PL Imaging – Key Technology behind Better Cheaper Solar Panels

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BT imaging

Swinburne University, 17 October 2019

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- **Why silicon solar cells matter**
  - The role of silicon PV in the global energy revolution, past and future
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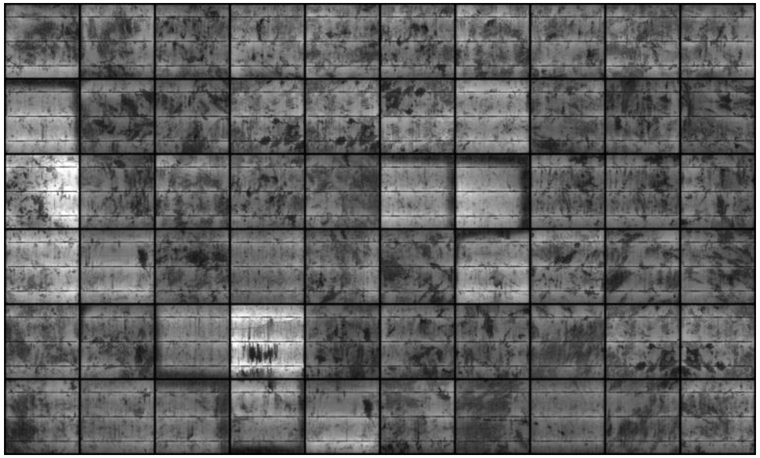
  - Photoluminescence imaging – a UNSW technology that has made a difference
- **Our commercial journey**
  - BT imaging
- **Hints for aspiring entrepreneurs**
- **Acknowledgement**



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Motivation
- Why Photovoltaics matters?

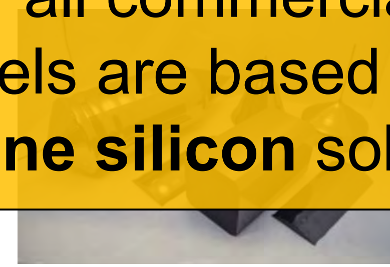
- We live in the age of anthropogenic climate change
- Energy supply is a major contributor to climate change
- The way we generate, distribute, store and use energy
  - must,
  - will,
  - has started to

  change **radically**

"Electricity generated using solar cells is one of several key pieces in a complex puzzle"

The PV Value Chain
- How Silicon Solar panels are made

>95% of all commercial solar panels are based on **crystalline silicon** solar cells



- Sand
- High Purity Feedstock
- Silicon Ingot
- Silicon Wafer
- Silicon Solar Cell
- Silicon Solar Module
- Photovoltaic System

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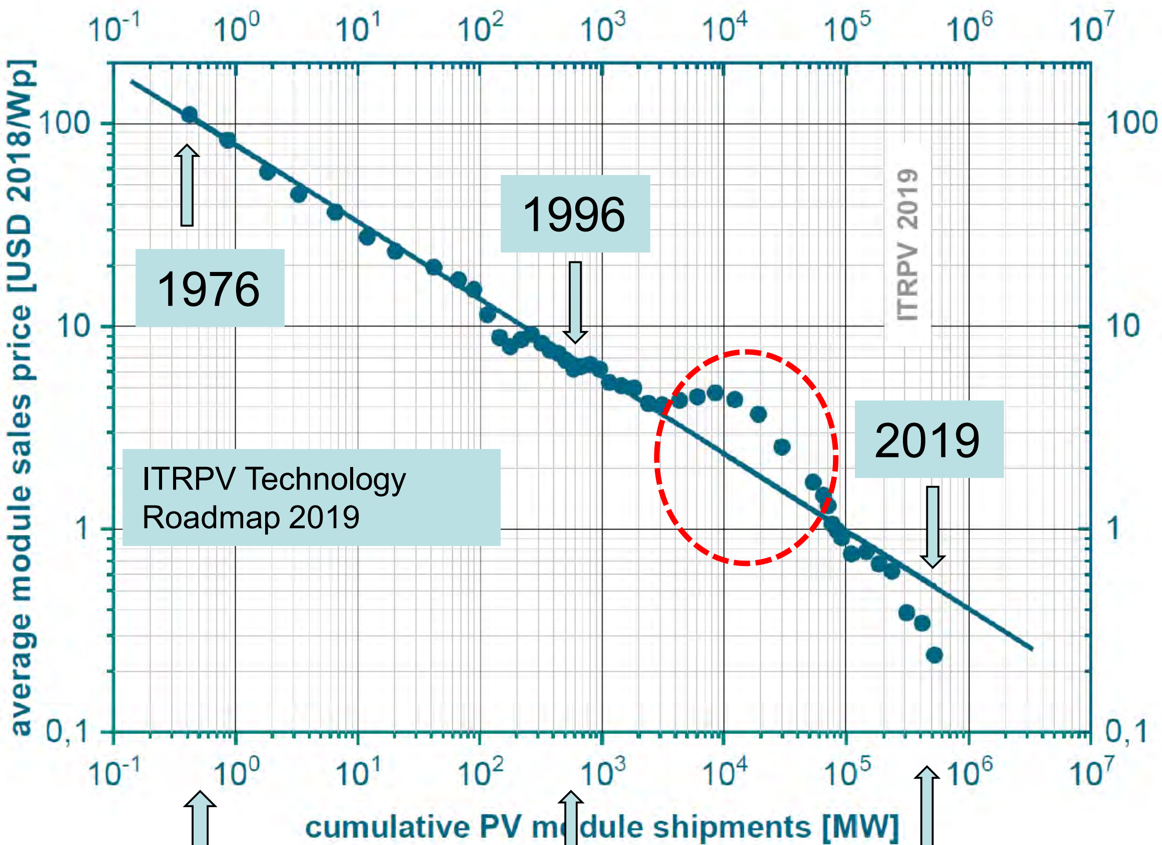
The Past

- PV learning curve



Learning Curve: Photovoltaic panel prices have followed this curve consistently for 40 years:

Prices dropped almost **500x over 40 years**

Accelerated learning rate over the last 10 years

Sun doesn't shine at night: Capacity factor!

1976: TT starts primary school

~600kW: Few 100 rooftop systems

1996: TT PhD student

~600MW: peak capacity < one coal fired power station

2019: TT at Swinburne Uni

~600GW: PV generates the equivalent of ~150 1GW power stations

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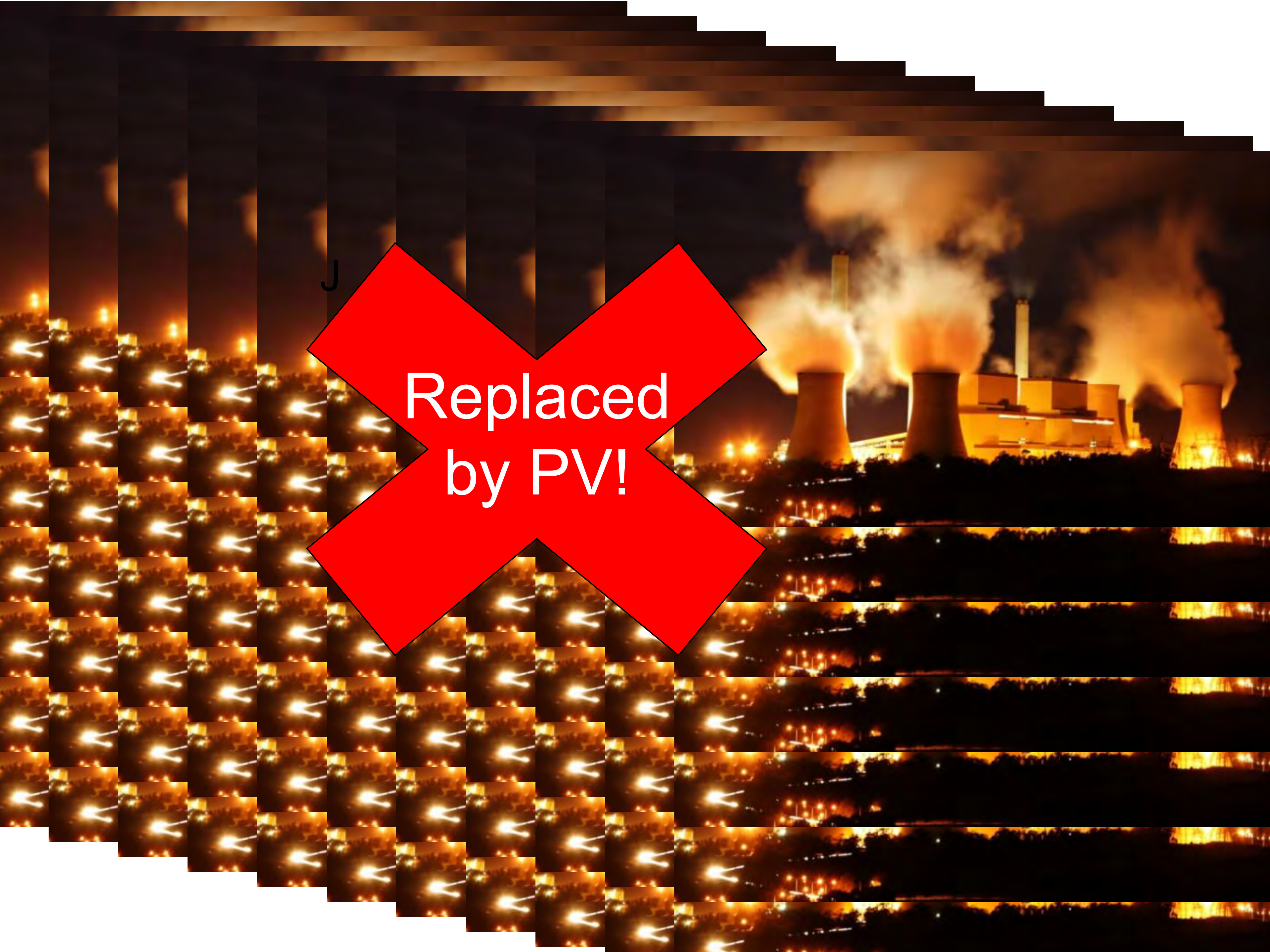
Loy Yang A power station in the Latrobe Valley: **2.2 GW**

Electricity from solar panels replaces ~75 similar stations today!

