Australian Government
Australian Renewable Energy Agency

ARENA

Perovskite Solar Cells: Establishing the Basis for Industrial Development

Project results and lessons learnt

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Executive Summary

In its ARENA funded Measure, Dyesol set out to establish the viability of perovskite solar cell technology for scale-up and manufacture. This activity involved examining a number of important elements to assess whether the technology was ready for the next phase of investment:

1. Were perovskite solar cells efficient enough?
2. Could they pass basic stability tests indicating prospects for good product lifetime?
3. Was it possible to prove this at a scale beyond the laboratory size?
4. Could this be done in larger quantities to ensure reproducibility?
5. Externally validate the achievements where possible.
6. Investigate the fabrication process sequence and assess the manufacturing implications.
7. Understand the materials cost breakdown.
8. Review the data to determine projected panel costs and energy costs.
9. Survey the intellectual property space to understand freedom to operate.
10. Build networks within Australia to support industrialisation of this technology.

As much as possible these steps were conducted experimentally, up to the size of small modules. This generated much more robust validity to the subsequent analysis, as it was based on hard evidence rather than speculation.

Dyesol found that perovskite solar cells of the appropriate architecture (carbon-based) were both efficient and stable. This was proven on multiple double-digit batches, and externally certified by an internationally recognised testing authority. Further, the carbon-based perovskite solar cell architecture was determined to be such low cost in materials and manufacture that it led to a final panel cost metric ($ per Watt-peak) of around half that of existing solar cell technologies. This led to competitive costs being projected using ARENA's levelised cost of electricity calculation template, noting that the underlying assumptions will need to be further tested once scalable manufacturing techniques have been fully validated.

An in-depth review of the intellectual property space also validated the freedom to operate for Dyesol in the most prospective device architectures (carbon-based). The business opportunity was further substantiated by the rapid deployment of the simple fabrication processes and extremely high scalability of the technology due to its use of abundant and low-cost materials. Finally, a strong network of collaboration across academia and industry was built, providing a research and development engine to power the next phase of commercialisation and scale-up of this exciting, third-generation photovoltaic technology.

Dyesol is now progressing towards a major demonstration Project. Plans are already drawn up to undertake subsequent pilot production once major-area device designs and deposition technologies are proven. This will underpin a unique, Australian-based technology, manufacturing opportunity creating value added employment and export. The future is very bright for this innovative technology, identified as number 4 in the World Economic Forum's "Top 10 Emerging Technologies of 2016", and Australia's Dyesol seeks to be a key player in the global market.

Project Overview

Project summary

The Measure confirmed the viability of perovskite solar cell (PSC) technology for transition to commercial-scale manufacture. This was demonstrated by meeting industrially relevant performance and durability targets consistent with existing solar photovoltaic (PV) product certification standards. In addition, the Measure assessed and confirmed the manufacturability and cost competiveness of the technology at modest industrial-scale manufacture. The Measure also sought to produce new knowledge that would assist Australian researchers to better coordinate and focus their activities in this rapidly emerging technology sector. Key outputs of the Measure included:

1. Selecting the preferred PSC PV cell architecture suitable for scale-up into panels.
2. Confirming the viability of the preferred architecture by demonstrating key technical parameters associated with efficiency and stability.
3. Evaluating the feasibility of the preferred architecture for mass production and the competiveness of product for subsequent commercialisation.
4. Confirming the commercial competitiveness of the preferred architecture by undertaking comprehensive levelised cost of electricity (LCOE) modelling.
5. Through a global intellectual property (IP) evaluation demonstrating that Dyesol is well positioned and has freedom to operate from an IP perspective in commercialising this PSC technology.
6. Strengthening Dyesol's relationship with the key members of the research community working in the PSC field, including the Australian Centre for Advanced Photovoltaics (ACAP), to achieve better information sharing and cooperation, and coordinated activities.

