturing by delivering new metallisation and interconnection techniques that reduce reliance on scarce elements while maintaining industrial performance standards. It represents a practical step towards lower-cost, lower-impact solar cell production at scale.


Circularity and end-of-life innovation

Circular design and recycling technologies form another core pillar of PP5. In 2025, researchers developed a new conceptual framework for measuring circularity in PV systems and simultaneously advanced recycling processes from laboratory to market.

The revised Material Circularity Indicator (rMCI) and new Energy Circularity Indicator (ECI) provide a more complete understanding of how PV systems retain value. By recognising that modules generate energy over their lifetime, the framework captures benefits that traditional mass-flow analyses overlook. Published in *Cell Reports Physical Science*, the work offers a foundation for designing truly circular solar technologies that balance material and energy efficiency.



Researchers are developing algorithms to predict the remaining service life of solar panels, reducing waste and supporting second-life solar markets.



At the same time, ACAP-supported laser-induced delamination technology progressed to commercialisation through the UNSW spinout Hello Again Solar. Patents were filed, industry partners secured, and module trials completed. Lessons learnt led to a technology pivot and a commercialisation plan that attracted seed funding, demonstrating how research can translate directly into industrial impact.

These combined advances strengthen ACAP's contribution to sustainability and resource recovery. They ensure that end-of-life management, recycling, and circular-economy principles remain embedded within Australia's approach to low-cost solar manufacturing.

Re-use and second-life applications

As increasing numbers of PV systems reach the end of their first life, the ability to evaluate and redeploy used modules becomes essential. In 2025, PP5 initiated work to quantify residual useful life through automated analysis of performance data and imaging.

Using the largest dataset created worldwide so far of current-voltage curves and electroluminescence images for used modules, researchers began developing algorithms capable of predicting remaining service life. The aim is to integrate this automation into field testing equipment, enabling rapid triage of modules for reuse, recycling, or disposal.

This effort underpins ACAP's broader objectives for sustainability and performance optimisation. By establishing evidence-based criteria for safe module redeployment, the project supports circularity, reduces waste, and improves the economics of second-life solar markets.

Improving PV yield and operational modelling

Accurate prediction of long-term energy yield is vital for investment confidence and efficient operation of solar farms. PP5 researchers in 2025 advanced both physical and AI-assisted models to improve predictive accuracy and fault detection.

PP5 is driving down the levelised cost of electricity while fostering new Australian technology enterprises in the solar sector.

Enhanced thermal and electrical simulations now account for site-specific shading, transient temperature effects, and radiative exchange. A proof-of-concept tracking algorithm demonstrated reduced thermal loads and improved operational efficiency. Parallel studies introduced new metrics for UV exposure and its influence on degradation, providing better inputs for lifetime performance modelling.

Two commercial spinouts, P2AgentX and Foresight PV, emerged from this research, developing interactive analytics and physics-based modelling tools for asset owners.

Through these developments, PP5 directly supports ACAP's goals of improved characterisation, modelling, and yield analysis. The results help drive down the levelised cost of electricity while fostering new Australian technology enterprises in the solar sector.



Case study



Examining feasibility of green polysilicon production in Australia

The Australian Silicon Study (AusSi) has identified that a 50,000 tonnes per annum solar-grade polysilicon facility represents the minimum commercially viable scale for production in Australia – aligned with projected global demand of approximately 1.2 terawatts of new solar PV installations annually by 2030.

Funded by the Australian Renewable Energy Agency (ARENA) under the Solar SunShot Program, AusSi assesses the technical, commercial, and investment feasibility of establishing a large-scale polysilicon facility within the Hunter-Central Coast Renewable Energy Zone, powered by low-emissions renewable electricity.

ACAP's Dr Michelle Vaqueiro Contreras is contributing, building on her role in the 2024 APVI Silicon to Solar (S2S) study[1], which identified polysilicon as the most strategically relevant upstream segment of the solar PV value chain for Australia to consider. Today, more than 95% of global polysilicon production is concentrated in China. It is also the most energy-intensive and emissions-intensive stage of solar module manufacturing, with electricity costs driving both production economics and carbon intensity.

Australia has abundant renewable energy resources and an established metallurgical-grade silicon industry producing approximately 52 kilo tonnes annually. This presents a tangible opportunity to move beyond raw material exports and into higher-value manufacturing aligned with long-term decarbonisation and supply chain diversification.

AusSi moves beyond high-level supply chain mapping to rigorously test commercial viability. The study examines global market accessibility, price expectations, technology selection, plant scale optimisation, material flows, regulatory requirements, and detailed capital and operating expenditure modelling.

Polysilicon is the most strategically relevant upstream segment of the solar PV value chain for Australia.

AusSi tests whether renewable-powered manufacturing can underpin regional economic transition.

The brand-new control room at the Asia Silicon polysilicon production plant. Asia Silicon is providing critical access to current industrial data on state-of-the-art polysilicon production to the AusSi Study.

Technology assessment has identified the Siemens process as the most appropriate initial pathway, given its technical maturity, product quality profile, and compatibility with premium and traceable supply markets.

Polysilicon chemical vapour deposition (CVD) reactors represent the core unit operation in the Siemens polysilicon process. This stage accounts for more than 70% of total process energy consumption and is responsible for achieving the ultra-high purity deposition required for electronic and solar-grade polysilicon.

The work is led by Energus and delivered by Bright Dimension and ACAP as key analytical contributors, in partnership with world-leading polysilicon producer Asia Silicon, energy provider AGL, and engineering advisory firms across Australia and China. This collaboration ensures that industrial cost data and execution insights underpin the techno-economic assessment.

Asia Silicon in the Qinghai province, China, is one of the top five polysilicon producers in the world and a critical enabling partner for AusSi’s techno-economic analysis of a poly-plant in Australia. Asia Silicon provides access to current industrial data on state-of-the-art polysilicon production, including process configuration, capital intensity, operating cost structures, and material balance parameters within a global supply base that is highly concentrated in China.



Chemical vapour deposition (CVD) reactor hall used for the production of polysilicon. These large-scale reactor arrays deposit high purity silicon from vaporised trichlorosilane in hydrogen atmosphere onto heated silicon rods, forming the core step of the Siemens polysilicon production process. (Photo: Asia Silicon)



High purity crystalline silicon produced by the Siemens method courtesy of Asia Silicon, an industry partner of the AusSi Study. Polysilicon for the semiconductor and photovoltaic industries is among the purest human-made materials ever produced, with purity levels reaching 6 N to 11 N.



Now in its final phase, the AusSi study is refining capital and operating expenditure estimates and conducting sensitivity analysis across key cost drivers to determine overall investment feasibility. Findings will be synthesised in a public knowledge-sharing report expected to be released in 2026.

As lead ACAP contributor to the study, Dr Michelle Vaqueiro Contreras notes, “Polysilicon sits at the upstream heart of the solar industry. If Australia can competitively produce it using low-emissions renewable power, it would demonstrate that we can move beyond exporting energy and instead export the materials that enable the global energy transition. This study is about testing that proposition with rigour.”

For Australia, one of the world’s largest fossil fuel exporters, AusSi tests whether renewable-powered materials manufacturing can underpin regional economic transition while strengthening global solar supply chain resilience. ■

References

[1] Watt, M., Vaqueiro Contreras, M., Egan, R., Chang, N., Hartley, O., Rayward-Smith, W., Walden, M., Boylan, E., Thoran, A., Malbrain, C., Hallam, B., (2024). *Silicon to Solar Study*. Australian PV Institute.

Case study



Advancing solar farm diagnostics with daylight photoluminescence imaging

In 2025, UNSW's Daylight Photoluminescence (DPL) Imaging Group, led by Professor Thorsten Trupke and Dr Oliver Kunz, with ACAP support, continued to drive their drone-based imaging solutions which have great potential to transform how solar farms are assessed, monitored, and maintained.

Their pioneering DPL technology allows operators to 'see' hidden defects in solar panels in broad daylight, providing rapid, high-resolution diagnostics – that were previously only possible under controlled laboratory conditions or via measurements at nighttime.

Demonstrating automated drone-based DPL field inspection

Major progress has been made towards automated, field-deployable inspection systems. The team delivered successful demonstrations at Australian utility-scale solar farms, in conjunction with industry partner Gentari Solar Australia.

Substantial progress was demonstrated towards drone-based DPL imaging that combines automated pre-programmed flight paths with synchronised inverter switching. This is a significant step towards routine, low-cost, aerial inspection of large solar sites.

The group's drone inspection capabilities were demonstrated internationally during an on-site trial with US industry partner GAF Energy at its California headquarters, as well as in a customised residential setting.