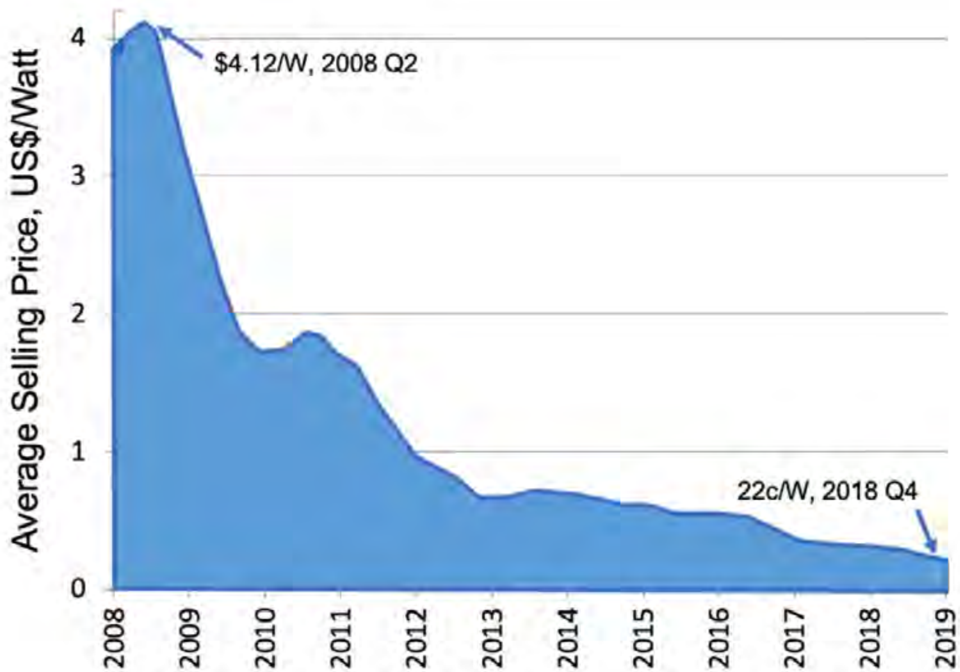
https://www.theage.com.au/politics/victoria/victoria-s-coal-fired-power-plants-the-least-reliable-in-the-country-20190614-p51xvb.html

*"Loy Yang A has experienced an **outage 29 times since the start of 2018**, including a breakdown of one of its four units, expected to take **seven months to repair**"*


J
Replaced
by PV!

The Past

- Rooftop systems now "dirt cheap"



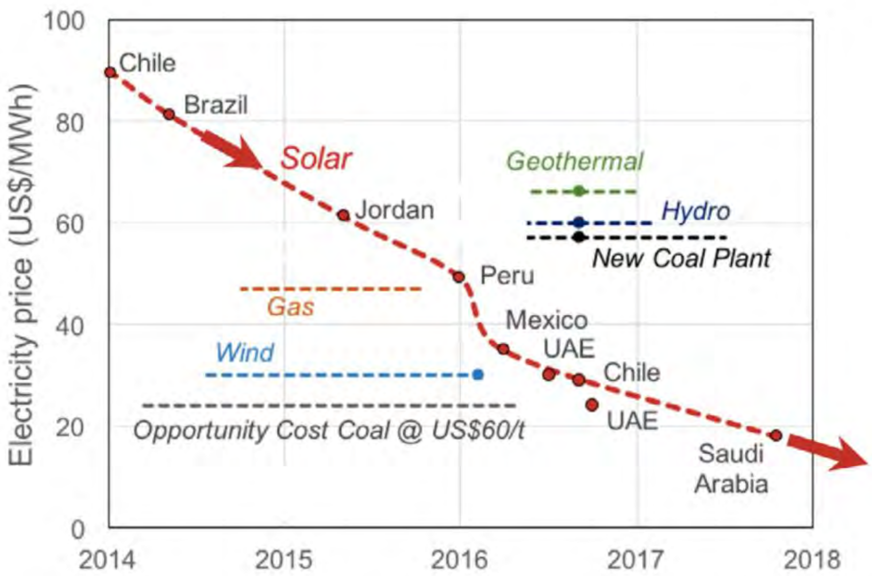
M.A. Green, Prog.Energy **1** (2019) 013001

- Unbelievable **collapse in prices**
- 22c/W equivalent to < $100 per 350W module

- Module cost for 5kW system:
  - ~US$ 20,000 in 2008
  - < US$ 1,500 in 2019

The Past

- Utility scale PV rapidly becoming the cheapest option



M.A. Green, Prog.Energy **1** (2019) 013001

$100 / MWh = 10c / kWh

A revolution in stages

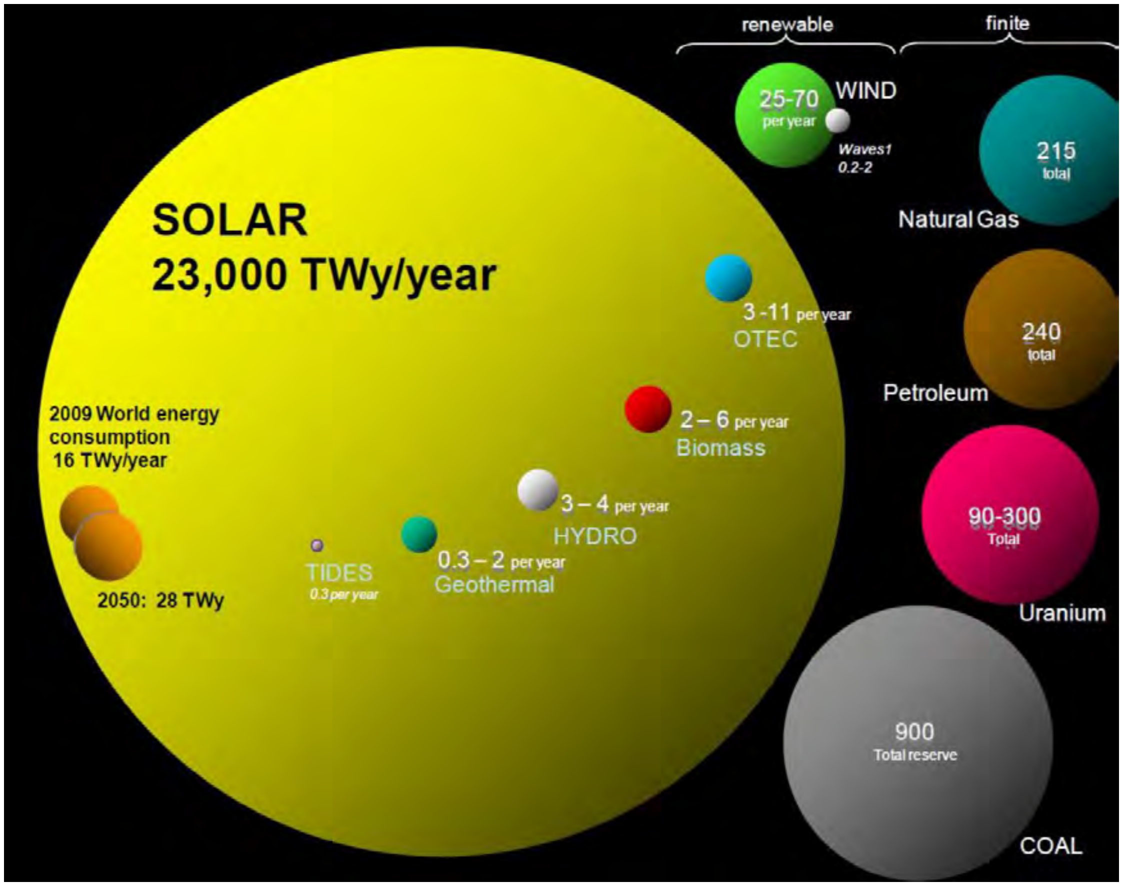
✓ **Stage 1 - Beating retail prices:** Grid parity used to be the holy grail of PV R&D