Project scope

This Measure aimed, by achieving tangible deliverables, to demonstrate that PSC technology is ready for the significant investment necessary for Dyesol to deliver this potentially game-changing technology to the PV market. The key outputs of the Measure were selected to provide greater clarity in the PSC technology space necessary for future commercial development, and help position Dyesol at the forefront of development of the technology. Thresholds selected for the Measure to demonstrate a viable proof of concept for the PSC architectures under consideration were:

1. achieving >10% efficiency for a batch of 1 cm^2 cells; and
2. successfully completing a minimum of 1000 hours of full sun light-soaking within test protocol specification.

These two critical thresholds were selected because they represent the fundamental criteria that are

necessary for a solar technology to be considered as viable to move to the next stage of commercialisation. They underpin the Milestones that were selected for the Measure which are detailed below:

Milestone 1 (10% Efficiency Target)

The deliverables for this Milestone included:

a. Achieving >10% efficiency for a batch of 1 cm^2 strip cells – this was for a batch of larger cells rather than individual, tiny spot cell performance that is usually reported by academia. While a number of architecture variations were thought viable to achieve the 10% efficiency target for 1 cm^2 strip cells, the Milestone required this to be achieved consistently on a batch basis and pre-screening for durability was also a consideration to select the architecture/s considered for Milestone 2.

b. Reporting on LCOE modelling undertaken that demonstrates the expected commercial competiveness of PSC PV technology. The modelling was to take into account the expected performance, durability and cost (the "Golden Triangle" parameters) for PSC panels. A comparison was made to selected competing technologies which included a sensitivity analysis of key parameters that impact on module performance. The analysis adopted the forecast module unit cost base ($\$/W_p$) once (modest) volume production level of PSC PV modules is achieved.

c. A final Risk Management Plan using the preferred ARENA template.

Milestone 2 (Light Soaking Durability Target)

The deliverables for this Milestone included:

a. Successfully completing 1000 hours of full sun equivalent light soaking within specification (<10% relative efficiency loss). This is an industry standard relevant test aligned with IEC 61646, and is a good indicator of underlying stability. It is worth noting that performance figures reported by academia are predominately devoid of any stability testing or analysis. This testing was on the preferred architecture/s selected in Milestone 1.

b. IP review and analysis report. This involved a high level search of the generic perovskite space by an external IP specialist with relevant experience in the 3rd generation PV technology space, which Dyesol augmented using its own IP expertise and IP attorney input. This was analysed to determine relevance, status, spread and stage of patent protection, and considered the impact of prior art on any claims that have been made that are relevant to the field. The key outcome was to confirm the freedom to operate in the PSC IP space.

c. Manufacturability review and analysis report. While outstanding PSC efficiencies are being reported by academia, these are typically achieved using processes that are either not scalable or feasible to use for volume manufacturing. The review considered a number of parameters, including large area deposition uniformity and patterning tolerance, process speeds, environmental control requirements, work health and safety, and material and equipment costs. The aim was to determine viability of mass manufacture and provide a

robust estimate of unit cost ($/$W_p$) of manufactured product.

Outcomes

During the period of Dyesol's ARENA Measure the key Milestone outcomes were:

a. achievement of >10% efficiency and external independent certification of this result;

b. achievement of <10% degradation in efficiency after 1000 hours of light soaking;

c. manufacturability and cost competiveness assessment of the preferred architecture;

d. LCOE modelling; and

e. evaluation of the IP landscape to determine Dyesol's freedom to operate.

Dyesol's preferred PSC architectures, which utilise carbon back contacts, were experimentally evaluated. Carbon is preferred as it has appropriate electronic properties and is also low cost in both raw material and deposition processes. Preferred cell architectures evaluated by Dyesol eliminate expensive organic hole transport materials (HTMs), improving the stability and lowering the cost of the cells. Dyesol achieved >10% efficiency for the average of a batch of 1 cm^2 strip cells, an excellent achievement at industrially relevant cell sizes with meaningful statistics. This result was subsequently independently certified by NewPort testing laboratories. Sealing was implemented and light soaking stability assessment began. After 1058 hours of light soaking, cells displayed a 9.2-9.8% relative loss in efficiency, thereby satisfying the Milestone target.