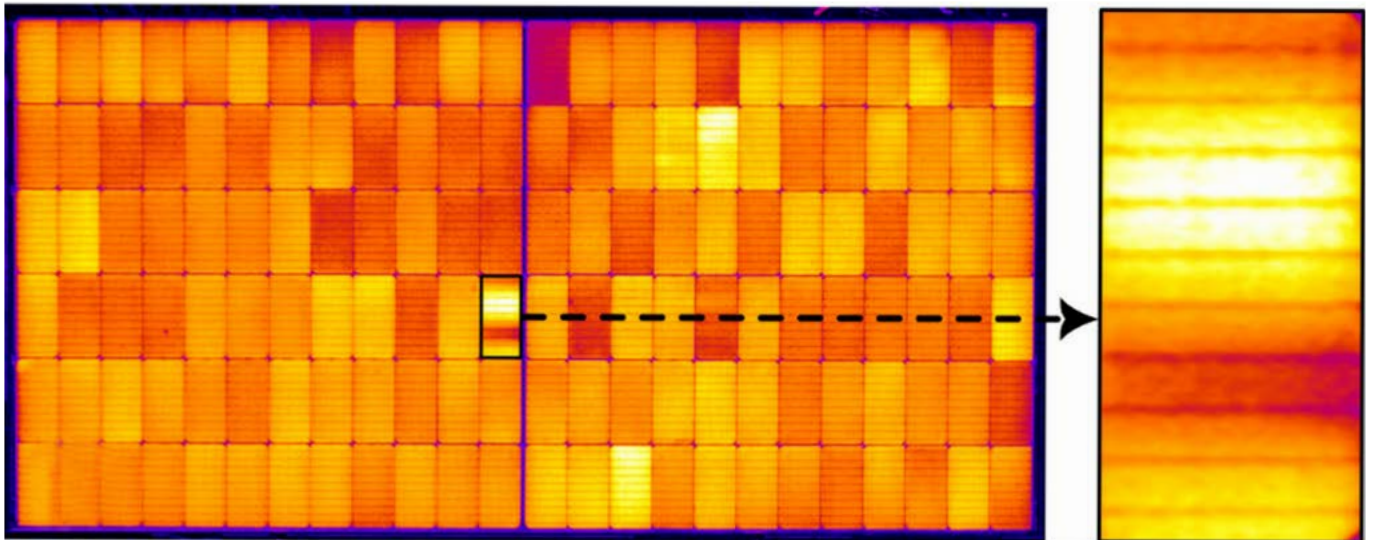
PL imaging specialist Juergen Weber, testing the DPL-equipped drone over a solar farm in Victoria. The ACAP supported team are developing DPL imaging of solar farms for routine, high-resolution, low-cost aerial inspection of large solar sites.

Advancing DPL image analytics and processing

The group also welcomed Dr Ryan Hall, who is driving advances in real-time image processing, including distortion correction and automated image registration, bringing the technology closer to commercial-grade performance.

Among the year's scientific milestones was the completion of a new method to quantify power losses caused by series resistance directly from DPL images – published in *Progress in Photovoltaics*[1], and securing an Australian Economic Accelerator (AEA) grant to accelerate the development of image analytics.

Series resistance problems are common in solar panels and occur when ageing contacts and cell interconnections make it harder for electric currents to flow. This reduces the panel's power output and often signals deeper wear and tear. Spotting these issues early helps explain and quantify performance losses.



DPL image of a solar module with partial current extraction, featuring a cell with a distinctive series resistance defect. The UNSW DPL team has developed a new method to quantify power losses caused by series resistance directly from DPL images.

Commercial DPL inspection services launched

Lab 360 Solar, a UNSW spinout developing DPL imaging systems and commercial inspection services (on-site inspections, quality assessments), was established in 2024 and began active operations in 2025, securing ARENA and NSW Government support and moving into new premises in Surry Hills.

ACAP's sustained backing has been central to this progress, supporting staff time, early equipment purchases and the stable environment needed to progress DPL imaging from a laboratory idea to a field-proven, globally recognised innovation. ■

Reference

[1] Gottlieb, H., Kunz, O., Weber, J., Ouyang, Z., Trupke, T., (2025). Power Losses From Series Resistances—Analysed Using Daylight Photoluminescence Imaging. *Progress in Photovoltaics: Research and Applications* 33(11), 1247–1259, <https://doi.org/10.1002/pip.70022>

Case study



Hello Again Solar – commercialising solar recycling

The patented delamination process separates and recovers all major materials - glass, silicon, silver, copper and polymer - with high purity outputs.

As solar deployment accelerates across Australia and globally, a new challenge is emerging: what happens to panels at end-of-life? Millions of modules are already being retired each year in Australia alone, with volumes projected to increase dramatically by 2050. Without effective recycling, valuable materials – silicon, glass, silver, and copper – are lost to landfill, increasing the resource and cost burden of future PV production.

ACAP-supported research is now turning that challenge into an opportunity.

Dr Rong Deng, Lecturer at the UNSW School of Photovoltaic and Renewable Energy Engineering and founder of Hello Again Solar, has spent eight years developing a new approach to solar panel recycling. For much of that time, end-of-life management was viewed as a distant issue. With gigawatts now installed nationwide, it is no longer theoretical – it is urgent.

The team has developed a patented, laser-based delamination process that separates and recovers all major materials – glass, silicon, silver, copper, and polymer – without shredding, harsh chemicals or high temperatures. The process produces high-purity outputs that are more valuable and easier to reprocess, shifting recycling from a cost burden to a value opportunity.

By enabling high-yield, low-cost material recovery, the technology supports a circular solar economy, strengthens supply security and reduces the lifecycle environmental footprint of photovoltaics.

In 2025, the formation of Hello Again Solar marked a major milestone in translating ACAP research into commercial impact. During the year, Rong Deng and team members Zibo Zhou and Matthew Murphy advanced the technology from proof-of-concept towards mini-module trials with industry partner Nutown Technologies. International patent filings have been lodged across major PV deployment countries, while early engagement with private investors is building momentum towards scale-up.



Matthew Murphy speaking to Hon. Penny Sharpe, Minister for Climate Change, Energy and Environment and Heritage in NSW on Hello Again Solar's technology at NSW Parliament House, September 2025

“
Our technology is ready to leave the lab, Australia has real volumes of retired panels, and government support is stronger than ever.
”

Reflecting on the journey, Dr Deng says: “I have spent eight years waiting for this moment – waiting for a technology capable of turning solar recycling from a cost burden into a value opportunity, waiting for the market to mature, and waiting for policy to catch up. Now the pieces have aligned.

“Our technology is ready to leave the lab, Australia is seeing real volumes of retired panels, and government support is stronger than ever. After years of saying ‘one day’, it feels very good to finally say: the day is here.”

Technology development continues with support from ACAP, providing the scientific foundation for commercial expansion. The company has also raised the profile of UNSW and ACAP through participation in high-level forums, including the UNSW Sustainability Showcase at NSW Parliament and the UNSW Investor Showcase, strengthening investor confidence and positioning the venture for further private and competitive grant funding.



The Hello Again Solar team at the UNSW Investor Showcase. (l-r) Dr Rong Deng, Matthew Murphy and Dr Zibo Zhou.

For ACAP, this project demonstrates how sustained research investment can catalyse not only technological innovation but also the emergence of a new circular industry, ensuring that solar remains not only clean but truly sustainable. ■

PV Futures and Knowledge Sharing

Program
Package 6



Technical Program Lead
Professor Kylie Catchpole

ANU

Program Package 6 (PP6) focuses on bridging PV research with real-world impact through technology foresight, industry engagement, commercialisation, and knowledge dissemination.

Building on ACAP's established strengths in collaborative research, communication and knowledge sharing, PP6 aims to extend the influence of PV innovation beyond the laboratory by increasing engagement with industry, government, and the broader community, raising the profile of research outcomes, and contributing to public discourse, while supporting the transition towards ultra-low-cost PV. stem design, reuse, recycling, and techno-economic analysis.

Key challenges

The PV Futures program targets the translation of the technology success in ultra-low cost solar to the end goal of low-cost electricity. The program challenges include (1) technology transfer – taking ideas from the lab to manufacturing, (2) reducing systems, deployment, and integration costs, (3) scenario mapping for economies powered predominantly by solar and (4) engaging with industry, policy makers, and community on the energy transition.

Prof Martin Green talks to media at China International Photovoltaic and Energy Storage Industry Conference in November in Chengdu, China.



Solution pathways

1. **PV futures:** translating ultra low-cost solar panels to low-cost electricity through siting and optimal integration.
2. **PV in emerging applications:** addressing the opportunities, needs, and synergies that arise in different sectors with the falling cost of solar.
3. **Collaboration and commercialisation:** translating and scaling technical achievements.
4. **Knowledge sharing:** accelerating the development and growth of Australia's renewable energy sector.

Key progress

1. PV futures

The wholesale price of solar panels is now below A\$0.15 per watt. This corresponds to about 10% of the levelised cost of solar electricity (LCOE). Balance-of-system costs incurred by solar farm developers and rooftop installers include transport, system design and approvals, site preparation, support structures, interconnection, and power electronics. Grid integration adds about 50% to the levelised cost of solar electricity at the solar farm or solar rooftop level, and includes transmission & distribution, storage (pumped hydro & batteries), and curtailment of output when the grid is congested, or demand is low.

Solar heatmaps

Optimum placement of solar farms is required to achieve ultra low-cost solar electricity. Given the difficulties of building new transmission infrastructure arising from delayed approvals and social pushback, it is important to take full advantage of existing transmission. Additionally, local storage can substantially reduce transmission requirements by ensuring that existing transmission operates with a high duty cycle for most hours of the year.

The heatmaps project examines optimal locations for solar farms at a resolution of 250 m, taking into account the local solar resource, protected and unsuitable land, distance to existing or approved transmission, aspect, slope, and availability of large-scale pumped hydro and battery storage. Landholders, local and state governments, and solar farm developers can inspect the [online maps](#) to identify optimal locations for solar farms.

Results are aggregated to all 547 Local Government Areas (LGAs) and 150 federal electorates and expressed as capital inflow, construction job-years, long-term jobs, and land-lease income.

