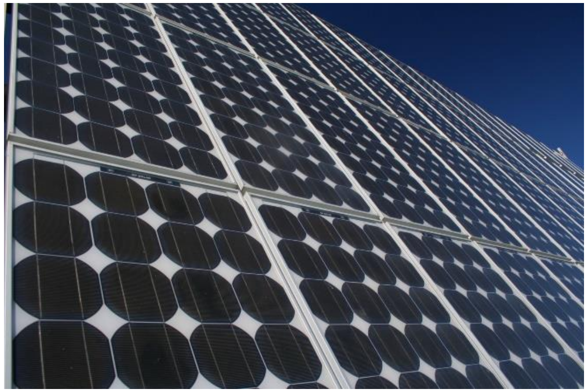
CSIRO PV PERFORMANCE LABORATORY

Dr Christopher Fell | Principal Research Scientist – CSIRO Energy Flagship

3 September 2015

Photovoltaics

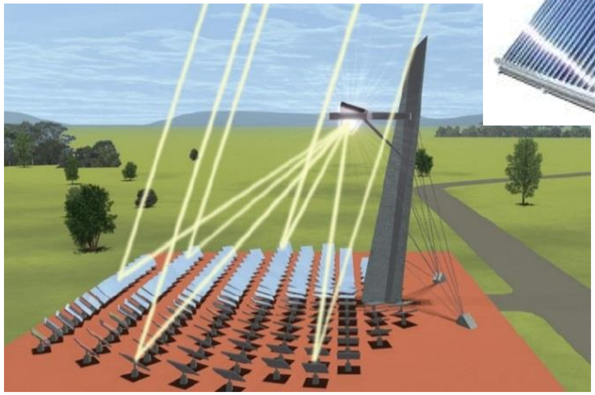
sunlight



electricity

Solar Thermal Energy

sunlight



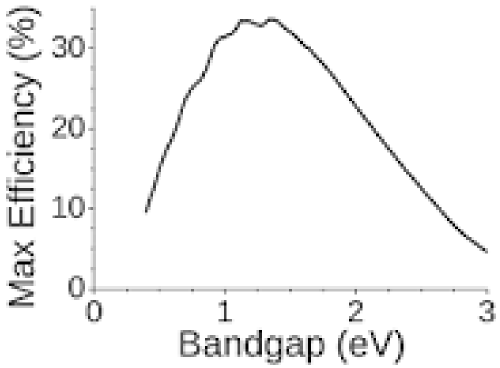
heat

other uses

electricity

= photovoltaic

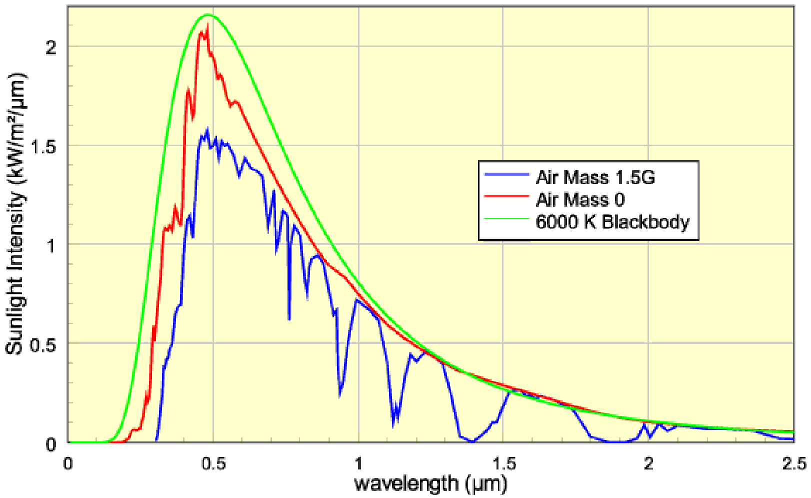
Solar cell **efficiency** is the ratio of the electrical output of a **solar** cell to the incident energy in the form of sunlight. The energy conversion **efficiency** (η) of a **solar** cell is the percentage of the **solar** energy to which the cell is exposed that is converted into electrical energy.