✓ **Stage 2 - Beating wholesale prices:** PV is the cheapest option for building **new** electricity generation in many countries

Stage 3 - Beating the running cost of existing plants: New PV plant cheaper than the *incremental* cost of existing coal fired power stations

The Future

Fossil Fuels are finite – Plenty of renewables

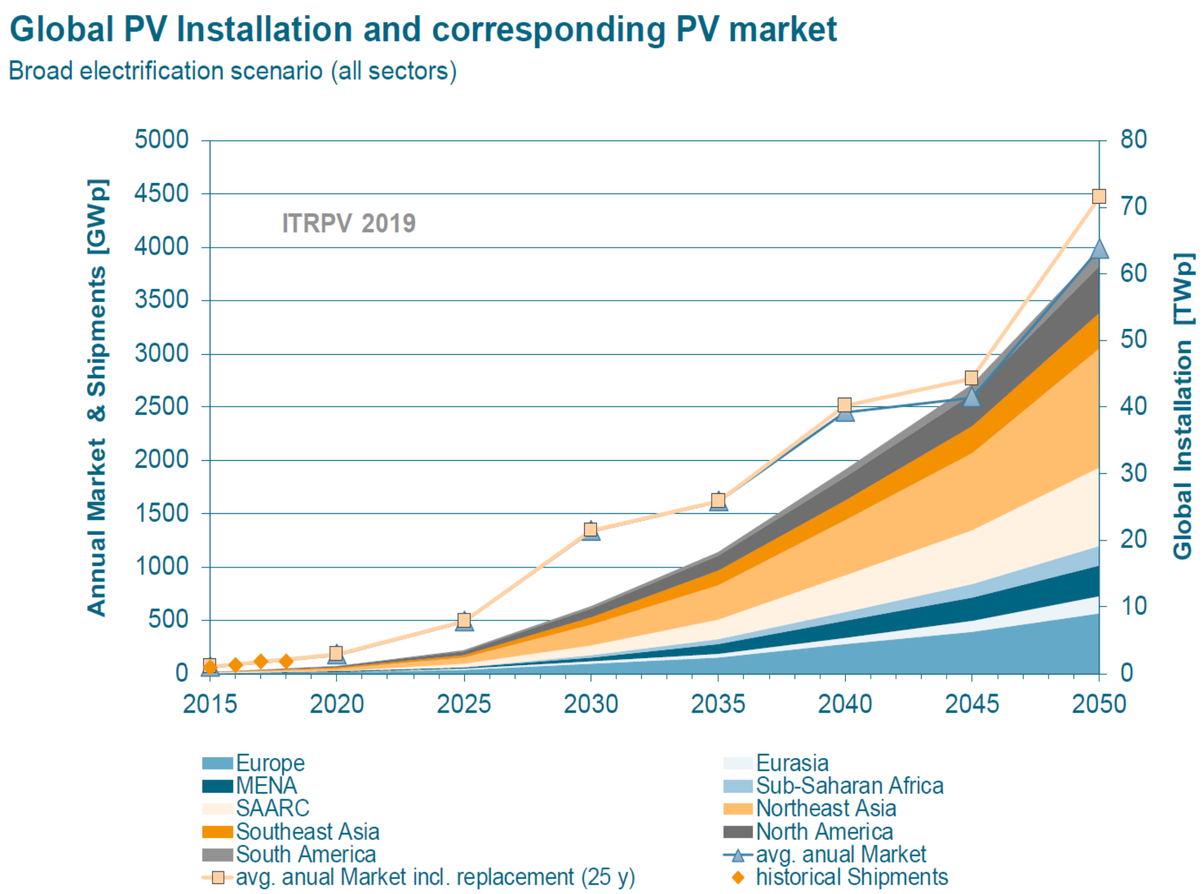


Courtesy Christian Breyer, Lappeenranta University of Technology

- 2050 global **primary** energy consumption of **28 TW**
- Estimated 900 TWy of coal resources, or 32 years of world's 2050 primary energy demand
- Fossil fuels will **not run out in my lifetime**, but possibly in my grandchildren's lifetimes
- Fossil fuels only burn once!
- Solar is by far the most abundant source of renewable energy

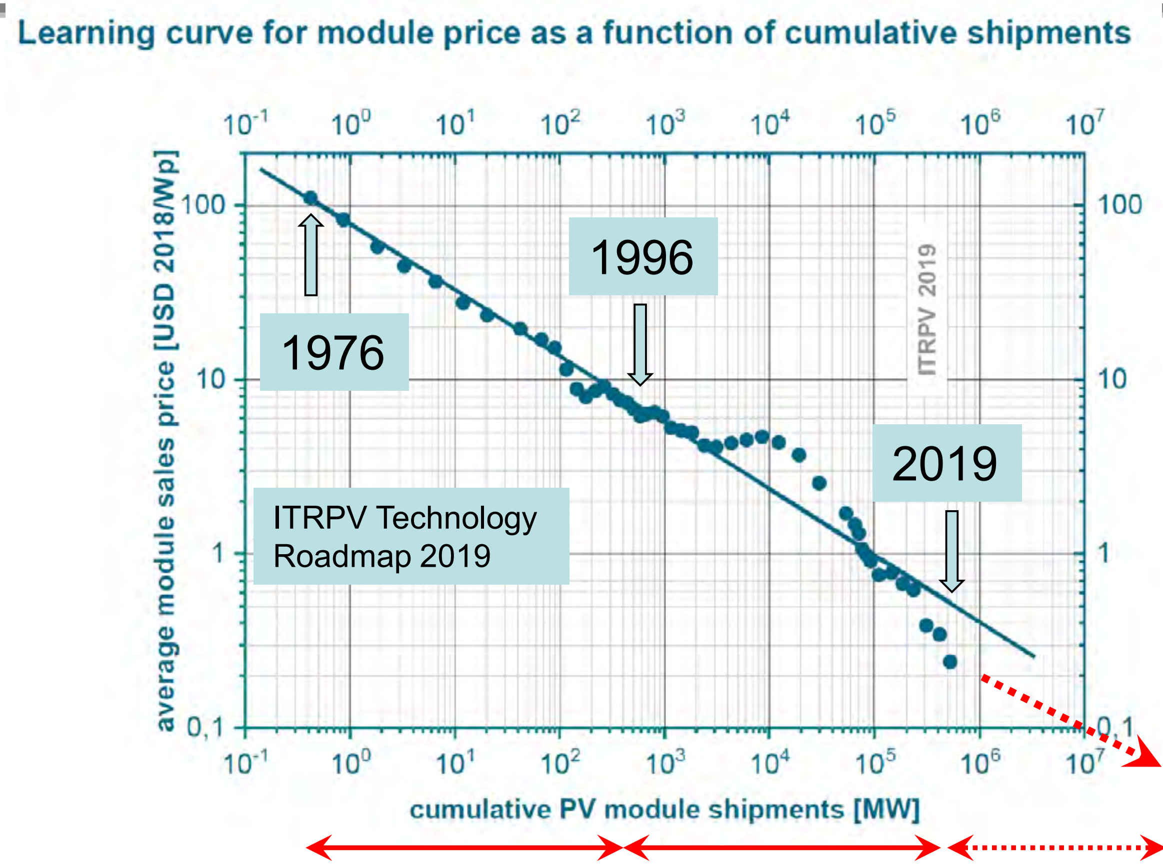
The Future

Tremendous growth of PV for years to come



- Increasing demand from electrification of transport
- PV capacity to grow to **>50 TWp** by 2050