The ANU team found that Class A solar sites (< \$50 /MWh) are abundant across Australia. Just 15% of LGAs, mainly within 100 km of the existing 275–500 kV transmission backbone, can host over half of the least-cost capacity. A single top-ranked LGA such as Toowoomba (Queensland) could attract around A\$33 billion in investment and sustain over 50,000 construction job-years. The results bridge the gap between state-level renewable energy zones and fine-scale site suitability maps.

Pumped hydro energy storage

The ANU global [Pumped Hydro Storage Atlases](#) have become an essential tool for governments and developers around the world as they consider large-scale storage to complement solar and wind deployment. With strong support from the Department of Foreign Affairs and Trade, ANU has been particularly active in engaging with senior energy officials from ASEAN countries as they contemplate a transition away from coal and gas, towards low-cost solar backed up by pumped hydro and battery storage. Read more in the case study, "[Global atlas of potential pumped hydro energy storage sites informs national renewable energy strategies](#)".

2. PV in emerging applications

The project 'Energy yield forecasting of agrivoltaic systems' investigates how solar energy generation and agricultural productivity can be optimised in agrivoltaic systems. A state-of-the-art solar irradiance measurement system has been installed at the University of Melbourne's Dookie Campus to support research on agrivoltaics. The project aims to quantify bifacial module performance and crop light availability in agrivoltaics, and supports research on solar resource dynamics, shading, and crop microclimates. In 2025, the project successfully deployed and commissioned an irradiance monitoring system at the Dookie Campus vineyard. The equipment is co-located on a ground-mounted reference PV system and the agrivoltaic array in the research vineyard, enabling side-by-side comparisons under identical environmental conditions. The installation will collect datasets capturing the seasonal and environmental variations in irradiance, albedo, and temperature. Initial results show that the vineyard modules operate at significantly lower temperatures compared to the reference modules and benefit from substantially higher rear-side illumination.

3. Industry partnerships and commercialisation

ACAP continues to cultivate and expand strategic industry research partnerships that are closely aligned with its mission, fostering collaborative innovation to advance the development, commercialisation, and global leadership of Australian photovoltaic technologies, while accelerating progress towards ACAP's goals.

In 2025, ACAP strengthened its position as a leading platform for collaboration between research and industry, with substantial progress achieved in both partnerships and commercialisation. A key milestone was the expansion of the ACAP Industry Consortium, with seven tier-one global solar manufacturers now committed to the consortium. Their involvement has reinforced ACAP's international standing and created new opportunities for collaborations that bridge fundamental research with large-scale industrial deployment.



JA Solar is a Platinum Partner of the ACAP Industry Consortium, with substantial research projects. JA Solar delegates met with UNSW SPREE Head of School Professor Ned Ekins-Daukes, ACAP founder Professor Martin Green, Dr Jessica Jiang and others on a visit to UNSW.

Two of our consortium partners have followed with substantial research project activity, including six research projects with JA Solar, totalling A\$3 million and one A\$4 million project with AIKO Solar. Read more about the Consortium in the Highlights section.

Collaboration has also broadened across both domestic and international partners, with established industry collaborators such as SunDrive, Nutown Lasers, Delphi Lasers, and Teraenergy. In addition, ACAP has established new collaborations through project funding with partners including Jinko Solar, FuturaSUN, PV Lab Australia, Arradinance Ltd, Nanoprint Innovation Ltd, and Risen Energy, further broadening the scope and diversity of its industrial engagement. Initial discussions with other potential partners present an opportunity to collaborate on large-scale projects and commercial demonstrations of emerging technologies.

ACAP has initiated an important industry collaboration on the commercialisation of large-scale, perovskite thin film and tandem research technologies. UNSW-ACAP has received a number of large-scale perovskite-based modules from commercial manufacturers for outdoor testing, performance, reliability, and fault analysis. Partners remain commercial in confidence.

Working closely with partners across ACAP ensures that research not only advances scientific knowledge but also delivers practical solutions that address critical challenges in cost, efficiency, and durability.

Commercialisation activities have gained momentum through multiple channels. By providing a platform for research support and capability building, ACAP supports many projects along the commercialisation pathway, including those in ARENA's Transformational Research Accelerating Commercialisation (TRAC) program, some of which were seeded under ACAP.

In addition, ACAP has supported entrepreneurship and collaboration through the Empowering Emerging Leaders in Clean Energy (ELICE) program, which provides early-stage innovators with mentorship, networks, and opportunities to advance their technologies towards market readiness. Read more about ELICE in the Highlights section of this report.

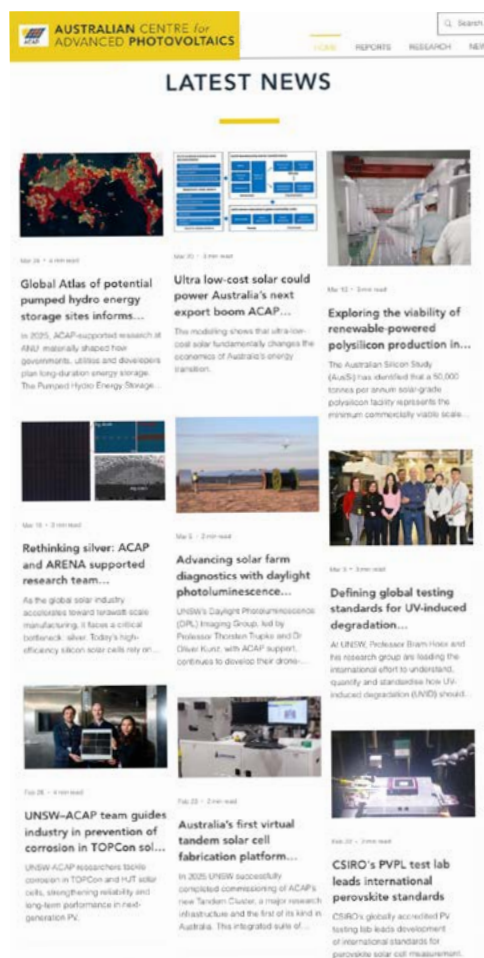
Building on past commercial outcomes (including start-ups Open Instruments Pty Ltd, Lab 360 Solar Pty Ltd, and Green Dynamics Pty Ltd) in 2025, ACAP saw the founding of recycling technology start-up Hello Again Solar Pty Ltd, which was also successful in securing support from the Trailblazer TRaCE. See case study, "[Hello Again Solar - Commercialising solar recycling](#)".

4. Knowledge sharing

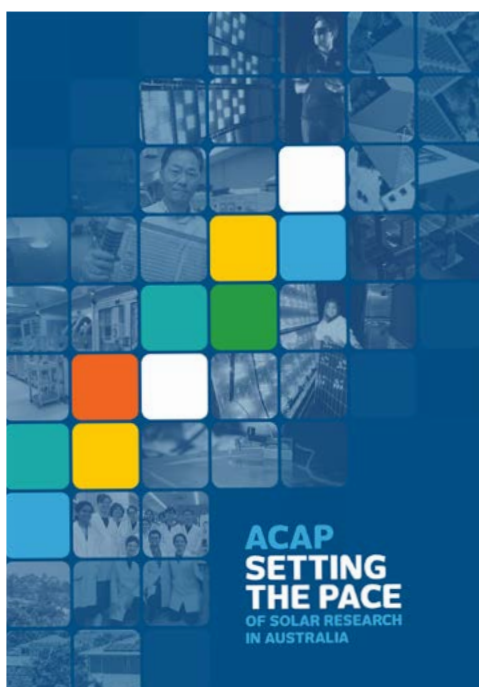
ACAP members engage widely to promote knowledge of the opportunities and successes of Australian PV research. We aim to add to the global body of knowledge, engage the next generation of researchers, and share insights with a broad audience spanning industry, government, and the public.

This is achieved through a wide range of activities, including events and public lectures; hosting the ACAP and Asia-Pacific Solar Research Conference; presenting at conferences and plenary sessions; running symposia and collaborative workshops; contributing to policy discussions; engaging with media, newspaper and magazine articles; sharing news via our website and LinkedIn; and facilitating visits and exchanges.

Communications



ACAP's website News page.



Setting the Pace of Solar Research in Australia reported on highlights from 2023-2025.

In 2025, the ACAP blog (<https://www.acap.org.au/blog>) delivered a weekly stream of stories showcasing the breadth of ACAP's research, capabilities and activities. Written for non-technical audiences, these concise updates connect cutting-edge science with real-world outcomes, illustrating how ACAP researchers, breakthroughs and innovations are shaping the future of low-cost, scalable solar energy.

Blog content and other news items are shared with ARENA and industry media (including *PV Magazine*, *PV Tech*, *Renew Economy*), and amplified through the ACAP LinkedIn page, which reached 2,000 followers at the end of 2025 (50 of whom are climate, energy and solar industry media professionals). With an average of one blog post and 2-3 LinkedIn posts per week over 2025, ACAP has cultivated an effective and efficient platform for knowledge sharing that reaches a diverse domestic and global audience.

In 2025, ACAP published a public dissemination report, *Setting the Pace of Solar Research in Australia*, highlighting key achievements from 2023-2025, and its Annual Report transitioned to a more accessible story-driven format, away from the academic style of previous years.

Major events

The 2025 ACAP Conference at UQ in Brisbane in December had record attendance numbers (over 110 registrations) and was delivered in partnership with the Australian Photovoltaic Institute's Asia Pacific Solar Research Conference (APSRC). ACAP was an official sponsor of the APSRC event, which was chaired by UQ Node Lead Associate Professor Paul Shaw, and ACAP research and people had a strong showing across the program. ACAP's exhibition table at the APSRC showcased our research programs and created space for questions and discussion, raising ACAP's profile among attendees.