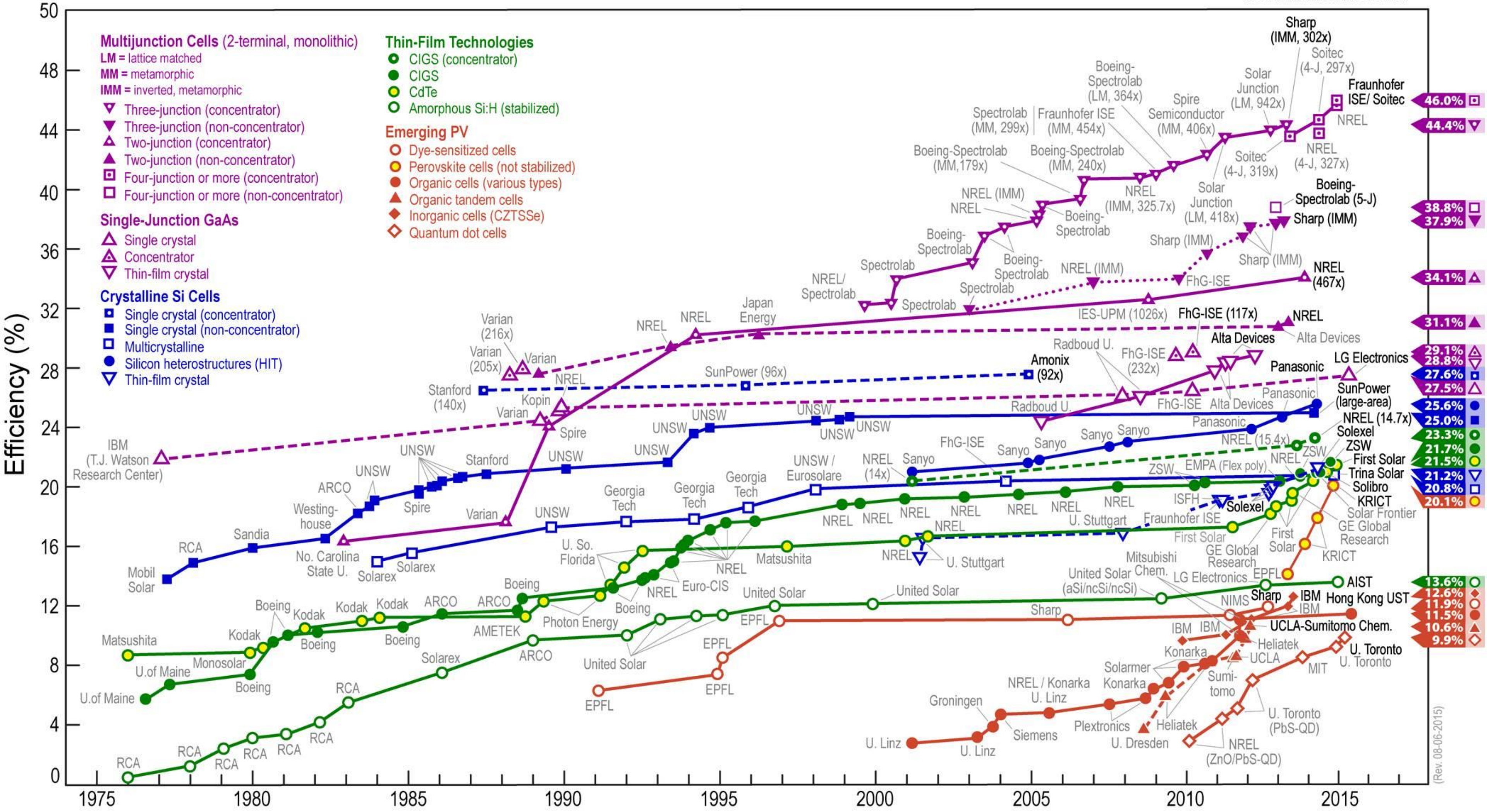
Solar cell efficiency - Wikipedia, the free encyclopedia
https://en.wikipedia.org/wiki/**Solar_cell_efficiency**

Standard Test Conditions:

- Cell temperature 25°C
- AM1.5G reference irradiance* (ASTM G-173 & IEC 60904)
  *spectrum integrates to 1000 W/m^2



Best Research-Cell Efficiencies



Sarah Kurtz and Keith Emery - National Renewable Energy Laboratory (NREL), Golden, CO

Multijunction Cells (2-terminal, monolithic)

LM = lattice matched
MM = metamorphic
IMM = inverted, metamorphic

- Three-junction (concentrator)
- Three-junction (non-concentrator)
- Two-junction (concentrator)
- Two-junction (non-concentrator)
- Four-junction or more (concentrator)
- Four-junction or more (non-concentrator)

Single-Junction GaAs

- Single crystal
- Concentrator
- Thin-film crystal

Crystalline Si Cells

- Single crystal (concentrator)
- Single crystal (non-concentrator)
- Multicrystalline
- Silicon heterostructures (HIT)
- Thin-film crystal

Thin-Film Technologies

- CIGS (concentrator)
- CIGS
- CdTe
- Amorphous Si:H (stabilized)

Emerging PV

- Dye-sensitized cells
- Perovskite cells (not stabilized)
- Organic cells (various types)
- Organic tandem cells
- Inorganic cells (CZTSSe)
- Quantum dot cells