The Future
- PV learning curve



- 50 TWp by 2050 forecast
- Requires ~80x growth over 30 years

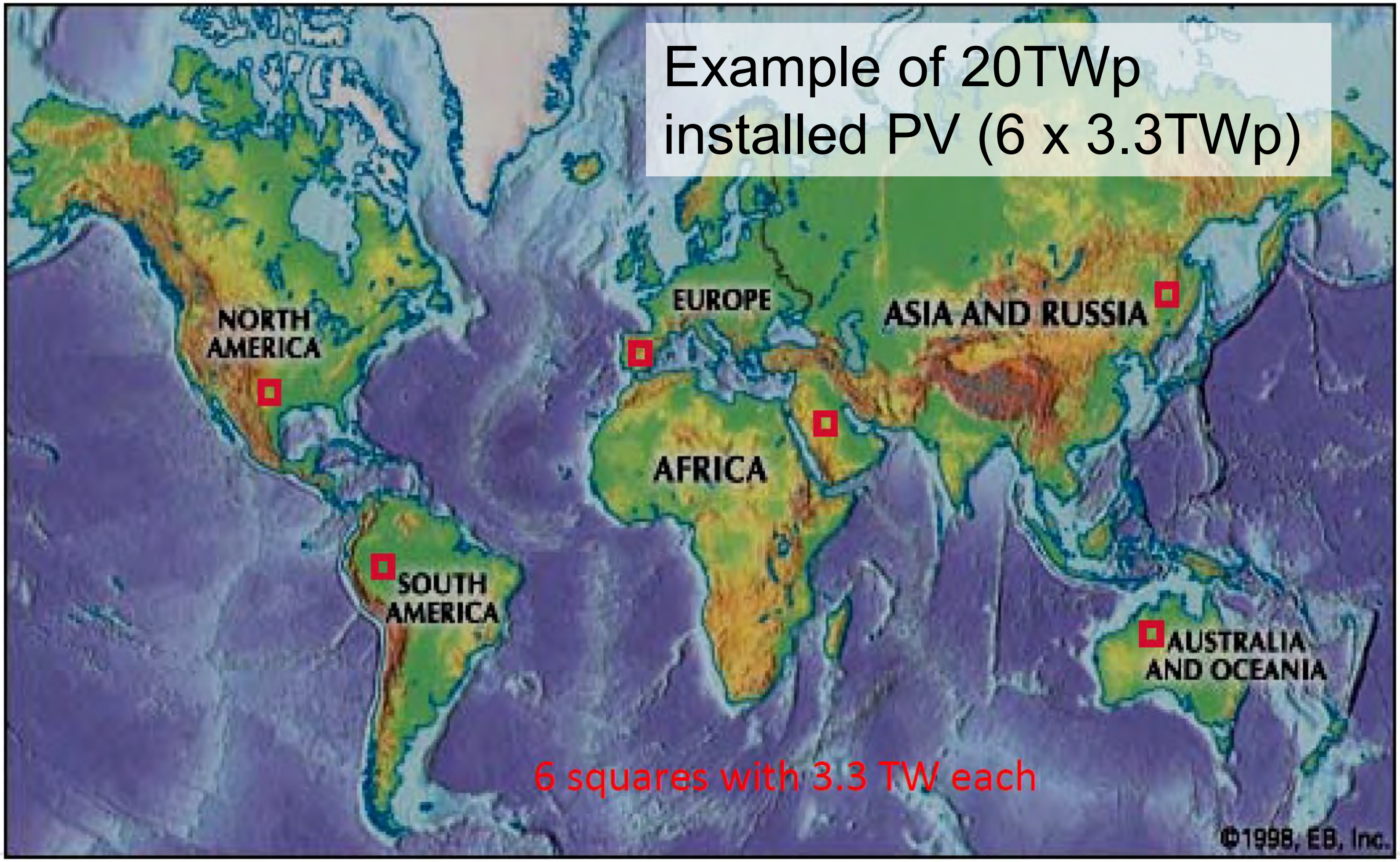
3 orders
In ~20 years

3 orders
In ~23 years

Another 2 orders over the next 20-30 years…?

The Future

- Area requirement

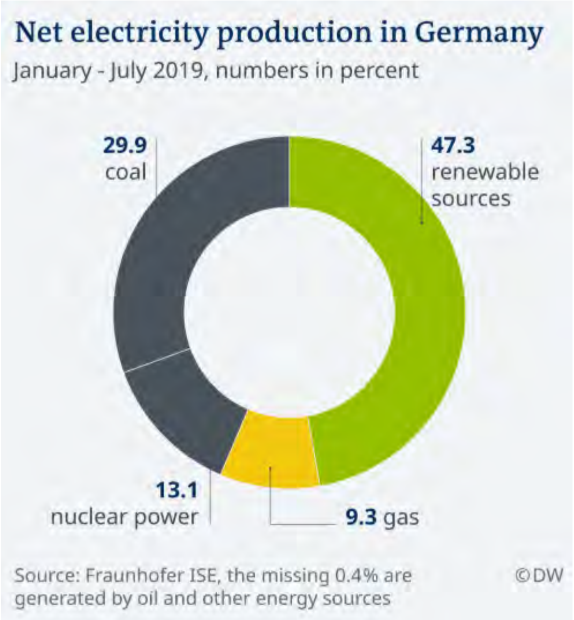


Armin Aberle,100% Renewables Workshop, ANU, 13-15 Feb 2019

The Future
- Exciting times to be in PV!

- PV generated electricity is becoming unbeatably cheap
- Globally installed PV capacity to grow to ~**50 TWp** by 2050
  - 24/7 global PV electricity generation of **~10 TW**
    - **For comparison:** 2018 global electricity generation capacity ~ 3TW
- PV is one of several key elements of an energy revolution:
  - Storage (batteries, pumped hydro)
  - Distribution (High voltage DC)
  - Demand side management
  - Energy efficiency
- Integration of a high % of renewables requires **innovation** and **systematic long term planning** (political leadership)

This can be done!



PV R&D

- Australia punching above its weight!

- PV R&D in Australia initiated and led by Prof Martin Green
- UNSW world leader in silicon solar cell technology over 40 years
- UNSW technology (PERC cells) taking over mass manufacturing
- Worlds first undergraduate PV program
  - UNSW graduates now in leading management roles in many globally leading manufacturers

Our technology

What is luminescence?

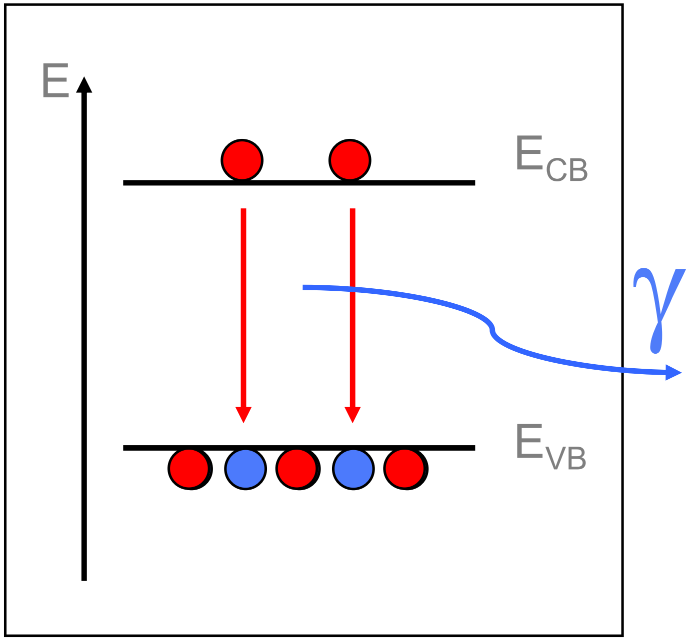
LED light bulbs are based on **Electroluminescence** (**cold emission**)

Incandescent light: Thermal emission (i.e. something gets really hot)

Photoluminescence: Emission of light under illumination with a different color

Our technology

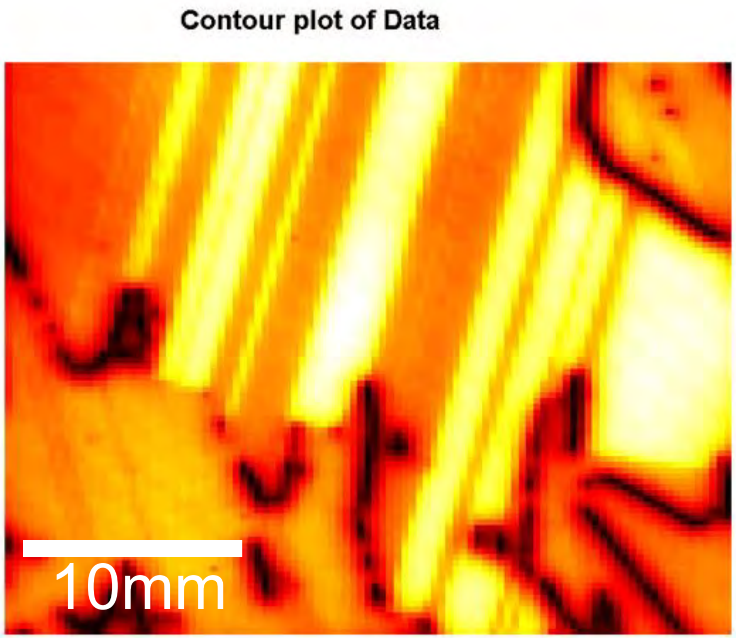
Some technical details for the nerds

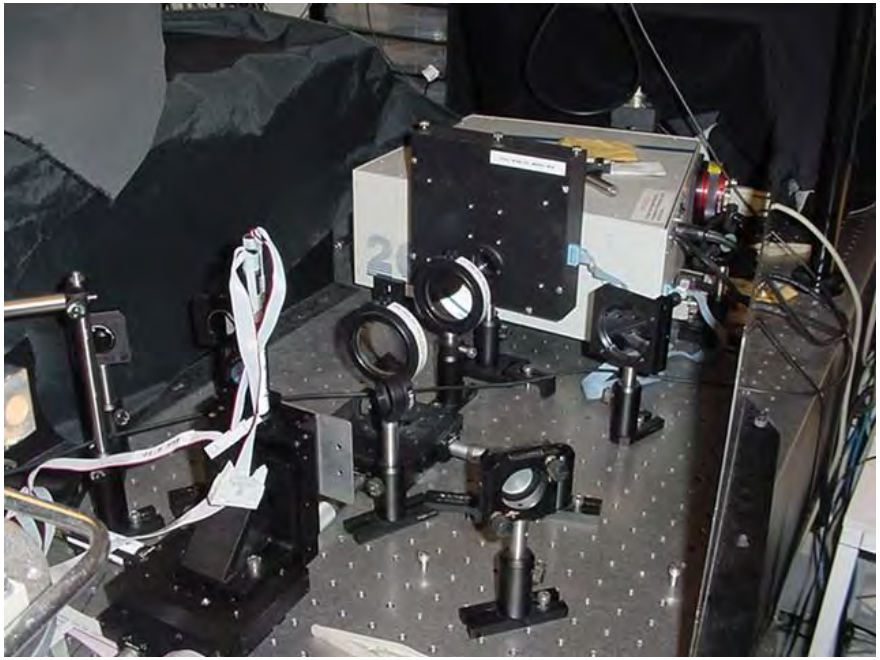


- Luminescence is emitted from semiconductors (like silicon) when certain electronic transitions take place
- Luminescence intensity closely related to key material parameters (e.g. minority carrier lifetime)
- **Silicon** is a **very inefficient luminescence emitter,** which is why LEDs (and lasers) are made from other semiconductors