Prof Renate Egan presenting at the ACAP Conference.



Attendees at the ACAP Conference at UQ.

Michelle Vaqueiro Contreras (UNSW),
Zi Ouyang (CTO of JA Solar), Renate Egan
(ACAP), and Nathan Chang (UNSW) at the
APSRC, UQ, December 2025.

Beyond these flagship events, ACAP also contributed to national engagement through sponsorship of the Australian Community for Advanced Organic Semiconductors Symposium; delivery of 22 lectures through the UNSW SPREE lecture series, and participation in the ANU Solar Oration.





Prof Dan Macdonald delivered a plenary presentation at the IEEE PV Conference in Montreal.

ACAP on the global stage

Throughout 2025, ACAP maintained a strong presence on the global stage. Professor Dan Macdonald delivered a plenary presentation at the IEEE PV Specialists Conference in Montreal on advancing silicon solar cell efficiency towards 27% in mass production. Professor Bram Hoex delivered a plenary presentation on the progress of the UVID testing standard at EU PVSEC 2025. Professor Andrew Blakers presented an opening plenary at the International Forum on Pumped Storage Hydropower in Paris, alongside global leaders in energy and policy. Professor Martin Green continued his international leadership as Honorary Chair of SNEC, the world's largest solar PV conference, and a member of its Advisory Board.

Prof Bram Hoex delivers a plenary presentation on the UVID testing standard at EU PVSEC 2025. Credit: EU PVSEC



Recognition through prestigious awards

ACAP researchers continued to win prestigious awards and international recognition, highlighting the global impact and strength of ACAP's research pipeline and ACAP's role in developing future leaders in solar energy.

Professor Martin Green received the Faraday Medal from the UK Institution of Engineering and Technology, its highest honour. Prof Green was also awarded the 2025 Goswami Prize from the US National Academy of Inventors. Emeritus Professor Andrew Blakers of ANU was appointed Officer of the Order of Australia for his distinguished service to solar cell development and advocacy for renewable energy and storage.

Associate Professor Heping Shen received the Stuart R. Wenham Young Professional Award at the 53rd IEEE PV Specialists Conference in Montreal, Professor Anita Ho-Baillie was awarded the Eureka Prize for Sustainability for her leadership in next-generation solar cells, and the NSW Premier's Prize for Excellence in Mathematics, Earth Sciences, Chemistry or Physics.

Maysa Sarsour won the EUPVSEC Student Award in Bilbao, Spain



Charlotte Fell was awarded the ANU University Medal for Engineering.



Emerging researchers within ACAP have also achieved significant recognition. Dr Guoliang Wang received the University of Sydney Faculty of Science Outstanding PhD Thesis Award; Ms Charlotte Fell was awarded the ANU University Medal for Engineering. Maysa Sarsour won the EUPVSEC Student Award in Bilbao, Spain, and Zhiwen Zheng was recognised with the Best Student Presentation Award at the IEEE PV Specialists Conference in Montreal.

And in January, ACAP Executive Director Prof Renate Egan and Prof Martin Green joined Jo Haylen, NSW Minister for Transport, NSW Premier Chris Minns and Howard Collins, Coordinator-General for Transport for NSW, for the launch of the new Martin Green River Class Sydney Ferry.

These awards highlight the global impact and strength of ACAP's research pipeline and ACAP's role in developing future leaders in solar energy.

Zhiwen Zheng received the Best Student Presentation Award at the IEEE PV Specialists Conference in Montreal.

Launching the new Martin Green ferry were (l-r): Jo Haylen, NSW Minister for Transport, Prof Martin Green, NSW Premier Chris Minns and Howard Collins, Coordinator-General for Transport for NSW.



Engaging with partners and stakeholders

Professor Martin Green gave an introduction to the Industry White Paper on Back Contact Technologies, while Professor Andrew Blakers and ANU collaborated with the Department of Foreign Affairs and Trade on solar, wind, and pumped hydro opportunities.

ACAP's regular International Advisory Committee meetings bring together researchers and industry to discuss progress in ULCS technology development. In August, the Centre convened its first National PV Roundtable, chaired by Adrian Turner of 5B, with the aim of positioning ACAP as Australia's leading technology reference group for solar cells and modules, and to identify opportunities to strengthen the domestic PV value chain.

Earlier in the year, Dr Shukla Poddar participated in Science Meets Parliament in Canberra, and independent MP Allegra Spender visited UNSW's Solar Industrial Research Facility to engage directly with ACAP researchers on solar innovation and commercialisation, including advances in solar panel recycling.

Driving research collaboration across the nodes

ACAP also continued to foster collaboration across its research nodes through targeted workshops and symposia. The Perovskite Stability Workshop provided a platform for open collaboration and strategic planning to accelerate the commercial readiness of perovskite solar cells, while the Characterisation Mini-Symposium enabled researchers to share results, challenges, and solutions in a collaborative setting.



Allegra Spender MP for Wentworth and Prof Martin Green tour UNSW's Solar Industrial Research Facility.

Case study



How large is the industrial opportunity when solar becomes ultra low-cost?

Using innovative system-level energy modelling, ACAP researchers from ANU and UNSW have shown that ARENA's 30-30-30 ultra low-cost solar (ULCS) target has the potential to achieve rapid economy-wide decarbonisation and unlock new export industries in Australia that are not yet cost-competitive at current energy prices.

The collaborative project is the first integrated modelling to quantify the full industrial and export opportunity created by ultra low-cost solar at a national scale. It is led by Professor Kylie Catchpole (ANU) and Professor Andrew Blakers (ANU), with key contributions from Dr Bin Lu (ANU), Dr Nathan Chang (UNSW) and Dr Simao Lin (UNSW).

ANU developed an integrated modelling framework to examine economy-wide decarbonisation and electricity market transformation, while UNSW contributed techno-economic analysis of green industries.

ULCS could support national energy systems delivering 1,000 TWh/year for domestic use and 2,600 TWh/year for export, creating a 2,000 GW-scale PV market in Australia. This is the scale required to power a fully decarbonised economy while enabling large-scale production of green metals for global markets.

Dr Lu said, "The magnitude of the opportunity revealed by the analysis is very exciting.

"Used smartly, 2,000 GW of solar PV could power a fully decarbonised domestic economy and support large-scale production of green metals for export – positioning Australia as a global supplier of green products while dramatically reducing national emissions."



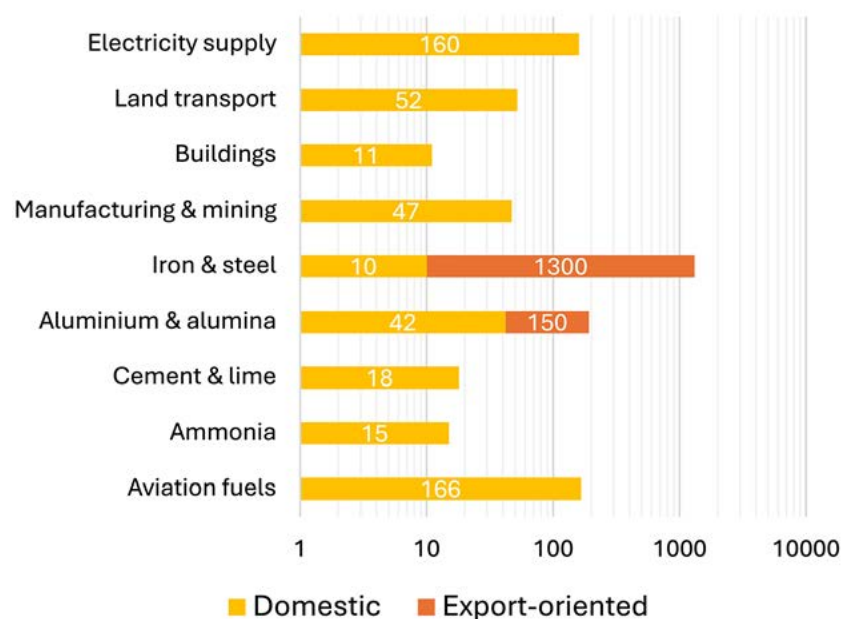
Dr Bin Lu presenting findings from modelling the economic and decarbonisation opportunities arising from ultra low-cost solar.

The modelling shows that ultra low-cost solar fundamentally changes the economics of Australia's energy transition. Under the 30-30-30 vision:

- Electricity markets can deliver reliable 100% renewable power at costs well below today's wholesale prices.
- Cost reductions flow directly into heavy industry.
- Green aluminium, ammonia, and steel production can reach cost parity with conventional production.
- Aviation electro-fuels move significantly closer to commercial viability.

The key innovation of this project is its integrated, system-level approach. Rather than treating industrial decarbonisation, electricity market transformation, and green commodity production separately, this study captures their interactions within an integrated, high-resolution modelling framework. The techno-economic modelling is conducted using the new FIRM Energy model, which evolves from an electricity-sector optimisation framework into an integrated, economy-wide energy system model that enables coordinated modelling of sectoral energy transitions.

PV market potential by sector (GW)



Ultra low-cost solar can drive economy-wide decarbonisation by supporting large-scale deployment of low-carbon technologies across sectors.

“
Cheaper renewable technologies could power Australia’s transition to a global supplier of green products.
”

The work was presented at the Asia-Pacific Solar Research Conference 2025[4], with follow-on analyses now examining electricity network transitions and export-oriented clean energy pathways.