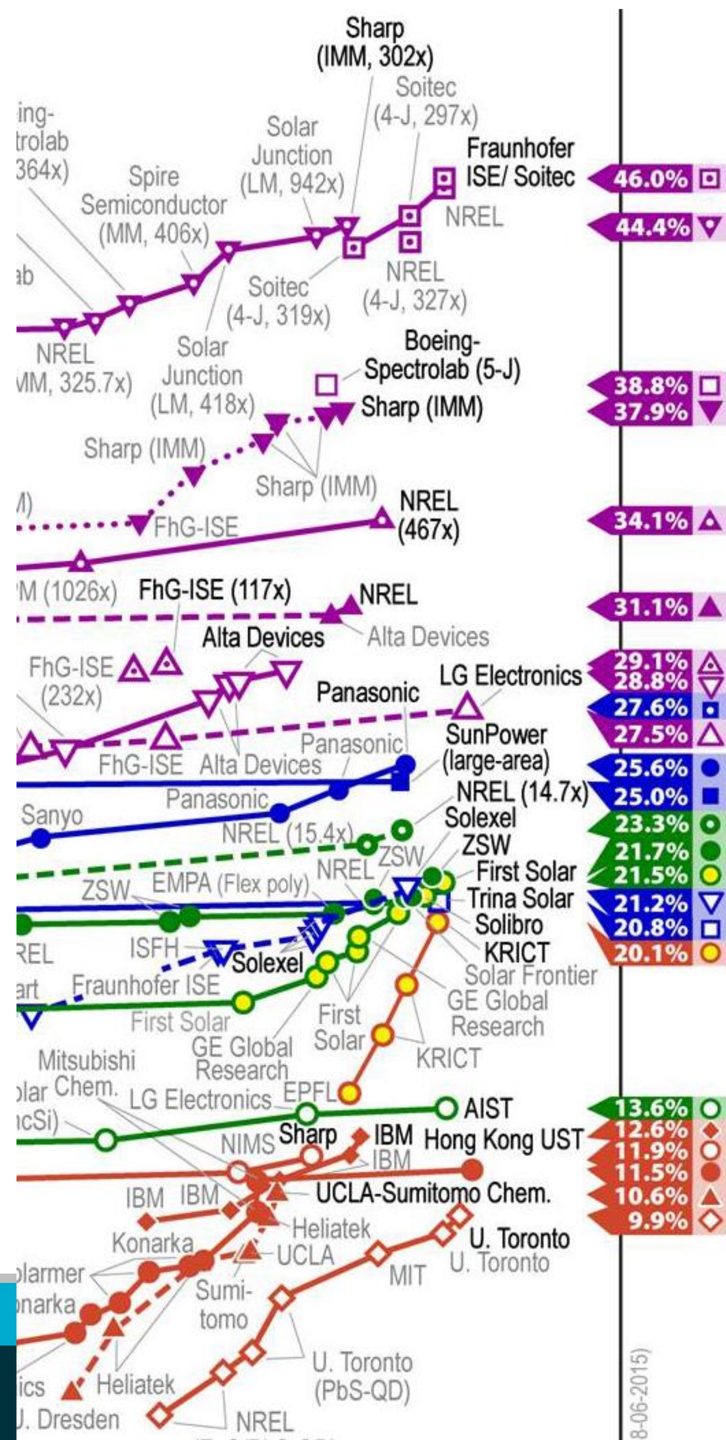


Table II. Confirmed terrestrial module efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at a cell temperature of 25 °C (IEC 60904-3: 2008, ASTM G-173-03 global).

Classification	Effic. (%)	Area (cm^2)	V_{oc} (V)	I_{sc} (A)	FF (%)	Test centre (date)	Description
Si (crystalline)	22.9 ± 0.6	778 (da)	5.60	3.97	80.3	Sandia (9/96)[a]	UNSW/Gochermann [32]
Si (large crystalline)	22.4 ± 0.6	15 775 (ap)	69.57	6.341[b]	80.1	NREL (8/12)	SunPower [33]
Si (multicrystalline)	18.5 ± 0.4	14 661 (ap)	38.97	9.149[c]	76.2	FhG-ISE (1/12)	Q-Cells (60 serial cells) [34]
GaAs (thin film)	24.1 ± 1.0	858.5 (ap)	10.89	2.255[d]	84.2	NREL (11/12)	Alta Devices [35]
CdTe (thin film)	17.5 ± 0.7	7021 (ap)	103.1	1.553[e]	76.6	NREL (2/14)	First Solar, monolithic [36]
CIGS (Cd free)	17.5 ± 0.5	808 (da)	47.6	0.408[f]	72.8	AIST (6/14)	Solar Frontier (70 cells) [37]
CIGS (thin film)	15.7 ± 0.5	9703 (ap)	28.24	7.254[g]	72.5	NREL (11/10)	Miasole [38]
a-Si/nc-Si (tandem)	12.3 ± 0.3[h]	14 322 (t)	280.1	0.902[i]	69.9	ESTI (9/14)	TEL Solar, Trubbach Labs [39]
Organic	8.7 ± 0.3[j]	802 (da)	17.47	0.1065[f]	70.4	AIST (5/14)	Toshiba [8]

Solar cell efficiency tables (Version 45)

Martin A. Green[1]*, Keith Emery[2], Yoshihiro Hishikawa[3], Wilhelm Warta[4] and Ewan D. Dunlop[5]

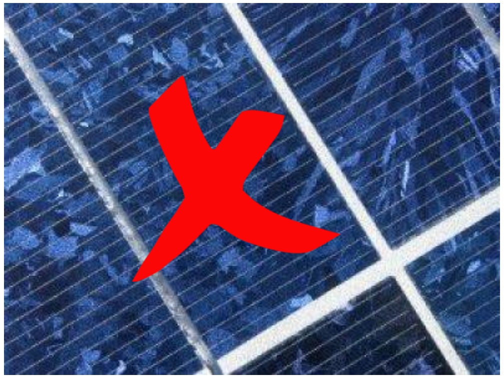
PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. 2015; **23**:1–9
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.2573

Who should care about (PV) efficiency ?

- Researchers
- Manufacturers
- Consumers

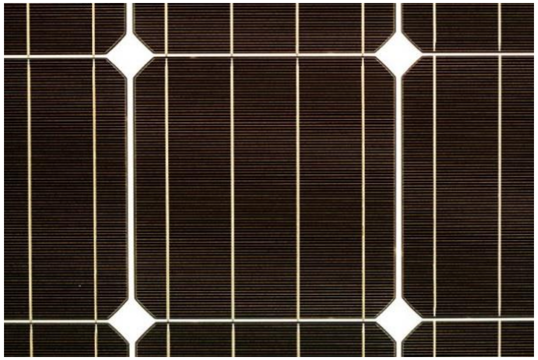
Consumers more likely to care about: price, durability, appearance.

Prevailing module designs available today

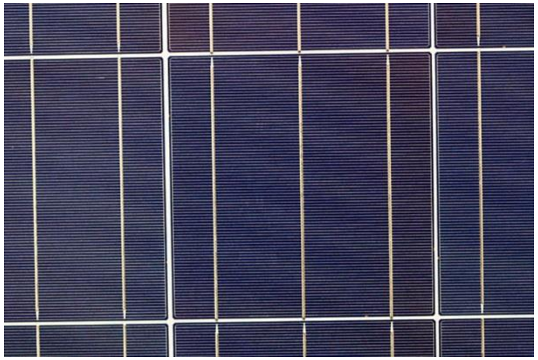


large grain crystalline ("poly")