Our technology

2004: Early experiments with raster scanning



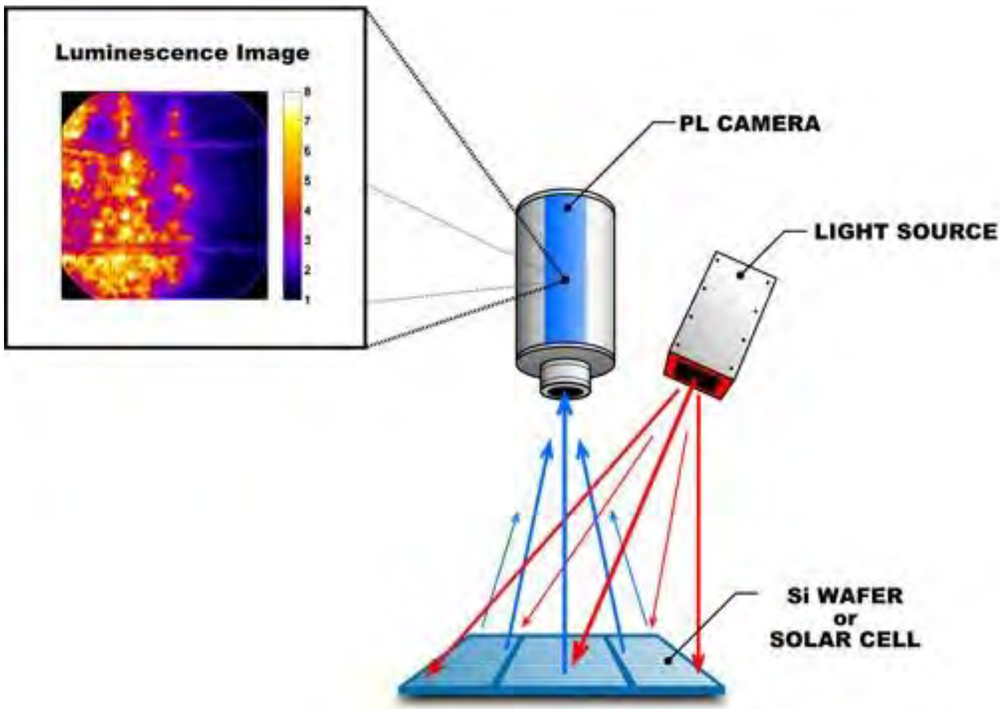


Scanning spectral PL tool: **several hours per sample, TOO SLOW!**

→ "Let's try camera based PL imaging!"

Our technology

2005: First PL imaging prototype



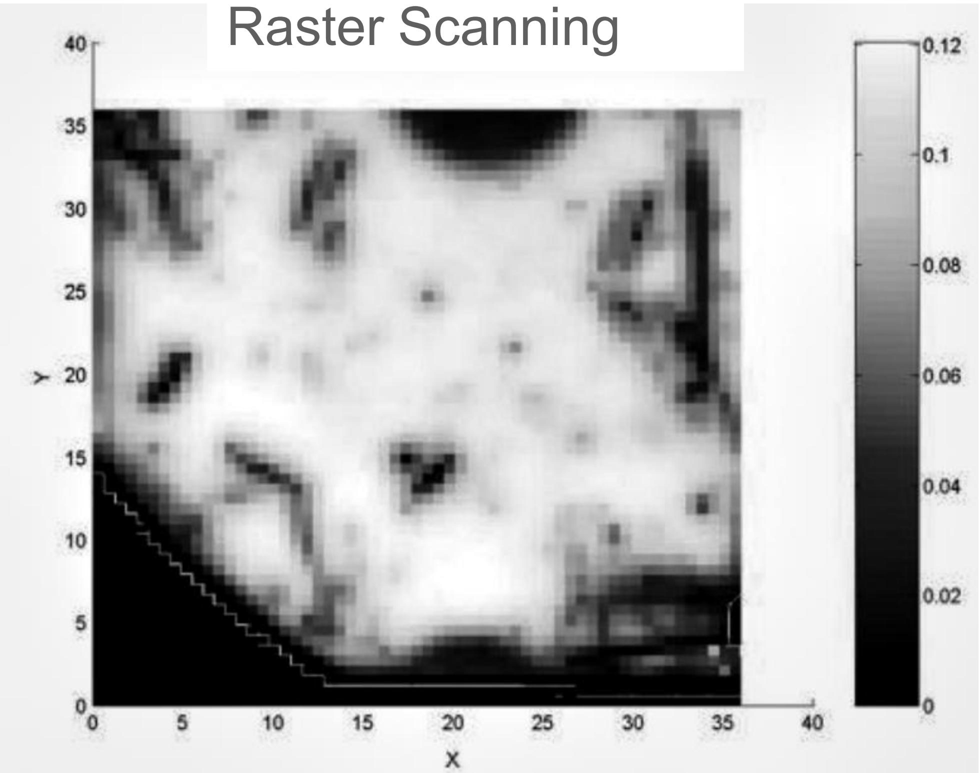
First PL imaging prototype
in the UNSW EE building

- The 100W laser challenge
- System is still in operation at UNSW.

Our technology

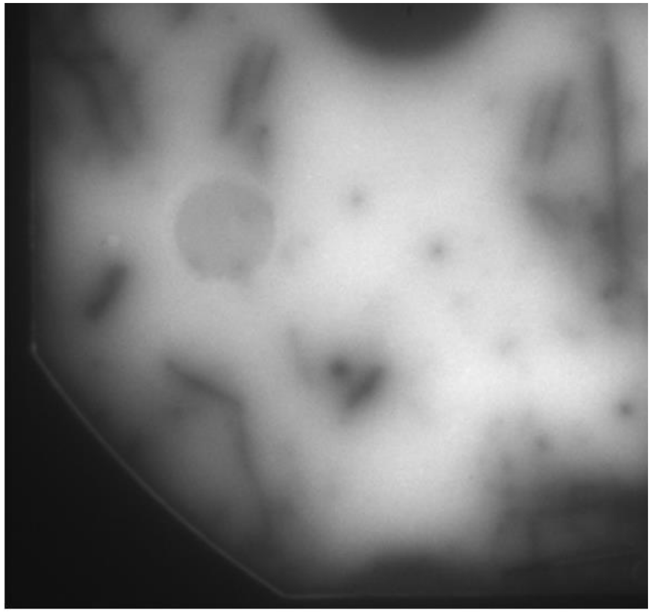
2005: First PL images

Raster Scanning



- Up to several hours
- Typically 1mm per pixel

PL imaging



- 1s
- 0.1mm per pixel

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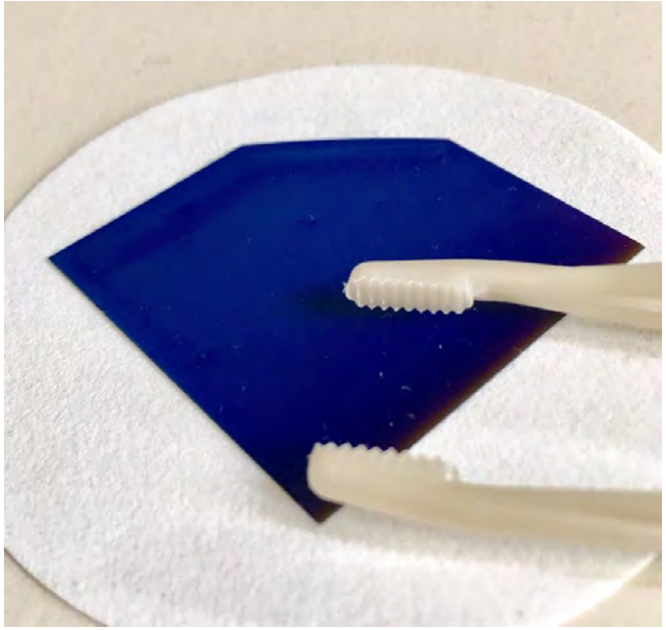
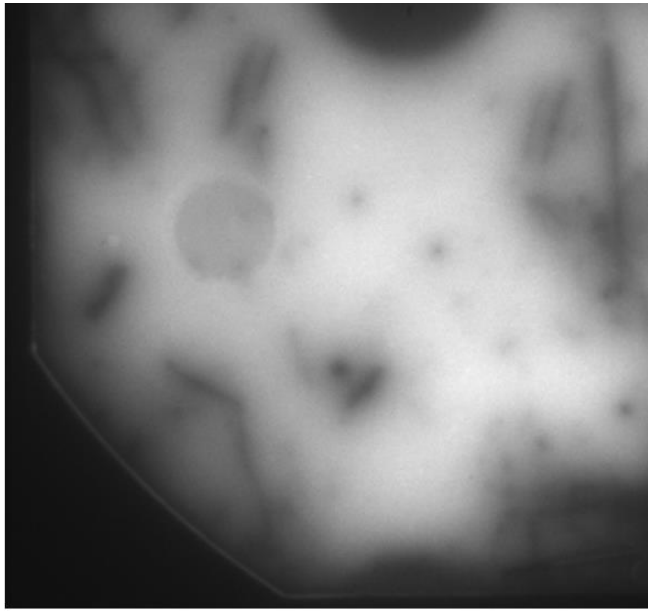
Our technology