The findings have attracted national and international media attention. *Taiyang News* and *PV Tech* reported the findings. *Renew Economy* highlighted that cheap solar, coupled with smart integration and energy, is essential to decarbonising industry.[2] In the *Canberra Times*, Bin Lu and Kate Lawrence outlined how solar-derived e-fuels could underpin a new export sector for Australia.[3]

The findings shift the national conversation from ‘How much will decarbonisation cost?’ to ‘How large is the industrial opportunity when solar becomes ultra low-cost?’

Dr Lu sums up, “Australia has abundant solar resources, and some of the world’s richest mineral reserves, such as iron ore and bauxite. Used smartly, cheaper renewable technologies could power Australia’s transition to a global supplier of green products.” ■

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Case study



ACAP's global collaborations and high-impact publications

ACAP continues to lead on international collaboration and industry engagement, shaping the direction of PV globally and at scale. In 2025, the ACAP Industry Consortium grew to seven active industry partners, and two Platinum Partners, [AIKO Solar](#)[1] and [JA Solar](#)[2], established significant research projects.

In a defining piece of work published in *Joule* titled, "[State-of-play of contending silicon photovoltaic technologies](#)"[3], ACAP Founder Scientia Professor Martin Green and senior ACAP researchers joined technical leads from ACAP industry partners AIKO, LONGi, Huasun, JA Solar and Trina Solar to provide an overview of past research, and discuss the strengths and weaknesses of competing silicon PV technologies.

These companies represent a substantial share of global module production, and the paper brings together expertise spanning both laboratory innovation and gigawatt-scale manufacturing. The collaboration highlights the depth of trust ACAP has established with the world's leading PV manufacturers.

AIKO delegates visited ACAP leaders at UNSW. In 2025 AIKO became a Platinum ACAP Industry Consortium Partner.



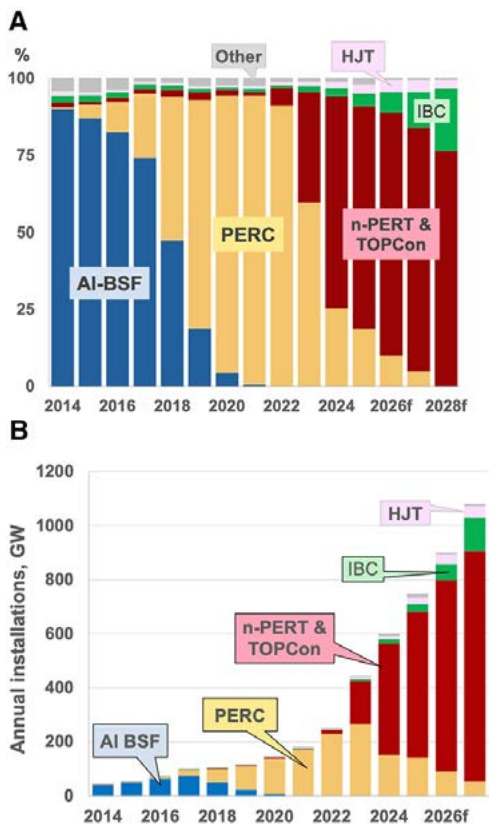


Figure from the *Joule* paper showing: (A) Past and projected market share of the different silicon solar cell technologies. (B) Total annual installation of solar modules, with breakdown by technology.

Published at a time when annual global solar installations have reached around 600 GW and silicon technologies account for more than 97% of the market, the landmark *Joule* paper traces the evolution of silicon cell architectures, from AI-BSF and PERC to today’s dominant TOPCon technologies, while critically assessing the performance, cost and manufacturability of HJT, IBC and emerging tandem concepts. Rather than advocating a single pathway, the analysis provides decision makers with a realistic framework for navigating efficiency gains, capital investment and long-term scalability.

The *Joule* publication complements an opinion piece[4] by Professor Martin Green published in the highly-prestigious *Nature Energy* in the same month, “Advances in the performance and adoption of solar photovoltaics”, as well as the global TW4 ‘think-tank’ publication on the era of multi-terawatt photovoltaics also in *Nature Energy*[5] in December 2025, with co-authors from ACAP (See case study, “ACAP leaders join global collaboration to plan multi-terawatt solar”).

Transformational technical publications

These industry-guiding, global perspectives are supported by technical publications about discovery and technology development, delivering on the ACAP mission of collaboration and knowledge sharing. These include (among others) three recent papers led by Professor Xiaojing Hao at UNSW:

- Two *Nature Energy* papers that detail world-leading efficiencies and advances in the development of antimony chalcogenide solar cells[6] and kesterite solar cells[7], both of which are promising top cell candidates for tandem devices.
- An advance article[8] published in the elite journal *Energy & Environmental Science* identifies how UV radiation damages high-efficiency silicon solar cells, which in turn is expected to help discover processes to help the cells recover using normal sunlight.

Benchmarking global progress – the “Solar Cell Efficiency Tables”

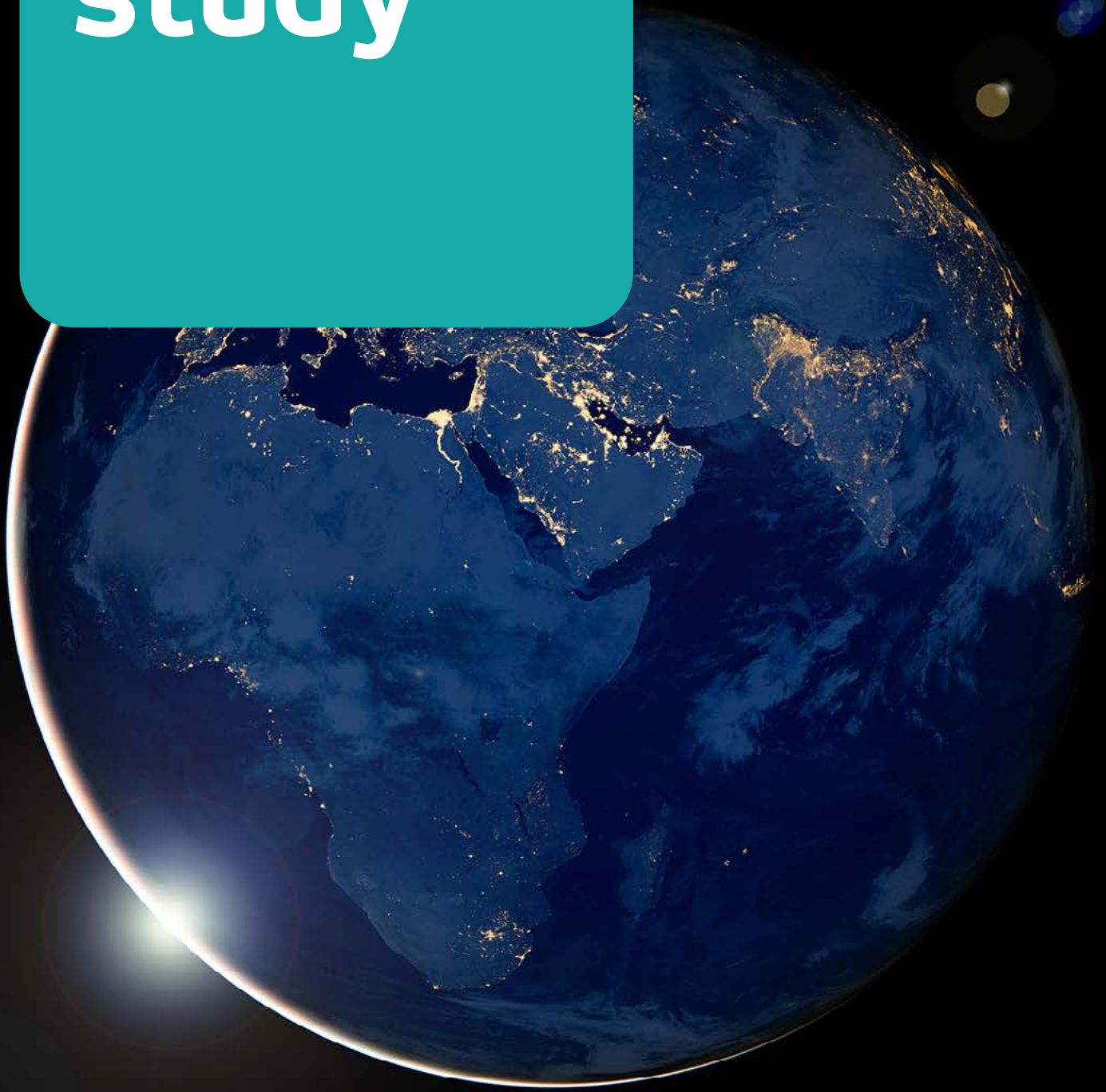
First published 33 years ago, the PV industry’s beacon of progress, the “Solar Cell Efficiency Tables” was updated to Version #66 in May 2025 and #67 in January 2026.[9] The Tables remain the gold standard for tracking the highest independently confirmed efficiencies in PV technologies.

Led by Professor Martin Green, with ACAP’s Professor Xiaojing Hao and Dr Jessica Yajie Jiang and an international team, and published biannually in *Progress in Photovoltaics*, this series is one of the most highly cited and influential resources in solar energy research. Its rigorous methodology and global recognition make it a cornerstone for both academic and industrial stakeholders seeking to benchmark and validate solar cell performance. ■

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Case study



ACAP leaders join global collaboration to plan multi-terawatt solar

In late December 2025, *Nature Energy* published an article penned by ACAP leaders and another ~70 world-leading solar PV experts outlining a strategic global framework for accelerating solar PV deployment as the world enters a multi-terawatt era.