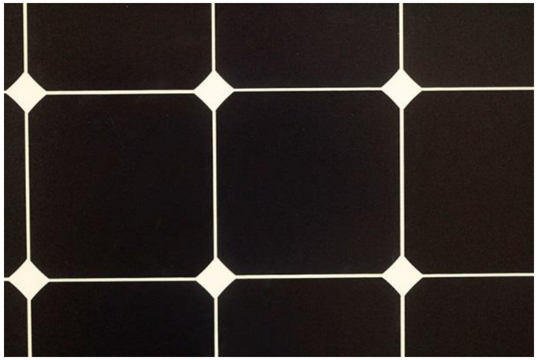
thin-film (CdTe + some CIGS)



(mono)crystalline Si

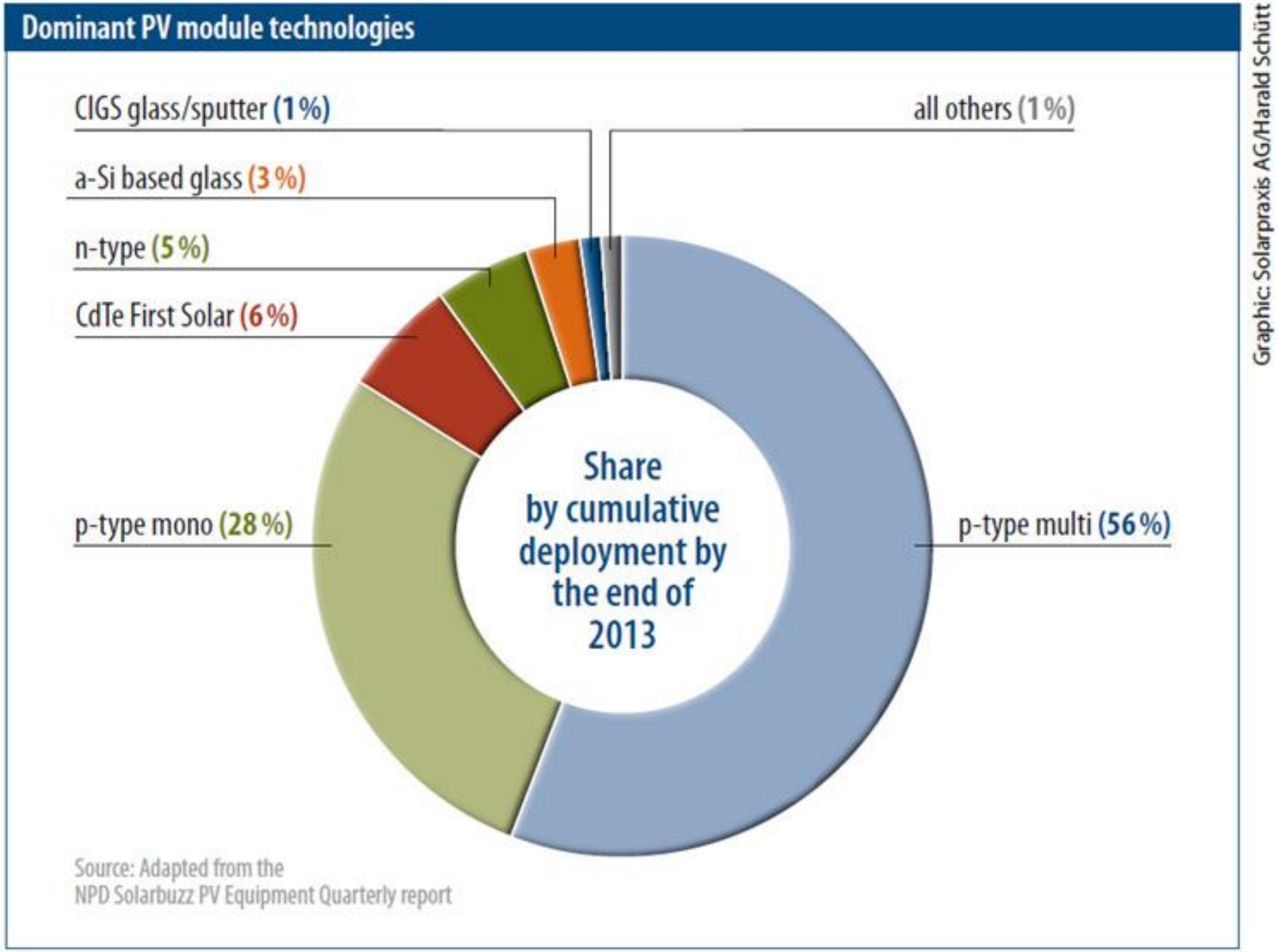


multicrystalline Si

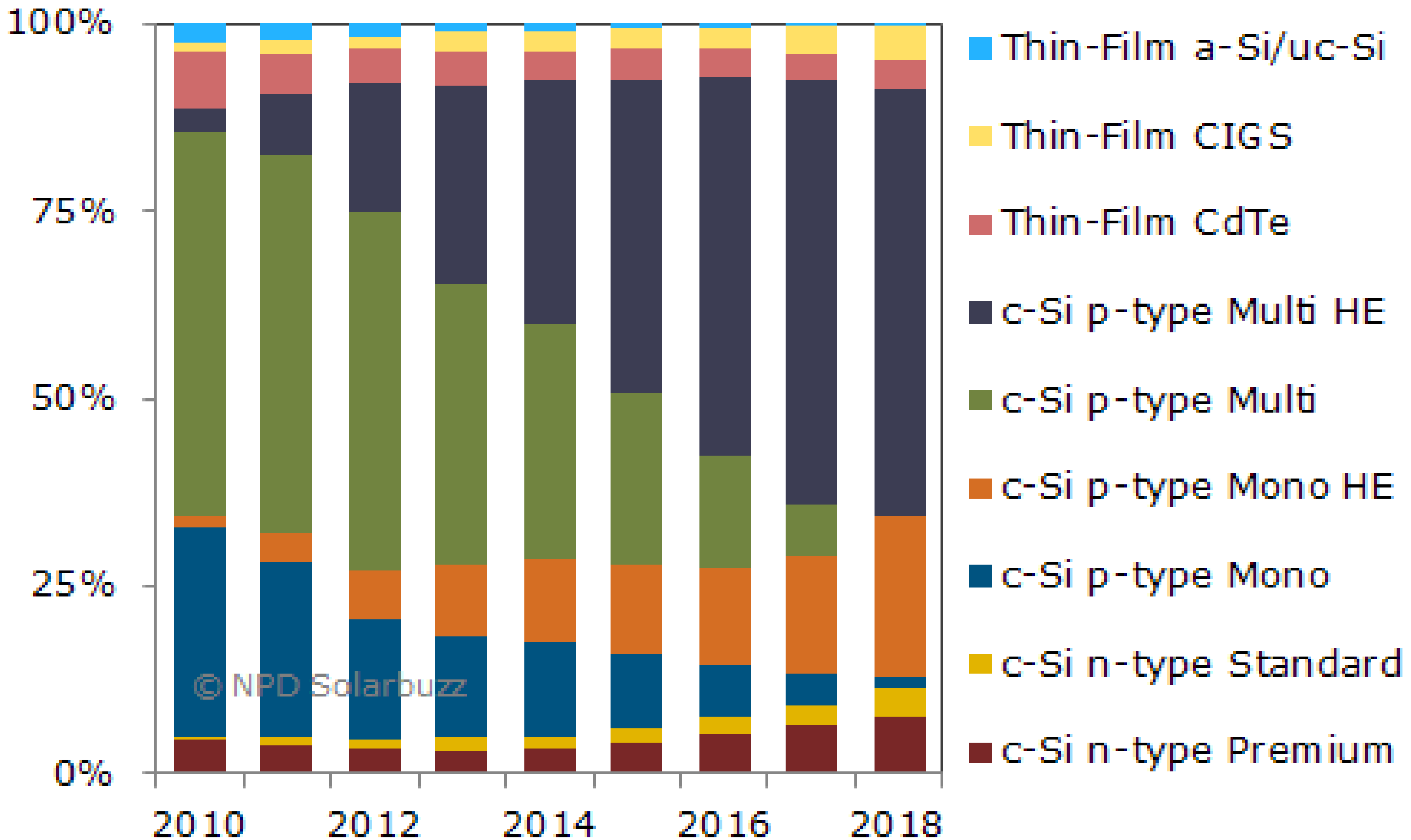