Practical evaluation of the manufacturing prospects for the system was at 100 cm^2 module size (shown to the left) to provide real-world validation of the suitability of processes. Trials proved successful, and a desktop study was undertaken to review prospects for full-scale manufacturing of panel or commercial sized product. Considerations included: tolerances to meet required active area, deposition accuracy over the full panel area, processing speeds to achieve target throughputs, and cost estimations. A careful review of environmental implications was undertaken, highlighting minimal concerns with lead (Pb) in end applications.

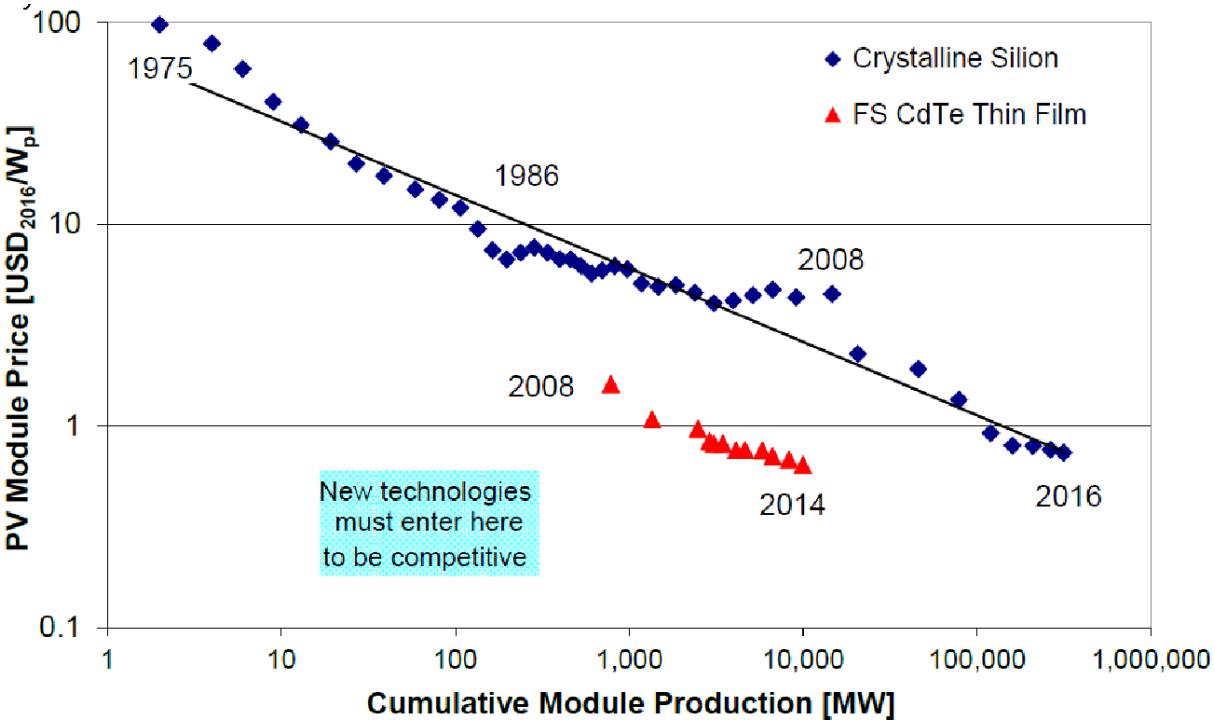
LCOE modelling took as inputs: bill of materials, process flow, and cost estimates for large-area equipment. Material costs at scale were projected using Dyesol's knowledge of scale-up of the materials. Standard industrial process scaling factors were used where appropriate. Calculations were supported by robust assumptions for Australian manufacturing at modest 100 MW capacity, and small solar farms of 20 MW size in Australia. Projected module cost is AU$0.20-0.30/$W_p$. ARENA's LCOE model with irradiance data from Meteonorm used in the US National Renewable Energy Agency's (NREL's) SAM software to calculate projected energy yield resulted in LCOE values of AU$103.10/MWh to AU$127.66/MWh.