“Historical and future learning for the new era of multi-terawatt photovoltaics” reflects the outcomes of the Fourth Terawatt Workshop (TW4) convened by the National Laboratory of the Rockies (US), the National Institute of Advanced Industrial Science and Technology (Japan) and Fraunhofer ISE (Germany), in California in June 2024.[1] It charts a path forward based on learning – combining research and development, experience, and global collaboration – and identifies emerging priorities such as tandem technologies, reliability, and sustainability metrics.

Every two years, the Terawatt Workshop series gathers a select group of global leaders in solar PV research, industry, and policy to develop strategies for scaling photovoltaic deployment to meet future energy demand, cut carbon emissions, and ensure sustainable, coordinated global growth.

ACAP’s Professors Renate Egan and Dan Macdonald and Dr Jessica Yajie Jiang joined experts in PV and related areas for the 4th Terawatt Workshop. Photo credit: Harrison Dreves, National Laboratory of the Rockies.





**The Terawatt
Workshop gathers
a select group of
leaders to develop
strategies for scaling
PV deployment.**



TW4 invited 73 key experts from 56 organisations spanning North America, Europe, Asia, Africa, and Oceania. Among them were ACAP's Executive Director Professor Renate Egan, UNSW Node Lead Dr Jessica Yajie Jiang and ANU Node Lead Professor Dan Macdonald, along with ACAP industry partners Dr Yifeng Chen (Trina Solar) and Dr Pierre Verlinden (Yangtze Institute for Solar Technology).

Hosted in 2024, by the National Renewable Energy Labs (US), major research groups represented alongside ACAP included; Fraunhofer ISE (Germany), Trina Solar (China), National Institute of Advanced Industrial Science and Technology (Japan), King Abdullah University of Science and Technology (Saudi Arabia), Yangtze Institute for Solar Technology (China), Interuniversity Microelectronics Centre (Belgium), and the Indian Institute of Technology Bombay (India).

Key insights from the *Nature Energy* article

- **Historical learning as a foundation:** Today's scale of PV deployment is the result of five decades of cumulative advances in PV cost, efficiency, and reliability. The experience curve – linking cost reductions to cumulative production – has been accelerated by global collaboration, R&D breakthroughs, and knowledge sharing across regions and companies.
- **The scale of the challenge ahead:** Global PV deployment reached 2 TW by the end of 2024, with 550 GW installed in 2024 alone – more than all installations before 2018. Annual installations are expected to rise to 600–700 GW in 2025, **and projections to total installations exceed 75 TW by 2050**, requiring manufacturing capacity to grow to around **3 TW per year**. This scale-up must occur without compromising sustainability, resource availability, or reliability.
- **Emerging technologies and learning needs:** Tandem solar cells, particularly perovskite/Si architectures, offer efficiency gains beyond the limits of single-junction silicon. However, they face hurdles in reliability, scalability, and cost competitiveness. These technologies will need accelerated learning curves,

informed by lessons from Si, CdTe, CIGS, and III-V technologies.

- **Sustainability metrics take centre stage:** Future PV progress will be measured not only by cost and efficiency but also by environmental and social metrics:
 - material sustainability (reducing silver and silicon usage)
 - energy and water consumption in manufacturing
 - design for recycling and circularity
 - net impact on CO₂ emissions.

These factors will shape R&D priorities and influence technology adoption.

- **Reliability and lifetime:** Extending module lifetimes and ensuring durability under diverse climate conditions is critical for cost-effectiveness and reducing replacement needs. New technologies must meet or exceed current reliability standards to gain market acceptance. Developing robust, globally harmonised testing standards is essential to ensure the reliability and bankability of next-generation PV technologies, particularly as new module designs and tandem architectures introduce unfamiliar degradation modes.
- **Global collaboration as a catalyst:** The pace of innovation and deployment depends on coordinated global efforts – sharing data, harmonising standards, and pooling resources for R&D and testing. The TW4 consensus emphasises that no single region or company can achieve terawatt-scale sustainability alone.

Upon publication of the paper, Professor Renate Egan said, “ACAP’s engagement in TW4 and contribution to the *Nature Energy* article demonstrates our role guiding the global PV community towards sustainable, large-scale deployment, and positioning Australia as a renewable energy superpower.” ■

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Case study



Global atlas of potential pumped hydro energy storage sites

In 2025, ACAP-supported research at ANU materially shaped how governments, utilities and developers plan long-duration energy storage. The Pumped Hydro Energy Storage (PHES) Atlases, led by Professor Andrew Blakers and supported by ACAP, are now embedded in national strategies and commercial pipelines across multiple continents – accelerating the pathway to ultra low-cost solar (ULCS).

Solving solar's storage constraint

Ultra low-cost solar depends on one critical factor: storing abundant daytime generation and delivering it reliably at scale. Off-river pumped hydro energy storage (PHES) is the lowest-cost form of long-duration (16-160 hour) storage, while batteries cover short-term (1-8 hour) storage. Since 2016, ANU's PHES Atlases program has systematically mapped its global potential.

The Atlases identify 820,000 potential off-river sites worldwide, representing storage capacity equivalent to approximately two trillion EV batteries. Using high-resolution elevation data, the team calculates reservoir geometry, storage volumes, head height and indicative costs, producing consistent open-access global datasets. The analysis demonstrates that at least 50 times more viable sites exist than previously recognised. [1]

This work builds on foundational research into 100% renewable electricity systems[2], integration of pumped hydro in fully renewable grids[3], and the Global Atlas of Closed-Loop Pumped Hydro Energy Storage.[1]

In 2025, the methodology was extended to bridge pixel-level renewable siting data with regional planning, strengthening system-level decision-making.[4]

Batteries provide short-duration, high-power storage while PHES provides long-duration, low-cost bulk storage. Together, hybrid PHES-battery systems enable full replacement of gas peaking plants. The Atlases therefore

The Atlases identify 820,000 potential off-river pumped hydro sites worldwide, with the storage capacity of around two trillion EV batteries.

can guide the removal of a central technical barrier to renewable-dominated grids. Pumped hydro also increases transmission utilisation, enabling power lines to operate near full capacity day and night.

Shaping Australian infrastructure decisions

The PHES Atlases have directly influenced major Australian storage developments. Former Prime Minister Malcolm Turnbull credited ANU's mapping with overturning assumptions about limited hydro potential, helping underpin Snowy 2.0 (2.2 GW, 350 GWh).

A NSW Government feasibility study for suitable pumped hydro sites in the state involved a detailed review of the potential locations identified in the PHES Atlas maps, and several hundred site options within the NSW Government's Renewable Energy Zones were identified.

Two NSW pumped hydro projects used analysis of the PHES Atlases to identify their sites and secured Long-Term Energy Service Agreements in February 2025, and were declared Critical State Significant Infrastructure in February 2026:

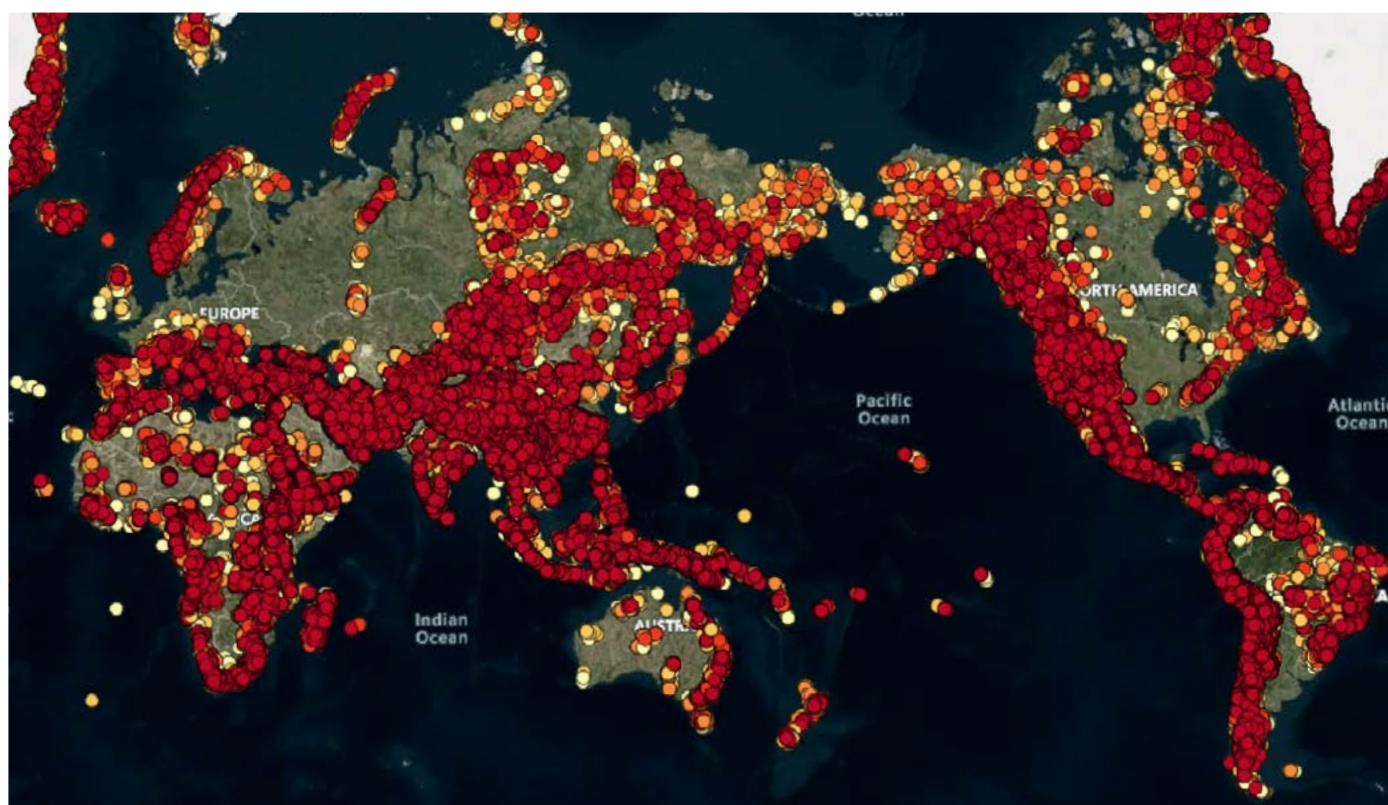
- The ACEN Australia Phoenix Pumped Hydro energy storage project (Yarrabin) in Central West Orana Renewable Energy Zone, NSW, will have the capacity to power 600,000 homes and businesses with a target storage of 12 hours (0.8 GW, 12 GWh).
- The Zen Energy A\$3.5 billion (1 GW), Western Sydney Pumped Hydro Project at Lake Burragarang is projected to power 500,000 homes and businesses for more than 8 hours.