(mono)crystalline Si
with back contacts

Existing installations

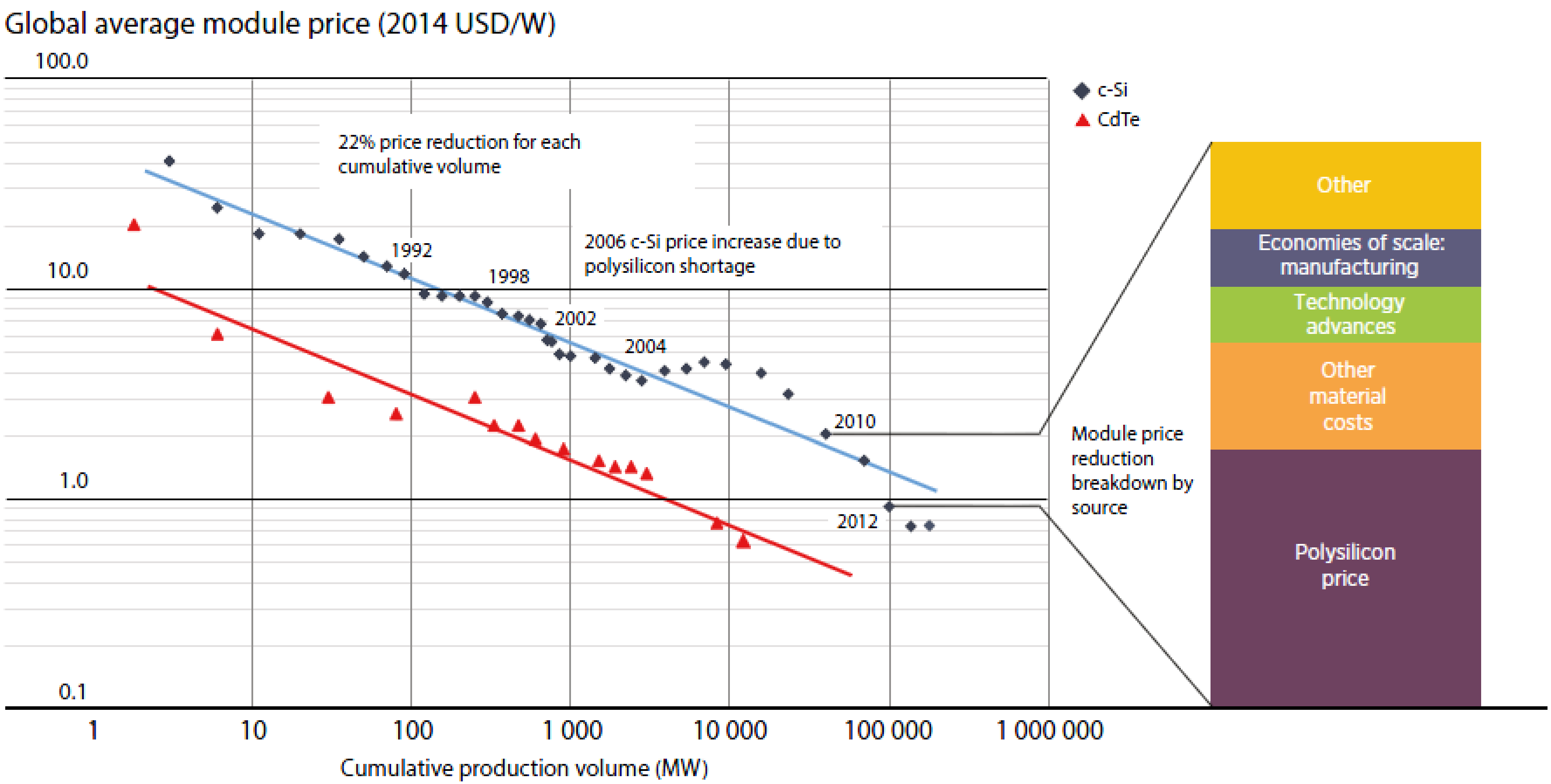


The next few years



SolarBuzz, September 2014

Price trends: (scale is the key factor)