A thorough review of the IP space was made using commercial-in-confidence internal and 3rd party

unpublished patent specifications available to Dyesol as well as expert inputs. Augmenting this was Dyesol's proprietary knowledge and critiques of the IP landscape. Good confirmation of the broader freedom to operate was identified, with limited barriers to Dyesol pursuing its preferred architecture in target markets.

Transferability

Dyesol's Measure sought to validate the commercialisation potential of PSC technology. Scaling-up PSC technology is only viable if the expected commercial returns are competitive and a sustainable business can be built around the concept. Ultimately, the technology needs to provide a competitive LCOE. The "Golden Triangle" (right) of LCOE is constructed from the energy yield, product lifetime, and costs over the lifetime. For PV technologies, the energy yield is mainly dependent on the efficiency, and costs are largely determined by panel costs. This important metric is usually represented as the $/W$_p$ of panels.



The figure below plots the costs calculated for Dyesol's market entry product specification, initial production scale quantities, and anticipated cost base at those production quantities. The data is compared to 1st-Generation silicon PV and 2nd-Generation CdTe PV data from the 2016 EU PV Status Report. Interestingly, the authors of the 2016 EU PV Status Report concluded that both crystalline silicon PV and CdTe PV had learning curves of around 20%. However, the two technologies lay on very different lines, with around an order of magnitude separation in cost structures at an equivalent

production capacity. The present market pre-eminence of silicon PV is principally due to its considerably larger scale, rather than its inherent cheapness. The authors also helpfully identified the region into which any new PV market entrants would have to fit in order to be commercially competitive in light of the considerable advantages of incumbency represented by the existing scaled-up silicon and CdTe product offerings. This essentially amounts to a third line on the figure, which is an order of magnitude offset again from the CdTe line. Of considerable comfort is that when Dyesol's expected scale and costs were overlaid on the figure, there was almost a perfect correlation with the identified region. This is an excellent confirmation that the technology development and market entry strategies envisaged by Dyesol are highly consistent with the parameters independently identified for developing a successful business opportunity.

Beyond the initial market penetration, there is every reason to consider that PSC technology has the capability to continue to remain competitive, given the initial estimated learning curve from Dyesol's modelling data is also around 20%. Cost reduction during further scale-up in production capacity will help to ensure the technology remains strongly competitive with silicon and CdTe PV. Superior to CdTe, the raw materials supply chain for PSC is effectively unlimited (much like silicon solar cells with the exception of silicon PV's dependence on silver). Thus, there is no inherent barrier to extensive scale-up of the technology once it is successfully industrialised, paving the way for a very large commercial opportunity. A MIT study concluded that PSCs are the only >20% PV technology that could supply 100% of global electricity in 2050 without drastic changes to global material supply chains. Thus, pursuit of scale-up of PSCs may be a key enabler for the continuing reduction in $/MWh LCOE of solar electricity, and also facilitate much wider uptake of renewable energy of this type than might have otherwise been possible given the limitations of existing PV technologies.

Dyesol's industrially focussed approach to assessing perovskite solar cell viability highlighted some areas of deficiency in the present academic research agenda on PSCs. In particular, the prevalence of work aimed predominantly at "novelty" in university and even government research laboratories, which helps foster increased publication rates, has to date fairly systematically failed to address the lifetime issue around PSCs, which is absolutely critical to achieving low LCOE. During the course of the Measure, Dyesol published 35 knowledge sharing items, including ASX releases, white papers, radio interviews and other communications about the work undertaken in the Measure. It is hoped that these efforts will help to highlight the priority areas needing research attention in this field. To build closer collaboration with important research groups within Australia Dyesol joined the Australian Centre for Applied Photovoltaics (ACAP) as an industrial partner and looks forward to fruitful collaboration seeking to solve the key issues around PSC industrialisation.

Publications

No academic journal articles have been published in this Measure.