In Queensland, Atlas outputs informed the SuperGrid Infrastructure Blueprint and assessments of Pioneer-Burdekin (5 GW, 120 GWh) and the Borumba project (2 GW, 50 GWh).

Global uptake of the Pumped Hydro Energy Storage Atlases in 2025

The Atlases identify 820,000 potential off-river pumped hydro energy storage sites worldwide.

International engagement intensified in 2025. The RE100 mapping platform and PHES Shortlisting Tool attracted thousands of users, with more than 700 site-specific submissions lodged this year alone.



Professor Blakers delivered a plenary address at the International Forum on Pumped Storage Hydropower at the UNESCO headquarters in Paris and presented renewable grid optimisation research at PVSEC 2025. With support from the Department of Foreign Affairs and Trade, the team conducted technical workshops and policy briefings across ASEAN, including Indonesia, Malaysia, Thailand, Laos, Cambodia and Vietnam.

Major international organisations are embedding Atlas outputs into formal planning processes. The World Bank circulates PHES Atlas results among hydropower specialists, and the International Hydropower Association has credited the work with materially improving long-term grid planning.

In India, the Ministry of Power directed utilities to examine Atlas-identified sites, and tenders in Andhra Pradesh reference Atlas data. The U.S. National Laboratory of the Rockies incorporated ANU's geospatial methods into national supply-curve modelling. Developers across North and South America are using the datasets for feasibility analysis.

As argued publicly in 2024, large-scale storage is no longer the limiting factor in energy transitions.[5] The Atlases provide the technical proof.

Sustained support and scale

The program began with ARENA funding (2016–2021), establishing its core methodology. Ongoing ACAP/ARENA support (2023–2030) and the Department of Foreign Affairs and Trade /Australian Water Partnership funding (2022–2025) enabled global expansion. A 2025 Prospera grant supported detailed site selection in Indonesia. Total CPI-adjusted funding exceeds A\$4.4 million.

System-level impact of the Atlases

Off-river pumped hydro is not simply a storage option; it is a system enabler for ultra low-cost solar. By delivering transparent global mapping, open datasets and sustained international engagement, ACAP-supported PHES research has shifted storage from perceived constraint to proven opportunity – enabling countries to plan confidently for solar-dominated energy systems. ■

Link to Pumped Hydro Energy Storage Atlases

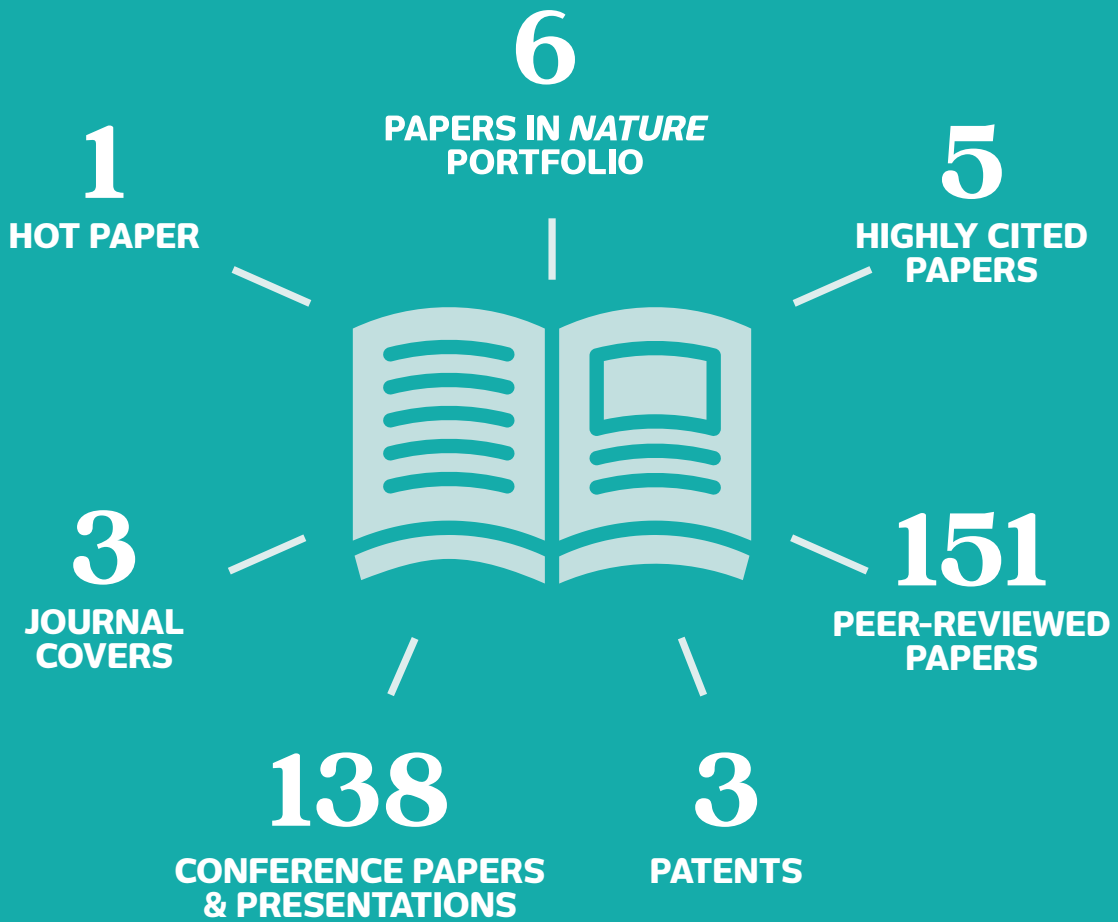
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IMPACT



HOT PAPERS ARE IN THE TOP 0.1% OF THEIR FIELD.
HIGHLY CITED PAPERS ARE IN THE TOP 1% OF THEIR FIELD.

AWARDS

3
INTERNATIONAL
AWARDS



5
NATIONAL
AWARDS



FOR IMPACT IN
PHOTOVOLTAICS

Publications



In 2025, multiple publications were featured in high-impact journals, including six in journals from the *Nature* portfolio.



In 2025, ACAP researchers maintained a strong and diverse publication record, reflecting the depth and breadth of the research activities. A total of 151 peer-reviewed journal papers, 138 conference papers and presentations, and 12 reports were produced. These were complemented by three patents, one book chapter, and 30 completed MPhil and PhD theses. These outputs span the full spectrum of photovoltaic research, from fundamental materials discovery to device development and system-level innovation, while also supporting techno-economic analysis and pathways to real-world deployment.

Importantly, ACAP research continues to achieve global recognition for its quality, impact, and influence. In 2025, multiple publications were featured in high-impact journals, including six in journals from the *Nature* portfolio, with five papers recognised as Highly Cited Papers and one as a Hot Paper, and three selected as cover articles. Further details are provided below. These achievements underscore the strong scientific influence, visibility, and international standing of ACAP research outputs and their role in advancing next-generation solar technologies.