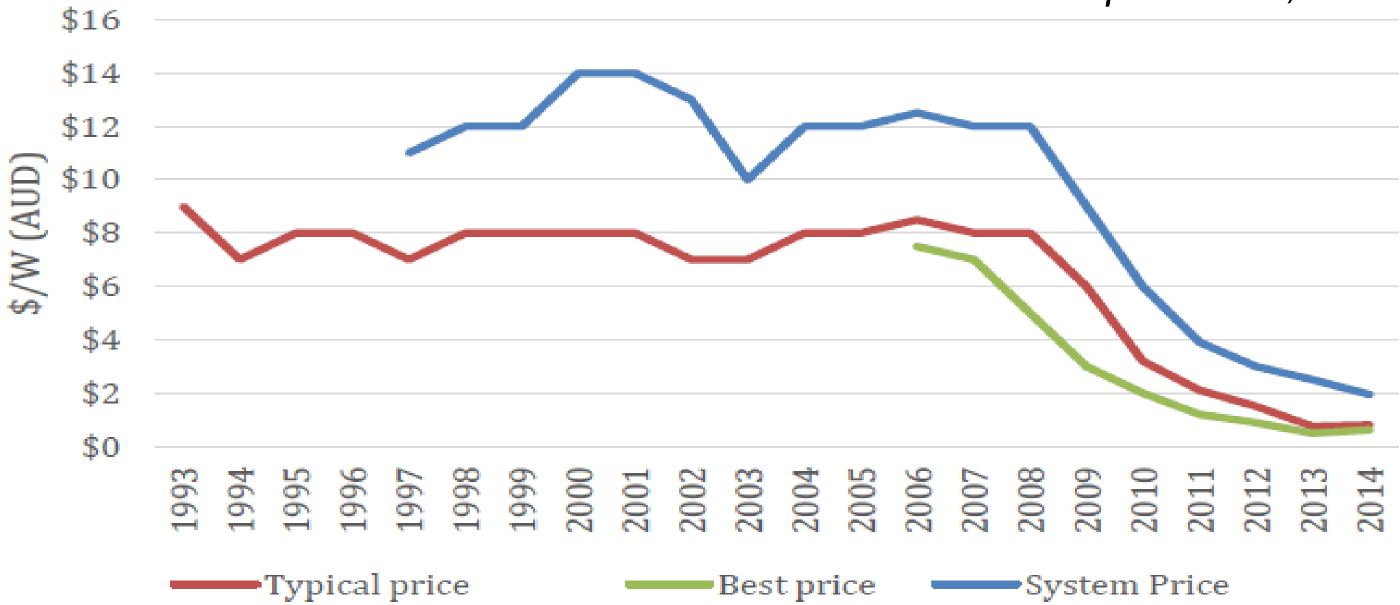


Sources: Based on data from EPIA and the Photovoltaic Technology Platform, 2011; GlobalData, 2014; GTM Research, 2014; Liebreich, 2011; pvXchange, 2014 and IRENA analysis.