2005: First PL images



What this sample
actually looks like…

PL imaging



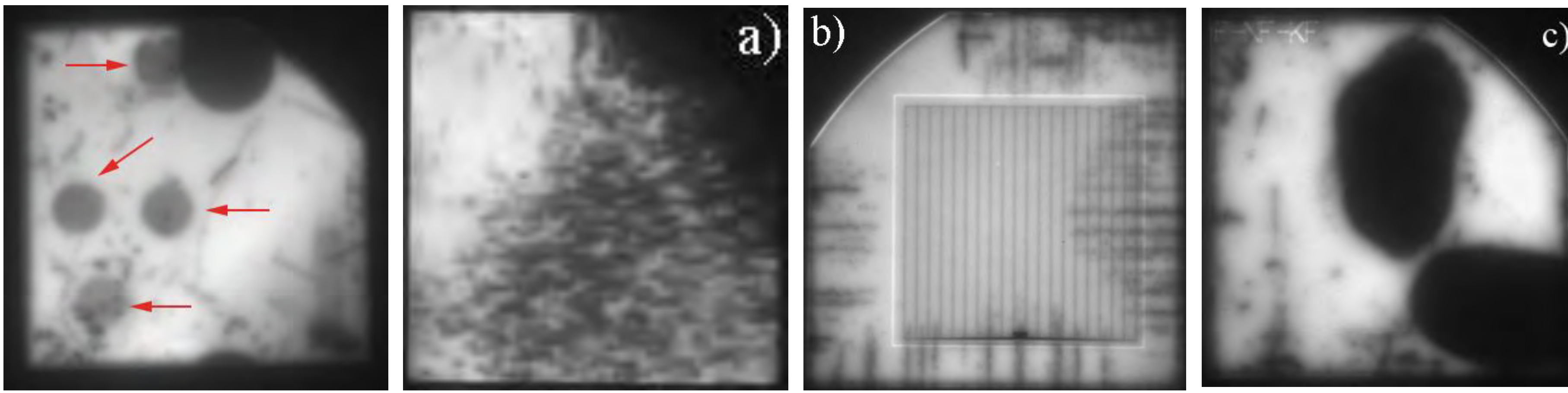
- 1s
- 0.1mm per pixel

Heureka!

2005-2006

- Rapid adoption by the R&D team at UNSW

PL imaging becomes a standard tool for routine inspection at UNSW



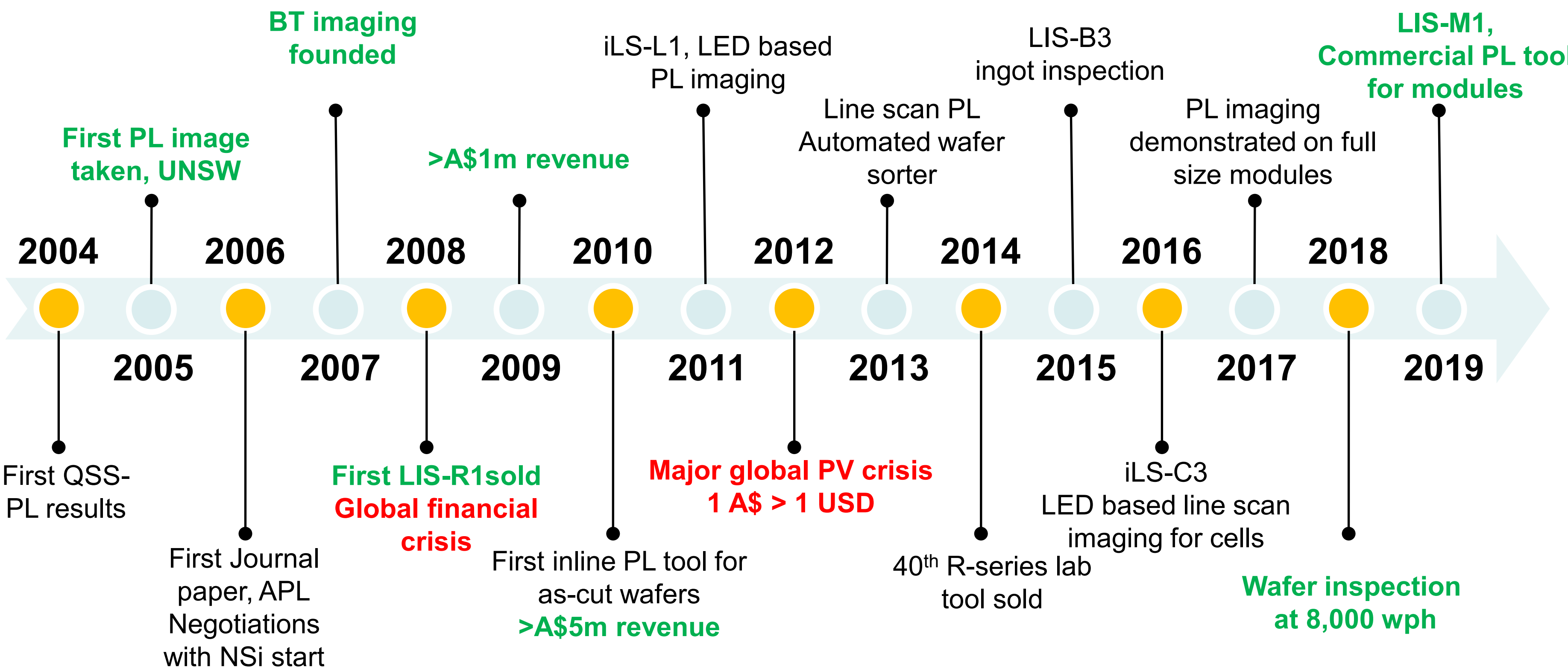
- Wide range of material- and process induced faults detectable
- Commercial potential becomes apparent in discussions with UNSW R&D teams

2006-2008

- First commercial steps

- Interest in PL imaging systems from industry emerges following "word of mouth" and publications
- Robert Bardos and Thorsten Trupke decide to start a commercial venture
- Commercial negotiations with New South Innovations start in early 2006
- BT imaging founded in late 2007 by Bardos & Trupke
  - A$1m seed investment, managed by Allen & Buckeridge
  - TT switches UNSW academic position to 1d/w (still 0.2 FTE to date)
- REC, Norway: UNSW visit in Dec 2007, First PO for a (non-existent) LIS-R1
- LIS-R1 presented at 2008 EUPVSC, Milan
- LIS-R1 installed at REC in 2008

Our innovation journey



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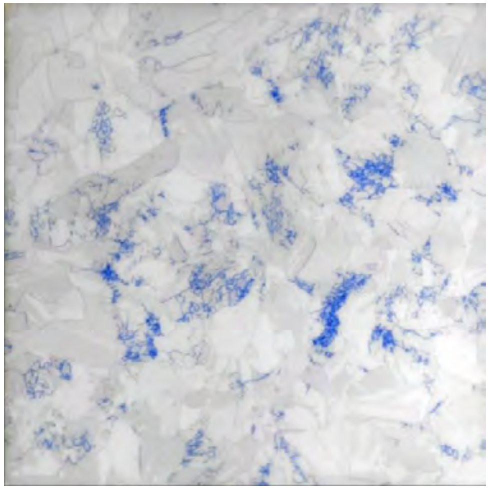
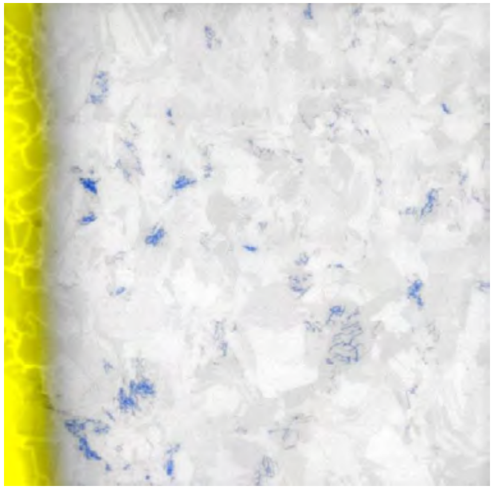
2010 - as-cut wafer inspection
an attractive value proposition

As cut wafer inspection



Dislocations



Impure edges

- These defects are detrimental to solar cell performance!
- PL imaging the only technology that is fast enough!