Intellectual Property: Patents / Licences

Considerable IP pertaining to materials, device architectures, operational dynamics, degradation modes and preferred manufacturing processes has been accumulated during execution of the Measure. These technical trade secrets are maintained by Dyesol in-house and no patents have

been filed as part of the Measure. Further, extensive business related IP has been generated by Dyesol during the work on manufacturability evaluation, cost modelling and IP assessment. The results of the IP assessment have been shared with ACAP. Manufacturability has been further explored beyond the measure by Dyesol and VDL Enabling Technologies Group, with a view to scale-up of PSCs to major area demonstration size and subsequent pilot production.

Awards

No awards were received in the context of this Measure.

Conclusion and next steps

Dyesol was pleased that the outcomes of the Measure strongly validated the commercialisation prospects of PSC technology. This validation occurred on a number of fronts, technical, economic, and business, and demonstrated the extensive opportunities presented by scale-up and industrialisation of this technology. Dyesol seeks to further capitalise on the progress to date, and undertake this scale-up in Australia, to generate maximum benefit for the Australian innovation ecosystem, Australia's energy system, and the Australian economy. Dyesol is advanced in planning for a major -area demonstration Project for which funding will be sought to supplement Dyesol's investment and improve the project timeline. This project provides critical support for a subsequent pilot production stage by confirming that large-area device designs and deposition technologies are suitable for volume manufacture. This not only helps to de-risk this important stage but also facilitates the timely transitioning of PSCs along the renewable energy technology development chain. This will underpin a unique Australian-based technology manufacturing opportunity creating value added employment and export. It is hoped that by drawing attention to the attractive prospects of the technology, alongside identifying the key areas for further work to enable the transition from lab-to-fab, that Dyesol will encourage others working in the PSC space to focus not only on academic novelty research, but also undertake activities that help achieve industrial and commercial viability. Early entry to market will be important in achieving commercial success in the PSC market space.

Lessons Learnt

Lessons Learnt Report: BOS Data

Project Name: *Perovskite Solar Cells: Establishing the Basis for Industrial Development*

Knowledge Category:	Financial
Knowledge Type:	Inputs
Technology Type:	Solar PV
State/Territory:	NSW

Key learning

- Non-module costs have dropped extremely rapidly in the period leading up to the Measure executed by Dyesol. This led to considerable potential for errors in LCOE estimations, particularly as Dyesol took a conservative approach to estimating these costs, and, thus, almost certainly used costs which were higher than those presently incurred by solar farm developers.
- It was not only Dyesol who found accessing reliable cost structure data difficult. During review of Dyesol's $\$/W_p$ figures by an ARENA selected expert at UNSW, a number of figures Dyesol used were criticised as being lower than data published in the academic literature. In these cases, Dyesol's data came either directly from recent quotations provided by international materials producers or using our established manufacturing costs. These are considerably more accurate than figures cited in academic journal articles.

Implications for future projects

As ARENA prefers to evaluate based on LCOE, then for or development of new photovoltaic technologies, it is necessary for non-module costs to be standardised in LCOE calculations. At present, this is not done, and the quality of data obtained may be questionable in some cases.

Knowledge gap

Given ARENA's knowledge sharing remit, and particularly as a number of large solar farms have been funded by ARENA, better quality cost breakdown data should be made available under ARENA's knowledge sharing requirements. At a minimum, some de-identified aggregated data of this nature would be expected to be available to facilitate future project alignment to current industry standards and numerate metrics.

Background

Objectives or project requirements

During financial modelling for LCOE, Dyesol found obtaining reliable data for non-module costs to be difficult, especially for the Australian context.

Process undertaken

Ultimately, Dyesol undertook an extensive survey of published balance of system (BOS) costs and sought to use the most recent data available when sufficiently detailed breakdowns of cost segments were provided. Trend mapping was also undertaken, in which the detailed breakdowns of costs were individually plotted over time to see the various changes in cost structures, and, thus, facilitate reasonable estimation of present and future costs which could be used in LCOE modelling.