Sourced from: IRENA (2015), *Renewable Power Generation Costs in 2014*

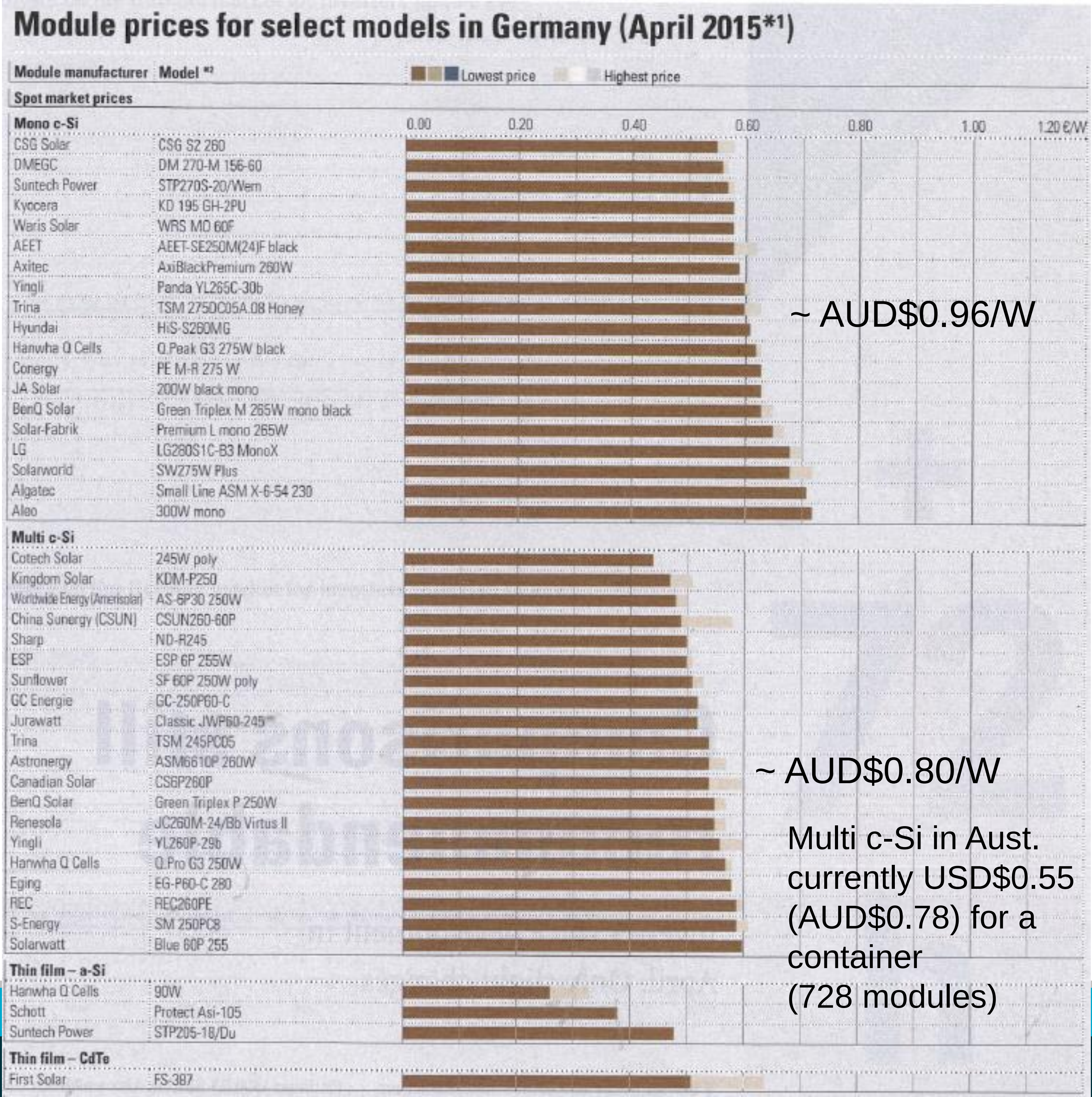
Prices in Australia

Source: *Australian PV in Australia Report 2014, APVI, June 2015*



Cost category	Average (AUD/W)
Module	0,77
Inverter	0,33
Other (racking, wiring)	0,21
Installation	0,35
Customer Acquisition	0,08
Profit	0,36
Other (permitting, contracting, financing)	0,04
Subtotal Hardware	**1,31**
Subtotal Soft costs	**0,83**
Total	**2,14**

Are we paying more than overseas?



~ AUD$0.96/W

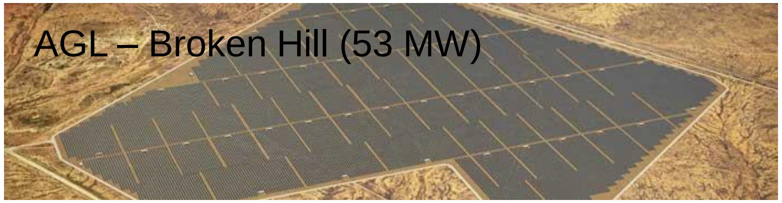
~ AUD$0.80/W

Multi c-Si in Aust. currently USD$0.55 (AUD$0.78) for a container (728 modules)

Sourced from: Photon International magazine (6-2015)

System size trend

Royalla 20MW
(2014 FRV lowest FiT bid @ 18.6c/kWh)



Timeline of the largest PV power stations in the world

Year[a]	Name of PV power station	Country	Capacity MW
1982	Lugo	USA	1
1985	Carrisa Plain	USA	5.6
2005	Bavaria Solarpark (Mühlhausen)	Germany	6.3
2006	Erlasee Solar Park	Germany	11.4
2008	Olmedilla Photovoltaic Park	Spain	60
2010	Sarnia Photovoltaic Power Plant	Canada	97
2011	Huanghe Hydropower Golmud Solar Park	China	200
2012	Agua Caliente Solar Project	USA	290
2014	Topaz Solar Farm[b]	USA	550
2015	**Solar Star**[b]	USA	579

Also see list of noteworthy solar parks
(a) year of final commissioning (b) capacity given in MW_{AC} otherwise in MW_{DC}

2-Gigawatt Solar Project Plan In Queensland Receives Approval

(!!)

Trends in research

[*42nd IEEE PV Specialists' Conference (New Orleans)*]

- 1029 presentations; 4300 authors from 46 countries

  (56% from outside US – Japan, China, India, Taiwan, Australia all prominent)
- Improving (high-tech) inline monitoring & robotics during manufacturing
- Translating high-efficiency methods into lab production –

  (narrower contacts, carrier selectivity, surface passivation, better light-trapping)
- Nanostructures for spectral manipulation
- Perovskites
- Overall trend in topics shifting more toward *systems, reliability and resource*

Industry priorities:

- Taking high-efficiency cell designs into mass production
- Driving down the cost of utility-scale systems

PV Performance Laboratory

Standardising PV measurements in Australia; understanding performance and durability under Australian conditions; supporting an Australian PV industry..

PV performance

CSIRO and ARENA have recently unveiled a suite of facilities aimed at better understanding the performance of solar cells and modules under Australian conditions. The new PV Performance Laboratory at Newcastle includes NATA accredited testing of solar cells, plus calibrated flash testing of modules, and an advanced outdoor facility for characterising a solar module's response to a host of environmental variables. ***Dr Chris Fell*** *believes the new facilities will provide important information for researchers, and assurance for the local PV industry and community that is long overdue in Australia.*

DRAMATIC REDUCTIONS IN THE PRICE of solar panels over the past five years have meant the cost of large scale solar is now competitive with coal fired power on an energy delivered basis. Many believe the last remaining hurdle for solar PV is that, like many renewable energy sources, the output varies over time in a complex way that is not trivial to predict. Since the output of PV systems depends on the weather, time of day, time of year and location, a stable electricity supply demands a thorough understanding of these variables and how the PV module responds to them.