- Potential for tool sales into thousands of production lines
- **2010 annual revenues >A$5m**
- **Massive industry growth!**
- Attractive value proposition for further investment (given the anticipated industry growth)
- Several additional investment rounds including investments by:

uniseed

APPLIED MATERIALS®
make possible

2008-2019

- Wide range of applications for PL imaging

Offline (lab) applications

- Process monitoring
- Minority carrier lifetime imaging
- Series resistance imaging
- Shunt imaging
- Diffusion length imaging
- Fe concentration imaging
- J_0 - imaging
- Cell efficiency - imaging
- Bulk lifetime on bricks
- Module inspection

Inline (production) applications

- Outgoing wafer inspection (wafer manufacturers)
- Incoming wafer inspection (cell manufacturers)
- Inline process monitoring (e.g. post diffusion)
- Final cell inspection (e.g. crack detection)

2008-2019

- BT imaging expands its product range

LIS-B3

- Ingots / Bricks

iLS-W3

- Inline as-cut wafer inspection
- 9,000 images per hour!

LIS-R3

- Multi function PL/EL imaging system for bricks, wafers, cells and mini-modules
- Workhorse in R&D labs
- Widely adopted

LIS-M1

- Module inspection

BT imaging
2019 Status quo

- SME with Headquarter in Sydney
- ~30 staff, including service and sales teams in Asia
- Distribution channels in ROW
- Almost all sales are outside Australia
- >70 granted patents worldwide

Challenges

- Strong dependence on PV market in China

→ Need for diversification

- Competition (e.g. low-cost copies from China)

→ Need for continuous innovation

UNSW PL research group
Continuous innovation and technology development

- UNSW team ~10-15 people (Academic staff, postdocs and PhD students)
- Fundamental studies, e.g. physics of luminescence from solar cells
- Methods and systems development
  - Short path from Lab to Commercial product (e.g. Rs-imaging, LIS-B3, LIS-M1)
- An outstanding bunch of students:

  2019 *Shuai Nie*, 46th IEEE PVSC, Best Student Paper Award
  2018 *Yan Zhu*, World Conference on Photovoltaic Energy Conversion, Best Student Paper Award
  2018 *Raghavi Bhoopathy*, World Conference on Photovoltaic Energy Conversion, Best Poster Award
  2018 Iskra Zafirovska, UNSW Faculty of Engineering Postgraduate Research Symposium, 1st prize
  2017 *Appu Paduthol*, EU Photovoltaic Solar Energy Conference, Best Student paper Award
  2015 M.K. Juhl, EU Photovoltaic Solar Energy Conference, Best Poster Award
- Several UNSW graduates now employed at BT
  - e.g. Dr. Chao Shen, head of sales

ARENA
Australian Government
Australian Renewable Energy Agency

bT imaging inspection systems

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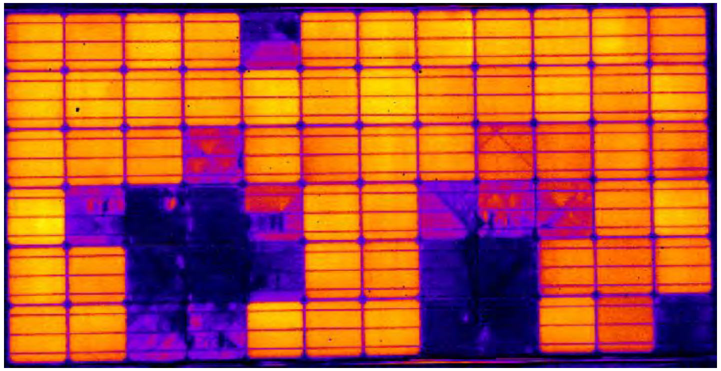
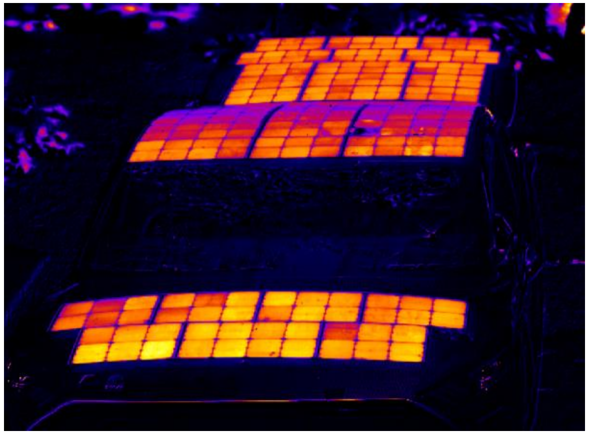
UNSW PL research group
Contactless outdoor PL inspection





POWERED BY

- Completion of CSIRO ON-Prime program
- Grant funding pending

BT imaging's 12 year journey
some thoughts from a "successful" entrepreneur

How to measure "success" in business?

- ✓ Following the "innovation journey" from conceptual idea at UNSW to a company that employs 30 people
- ✓ BTi systems are **heavily relied on** by virtually all PV manufacturers and R&D institutes globally
- ✓ PL imaging accelerates R&D and improves production globally and thereby **significantly contributes to the rapid adoption of PV**

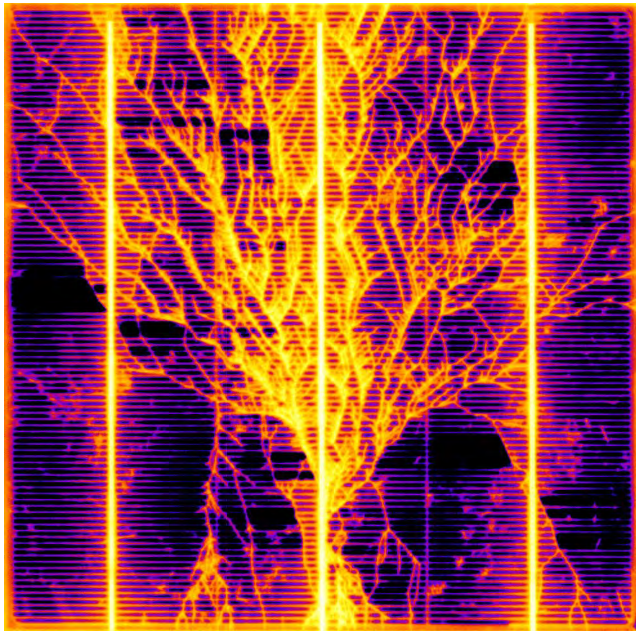
However…

- Supplying equipment into a hyper-growth industry is not a slam dunk for success
- After 12 years of operation BT imaging is still a small business

A 12 year journey
some thoughts from a "successful" entrepreneur

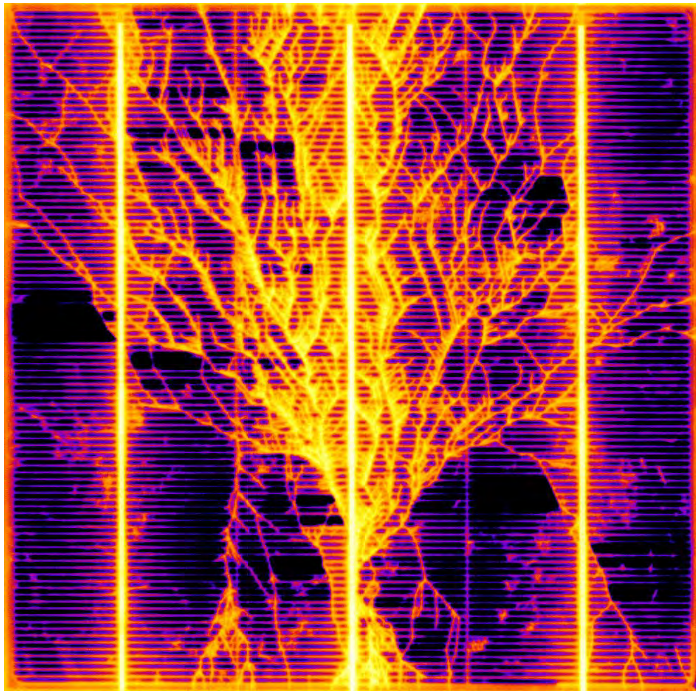
- Need for patience, resilience and stamina
- Not succeeding is likely but better than not trying
- Consider your personal situation
- Research and understand the market for your product
- Get good advice
  - The earlier the better
  - Find a mentor
- Easy, early money = expensive money
- Read and understand the documents (SHA etc)
- Share the load – let go but don't let go
- Surround yourself by people you trust
- Honesty and integrity matters
- Need good timing and lots of luck

- Have fun along the way!