***Nature* portfolio papers**

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Feng, K., Wang, G., Lian, Q., Gámez-Valenzuela, S., Li, B., Ding, R., Yang, W., Wang, K., Zeng, J., Zhang, Y., Jeong, S. Y., Xu, B., Ho-Baillie, A., Woo, H. Y., Facchetti, A., & Guo, X. (2025). Non-fullerene electron-transporting materials for high-performance and stable perovskite solar cells. *Nature Materials*, 24(5), 770–777. <https://doi.org/10.1038/s41563-025-02163-4>

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Feng, K., Wang, G., Lian, Q., Gámez-Valenzuela, S., Li, B., Ding, R., Yang, W., Wang, K., Zeng, J., Zhang, Y., Jeong, S. Y., Xu, B., Ho-Baillie, A., Woo, H. Y., Facchetti, A., & Guo, X. (2025). Non-fullerene electron-transporting materials for high-performance and stable perovskite solar cells. *Nature Materials*, 24(5), 770–777. <https://doi.org/10.1038/s41563-025-02163-4>

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Hot papers

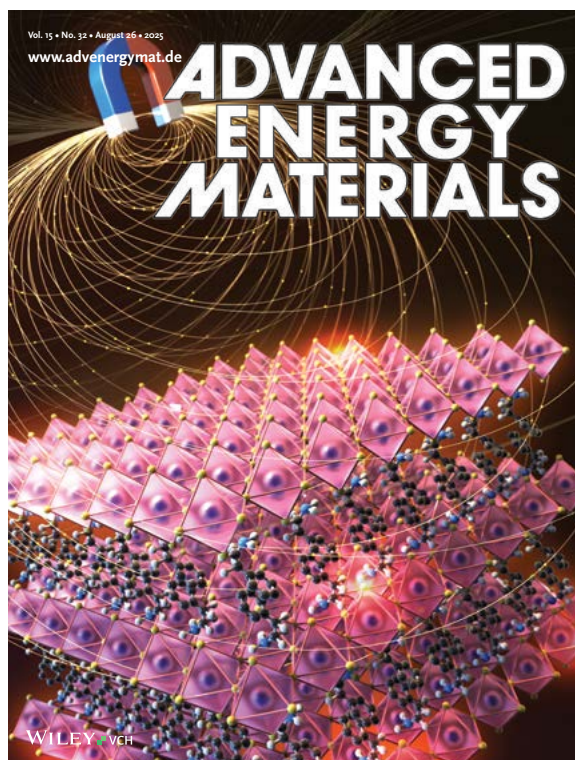
Green, M. A., Dunlop, E. D., Yoshita, M., Kopidakis, N., Bothe, K., Siefert, G., Hao, X., & Jiang, J. Y. (2025). Solar Cell Efficiency Tables (Version 66). *Progress in Photovoltaics: Research and Applications*, 33(7), 795–810. <https://doi.org/10.1002/pip.3919>

Papers selected for the cover

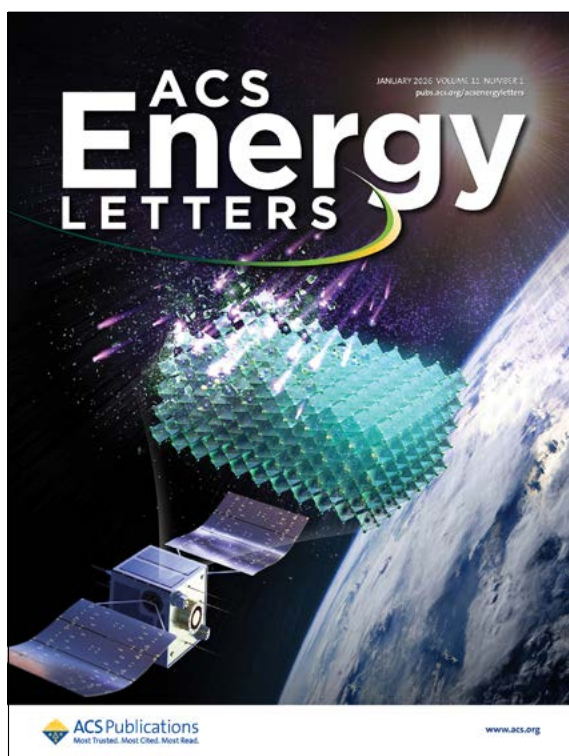
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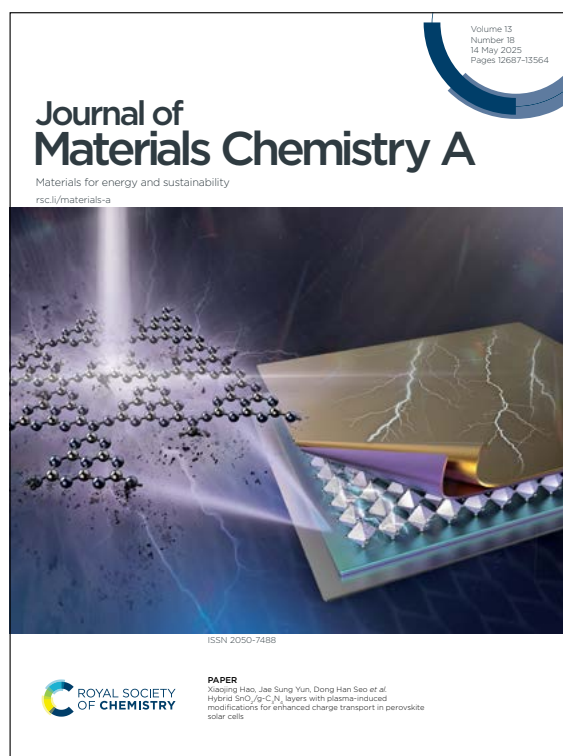
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Cover image for the article “Revealing Localized Dark-Exciton Populations in 2D Perovskites via Magneto-Optical Microscopy.”



Cover image for the article “Cerium Oxide Incorporation for Radiation Tolerance and Stability in Perovskite Solar Cells.”



Cover image for the article “Hybrid SnO₂ /g-C₃N₄ layers with plasma-induced modifications for enhanced charge transport in perovskite solar cells.”

Financial summary

In December 2012, a grant of \$33.2 million from the Australian Government through ARENA was announced to support an initial eight-year program of the Australian Centre for Advanced Photovoltaics (ACAP). This support leveraged an additional \$55.4 million cash and in-kind commitment from ACAP participants taking the total value of the project to \$88.6 million.

ACAP commenced on 1 February 2013 after signing of the Head Agreement between ARENA and UNSW, and receipt of letters of confirmation of participation under the terms of the Head Agreement by other Nodes.

In 2022, Minister Chris Bowen announced ACAP would be extended for a further eight years, with an additional \$45m of Australian Government funding to be provided through ARENA. This extension to 2030, now known as ACAP 2.0, was implemented through Variation 13 (3 January 2023). The ACAP 2.0 extension also permitted the inclusion of two additional Nodes, CSIRO Energy and the University of Sydney. The Collaboration Agreement between UNSW and the Nodes was amended and restated in Q3 of 2023. A stage-gate review of ACAP 2.0 was passed in August 2025.

The original project that started in 2013, now known as ACAP 1.0, was formally closed in 2024, with the delivery of Milestone 12B on 29 November 2024 and the approval by ARENA on 11 December 2024. Through variations and extensions to the program, including provisions of additional funding for Capacity Building Fellowships, Small Grants, Infrastructure, and partner contributions, the total ACAP 1.0 budget was \$197,107,897.

Two infrastructure projects were transferred from ACAP 1.0 to ACAP 2.0, with their completion postponed until 2026 (as per Variation 15, dated 1 November 2024).

In October 2024, the ACAP Management Committee unanimously supported the allocation of \$3.5 million of project funding to be distributed to 16 projects through a competitive allocation process. Most sub-contracts were executed by the end of 2025, with the first milestone payments processed in the last quarter of the year.

In August 2025, ACAP called for round 2 project funding proposals, with the successful projects announced internally in December 2025, awarding \$2.3m across 12 projects.

The 2025 financial summary covers the third year of operation of ACAP 2.0. Accounts for ACAP 2.0 in 2025 are presented.

The breakdown by institution of the \$23.1 million total cash and in-kind budget for ACAP 2.0 in 2025 is shown in Figure 1. (a).

The actual total 2025 cash expenditure and cash and in-kind contributions for all categories was \$21.2 million and its breakdown is shown in Figure 1. (b).

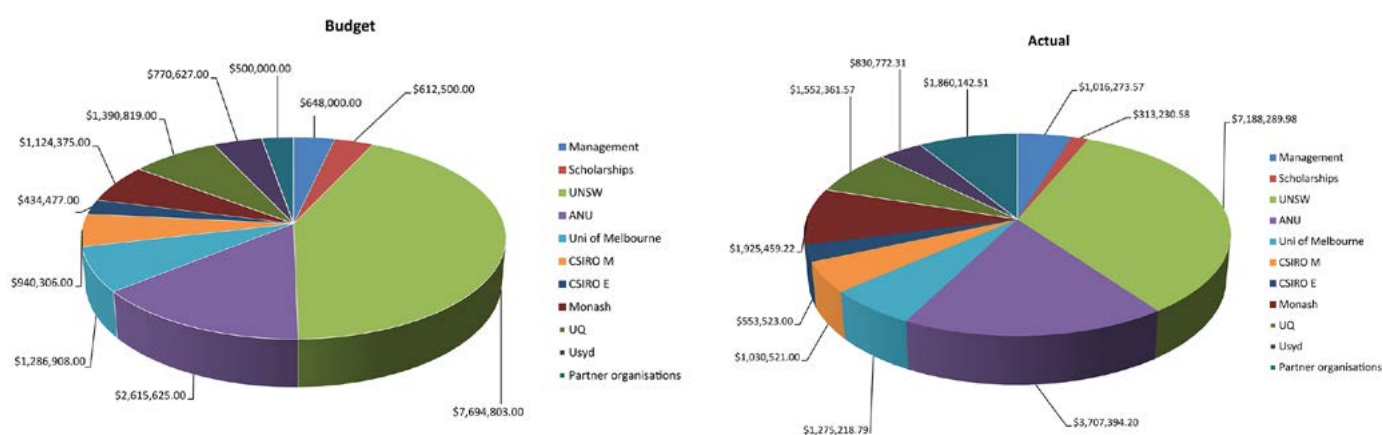
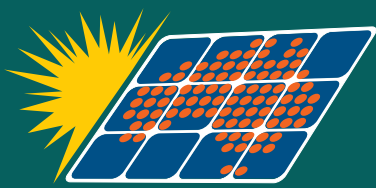


Figure 1. (a) Breakdown by institution of the \$23.1 million total cash and in-kind budget for ACAP 2.0 in 2025.

Figure 1. (b) Breakdown of actual 2025 cash expenditure and cash and in-kind contributions.



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