But stable operation on the electricity grid isn't the only challenge created by the complex output of photovoltaics. Several important questions have complicated answers, such as: Pricing – how is the output defined? Sizing – what size system will meet the requirements for power and energy? Financing – what will the return on investment be? Procurement – which type of solar panel best suits the site and application? Quality – how do we know if a system is well engineered? Durability – how do we observe subtle degradation in panel performance? Maintenance – how do we detect faults in the system?

The showpiece of the CSIRO PV Performance Lab is an outdoor research facility for diagnostic analysis of up to 60 PV modules. Testing modules individually (rather than assembled into complete systems) allows CSIRO to deconstruct their output and show how it depends on the prevailing environmental variables; irradiance, temperature, solar spectrum, and solar angle.

With this information it is possible to predict the performance of a given module under an arbitrary set of environmental conditions. This brings a number of benefits for understanding large-scale PV power systems. For example, since the output of the modules can now be easily predicted, it is possible to quantify the losses that occur at the system level, e.g. cabling losses, soiling, module mismatch, maximum power point tracking, inverter losses, grid matching and downtime. We can put a number on the effectiveness of a given system design, therefore benchmarking it against other systems, regardless of where those systems are installed.

The information extracted also allows different PV modules to be compared for their real outdoor performance. As input to calculations known as energy yield models, the information allows module performance to be simulated for any site in Australia (actually anywhere in the world). CSIRO is using the facility to examine the effectiveness of these models, which ultimately underpin all commercial software packages for predicting the output of PV systems.

Tests and measures

Another issue being addressed by the new laboratory is the quality of PV modules arriving on Australian shores. The facilities include a high-end indoor flash solar simulator for measuring the output of solar panels under Standard Test Conditions. This is the same measurement the manufacturers use to rate the module output power in the factory. A number of importers have already taken up this service to check they are getting what the manufacturer claims.

With flash testing, understanding measurement uncertainty is the key. Issues such as pulse duration, light uniformity, spectral mismatch and temperature control can lead to unacceptable measurement uncertainties in many, if not most, flash testing systems. His laboratory works with the US Department of Energy, National Renewable Energy Laboratory (NREL), to maintain three calibrated primary reference modules. The reference modules are used to ensure the CSIRO flash test system is as accurate as it is possible to be.

Accreditation's stamp of approval

The third pillar of the PV Performance Lab is an IEC17025 accredited laboratory for measuring the efficiency of solar cells. Although approximate measurements of solar cell efficiency are quite straightforward, accurate measurements require careful compensation for errors in the light level, light spectrum and cell temperature. These corrections can be challenging to perform and require well characterised and calibrated equipment.

As a result, scientific journals and funding bodies often prefer or even require research results to have been measured by an accredited laboratory. This is especially the case when breakthroughs in cell efficiency are being reported. Up until now, Australian researchers have had to send their valuable best devices to Europe or the USA for this type of measurement.

CSIRO's accreditation for PV measurements was awarded by NATA in January 2015 following a two-year project to develop a quality system, perfect procedures, characterise measurement tools and perform a detailed analysis of measurement uncertainties. Maintaining the accreditation requires annual calibration of 18 instruments, as well as participating in several international comparison measurements each year, and many hours of internal testing and cross-checking.

CSIRO hopes the new facilities will help simplify decisions around solar for Australian consumers, improve the quality of solar products coming into the country, and assist Australian developers to make the right choices when it comes to the type and design of large scale solar systems.

Steady path

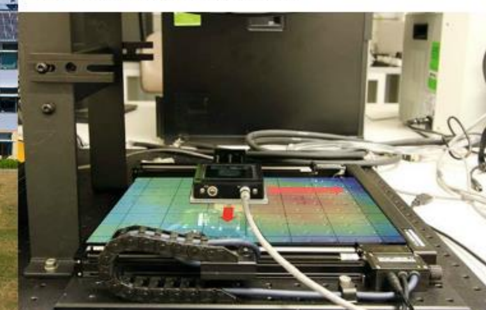
The genesis of the PV performance laboratory dates back to 2006, when CSIRO was part of an Australian consortium of scientists developing new organic solar cells. The tiny polymer-based cells on glass substrates behaved differently to the usual silicon cells so their performance was difficult to measure properly. The group noticed that measurement practices varied considerably across the consortium, and it was difficult to tell which approaches led to the best cells. Thus commenced a decade long search for perfection in solar cell measurements that Dr Fell says may never really be over.

In 2007 he approached the National Association of Testing Authorities (NATA) and determined the standard IEC 17025 would represent a stamp of approval that would show they were doing it right. What followed was eight years of trial and error, successes and failures, reading literature, talking at conferences, and the inevitable applications for funding. Postdocs and students have come and gone in that time; in all nearly a dozen people have worked on the project, and outside CSIRO at least that many again have contributed in some way.

More information about the facilities and services can be found at www.csiro.au\pv-performance.

The facilities described in this article were constructed with support in part from ARENA.

Dr Chris Fell is a physicist with a passion for photovoltaics and has been part of the Australian PV research community since 1998. In 2005 he joined CSIRO and assembled a group that went on to develop the first large area organic solar cell in Australia. His vision is to build Australia's premier PV measurement laboratory, fulfilling an equivalent role as key international labs like NREL, Fraunhofer-ISE and ESTI. Chris and his team are based at the CSIRO Energy Centre in Newcastle.



Reproduced from Solar Progress magazine (06/2015)

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