Lessons Learnt Report: Tandem Perovskite PV Technology

Project Name: *Perovskite Solar Cells: Establishing the Basis for Industrial Development*

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	NSW

Key learning

- It is commonly believed that silicon-perovskite tandems are the technologically "easiest" form of perovskite technology to industrialise and take to market. This, however, is probably more difficult in practice, as the technical requirements for a silicon-perovskite tandem include all the needs for a perovskite-only device, plus an additional number of challenges not required for a perovskite only device such as wavelength dependent transparency and interface complexities. These additional needs make the technology development pathway for silicon-perovskite tandems substantially more demanding than the pathway for perovskite-only devices.
- There is an existing concept that perovskite-silicon tandems will be able to effectively utilise incumbent silicon PV manufacturing assets. This concept probably is flawed as currently little overlap exists in the production processes. Silicon PV uses equipment for silicon ingot manufacture, silicon wafer slicing, silicon cell fabrication and silicon module layup, whereas PSC PV mainly uses equipment for cell layer deposition and panel patterning. The overlap primarily exists in module layup, encapsulation and balance of panel operations. It is estimated that around 80% of the equipment to make a perovskite-only device would still be required to also make a silicon-perovskite tandem (in addition to the 100% of silicon manufacturing equipment).
- For silicon-perovskite tandem products to generate much lower $\$/W_p$ cost the perovskite component has to be both high performing and low cost. This indicates that considerable effort needs to be focussed on stand-alone perovskite cell performance in order to be able to achieve any significant tangible benefit from silicon-perovskite tandems. It is conceivable that lower $\$/W_p$ figures will be obtained from perovskite-only devices or perovskite-perovskite tandems, due to the inherently low cost base of perovskites.

Implications for future projects

A prerequisite for a successful silicon-perovskite tandem device is a viable perovskite-only device. If silicon-perovskite tandem device R&D is to be pursued, then a priority should be to first fund and deliver an industrially viable perovskite-only device to ensure that silicon-perovskite devices are worthwhile at all. Additionally, early research work outside Australia is demonstrating perovskite-perovskite tandem devices. These may have all the stated benefits of silicon-perovskite tandem devices, without all of the concomitant disadvantages. Ensuring that perovskite only, and perovskite-perovskite tandem R&D is adequately resourced is likely to be advantageous in the

medium term.

Knowledge gap

To date, the silicon-perovskite tandem discussion is generally speculative without robust technical or economic data being available. Detailed cost-modelling and breakdown of process sequences to manufacturing steps should be required to support the argument in favour and any future, new investment.

Background

Objectives or project requirements

Dyesol undertook a detailed evaluation of perovskite solar cell designs, material sets, processes for fabrication, and equipment for manufacture. This was to help determine the viability for large-area scale-up, better understand the technical hurdles and forecast financial costings of future products once volume manufacturing was achieved.

Process undertaken

During implementation of the manufacturability analysis and calculation of the $\$/W_p$ economic metrics, Dyesol closely explored the various technical and financial considerations around PSC embodiments from an industrial and commercial perspective. The purported benefits for silicon-perovskite tandem devices can only be achieved if high performing and low cost perovskite-only devices are available for integration. Analysis of the technical parameters and financial considerations at this stage does not support the claimed benefits of silicon-perovskite tandem combinations, and, at the very least, a balanced R&D effort will support a risk minimisation strategy to ensure the best long term outcome is achieved.

Lessons Learnt Report: Testing Facilities & Protocols

Project Name: *Perovskite Solar Cells: Establishing the Basis for Industrial Development*

Knowledge Category:	Logistical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	NSW

Key learning

- There is a paucity of testing facilities in Australia, especially around stability/durability evaluation.

Implications for future projects

Testing standards need to be developed for PSCs, as there are significant differences in how they perform when compared to existing photovoltaic technologies.

Knowledge gap

While some efficiency testing facilities exist, they lack the experience and expertise needed for testing new technologies – Dyesol needed to go offshore for its certification.

Background

Objectives or project requirements

Dyesol sought to undertake 3rd party validation of as many of its technical achievements as possible during the Measure. While this was not possible for stability/durability metrics due to a lack of suitable facilities in Australia, it was, in theory, possible for efficiency metrics.

Process undertaken

Experience soon showed that not only facilities are required for this to work, but also processes for handling unfamiliar PV devices which required adapting testing regimes to suit the new technology. At the time this expertise did not exist in Australia outside Dyesol, and testing at NewPort in the USA was undertaken, as it had considerable experience in non-mainstream solar cell certification.

Appendix

Keywords

Solar Cell
Photovoltaic
Perovskite
PSC
Efficiency
Stability
Durability
Levelised Cost of Electricity
Levelised Cost of Energy
LCOE
Module Cost
Panel Cost
$\$/W_p$
$/MWh
$/MHhr
c/kWh
c/kWhr
Manufacture
Manufacturing
Manufacturability
Fabrication
Scale-Up
Intellectual Property
IP

Glossary of terms and acronyms

Term or Acronym	Definition
$/MWh	Also $/MWhr, dollars per mega-Watt-hour, a measure of the cost of electricity
$/$W_p$	Dollars per Watt-peak, a measure of the cost per power output of a solar cell device under a standardised condition
1st Generation PV	Traditional crystalline silicon solar cells, including poly-crystalline silicon and single-crystalline silicon
2nd Generation PV	"Thin film" solar cells, including amorphous silicon, CIGS and CdTe
3rd Generation PV	A new series of solar cells, beyond the conventional crystalline silicon or "thin film" technologies, also called "emerging PV"
ACAP	Australian Centre for Applied Photovoltaics
ASX	Australian Securities Exchange
c/kWh	Also c/kWhr, cents per kilo-Watt-hour, a measure of the cost of electricity
CdTe	Cadmium-Telluride, the most successfully commercialised "thin film" 2nd Generation PV
CIGS	Copper indium gallium selenide, an example of a "thin film" 2nd Generation PV technology
EU	European Union
Golden Triangle	The three parameters that make up an LCOE calculation: lifetime energy yield, lifetime cost, and system lifetime
Hole Transport Material	A component of a solar cells responsible for transferring electrons back into the light absorber
IEC	International Electrotechnical Commission, the international standards and conformity assessment body for all fields of electrotechnology
IEC 61646	An international standard for testing ruggedness of solar cells entitled "Thin-film terrestrial photovoltaic (PV) modules - Design qualification and type approval"
IP	Intellectual property
ISO	The International Organization for Standardization
kWh	Also kWhr, kilo-Watt-hours, a measure of energy output or consumption
LCOE	Levelised cost of electricity (measured in either $/MWh or c/kWh) a calculation showing the total cost per unit of electricity generated over the lifetime of the generating system
Learning Curve	A percentage figure indicating the reduction in cost with each successive doubling of production capacity
Meteonorm	Software for calculating solar irradiance data usable in SAM

MIT	Massachusetts Institute of Technology, a prestigious US tertiary institute
MW	Mega-Watt, a size parameter for solar cell manufacturing plants (W_p output of modules per year) or solar farms (W_p output of energy per year)
MWh	Also MWhr, mega-Watt-hours, a measure of energy output or consumption
NewPort	An ISO accredited international solar cell testing and certification organisation in the USA
NREL	The USA's National Renewable Energy Laboratory, one of the world's premier solar cell research entities
Perovskite	A particular arrangement of atoms in crystal lattice shared by many materials with different compositions
PSC	Perovskite solar cell
PV	Photovoltaic
SAM	System Advisor Model, an NREL software package for evaluating solar panel array power output
Tandem	A photovoltaic cell which has two light absorbing layers, each capturing a different part of the sun's light
UNSW	The University of New South Wales
US	Also USA, United State
USA	Also US, United State of America
VDL Enabling Technologies Group	A tier-1 contract manufacturing partner
W_p	Watt-peak, the power output of a solar cell device under a standardised condition