Acknowledgement

- 12 years of development: PL imaging has come a long way.
- **An exciting journey:**
  - Would I do it all again? **Absolutely!**
- Thanks to
  - the outstanding teams at UNSW and at BTi, various industry partners and collaborators.
  - UNSW for enabling a flexible workplace arrangement for many years
  - the Australian Academy for Technology and Engineering (ATSE) for the fantastic recognition of our work (2019 Clunies Ross Award)
  - ARENA and the Department of Industry, Innovation and Science for financial support



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Australian Government Department of Industry, Innovation and Science

ARENA Australian Government Australian Renewable Energy Agency

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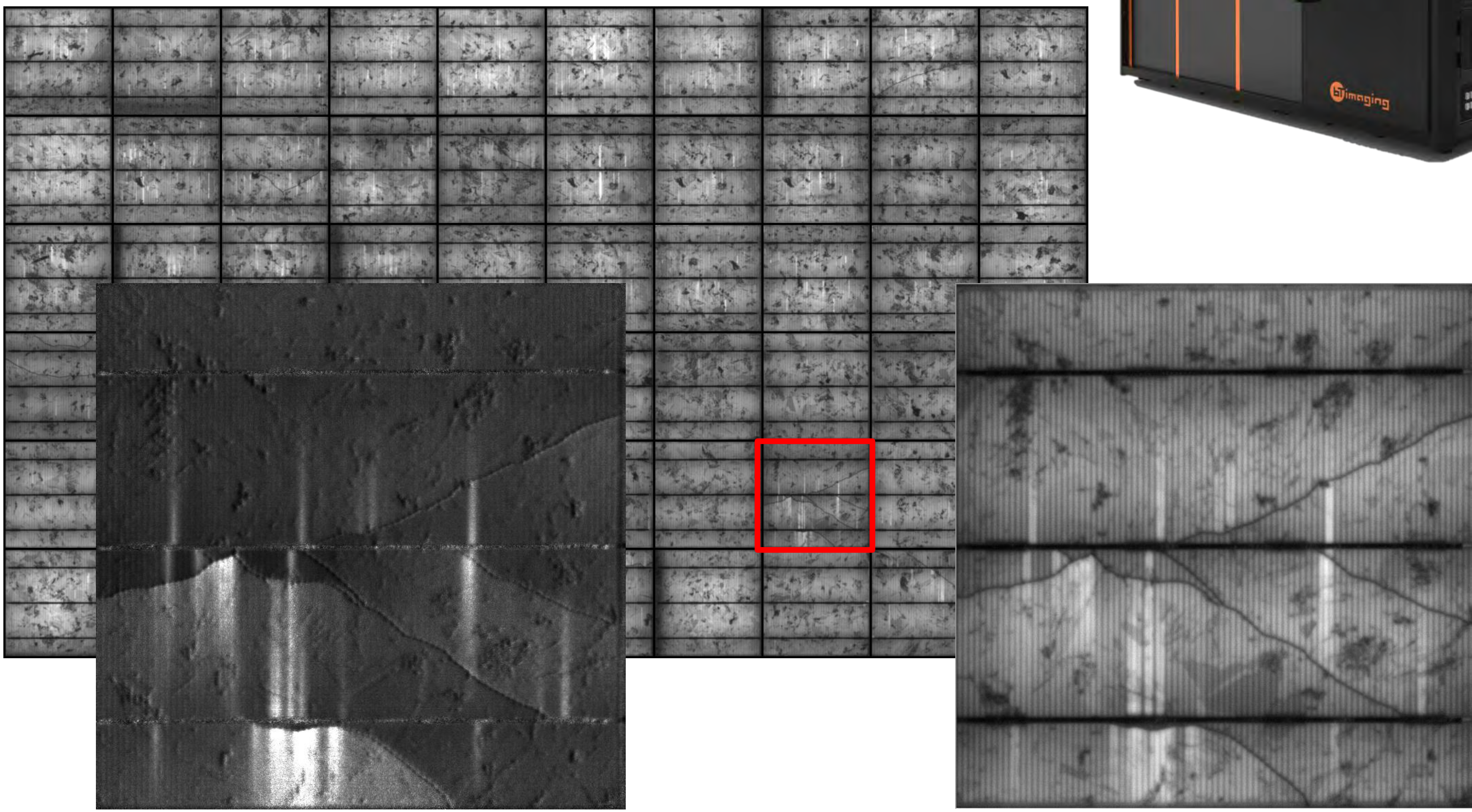
2019

- LIS-M1: Advanced module inspection



PV at the Terawatt scale –
plenty of opportunities

C. Breyer: *“Not many have yet understood what 10 USD/MWh PV generation cost means!”*

- Increasing role in electrification of transport
- Currently unviable application in the chemical industry
- Material (e.g. Copper, Aluminium) refining (e.g. in Australia)
- Direct generation of hydrocarbon fuels
- Hydrogen

http://www.cleantechconcepts.com/2017/06/creating-hydrocarbon-fuels-with-solar-power-and-co2/

PV at the Terawatt scale
- Australia once again the lucky country?

“Integration of a large proportion of intermittent solar and wind into the global energy supply chain not a trivial task!”

- **Need for innovation - creates opportunities**
  - Transport / export electricity via High voltage DC:

SUN CABLE

  - Pumped hydro storage:

Australia could produce 200% of energy needs from renewables by 2050, researchers say

New report shows roadmap for Australia to be global green energy export leader

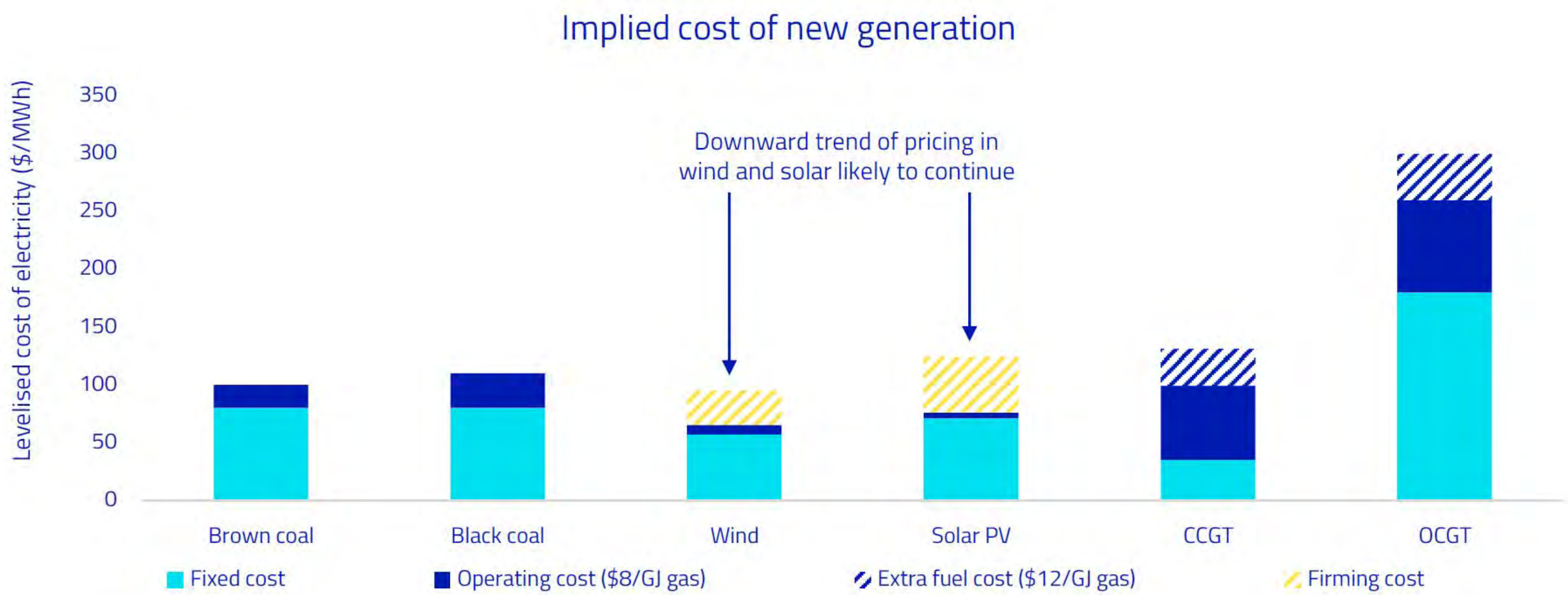
▲ Scientists from the Australian-German Energy Transition Hub say Australia could produce double its energy needs from renewables by 2050. Photograph: Calla Wahlquist/The Guardian

https://www.theguardian.com/environment/2019/sep/19/australia-could-produce-200-of-energy-needs-from-renewables-by-2050-say-researchers

Cost of new development favours renewables

A major program of new build baseload thermal development in Australia is unlikely

agl



Brett Redman, CFO, AGL Energy, 2 May 2017:

"You will notice that nuclear is not on this chart. That is because I do not consider it relevant. Coal, shown here in the two left-most bars, is also arguably no longer relevant to the debate. We do not anticipate anyone building large-scale new coal in Australia."

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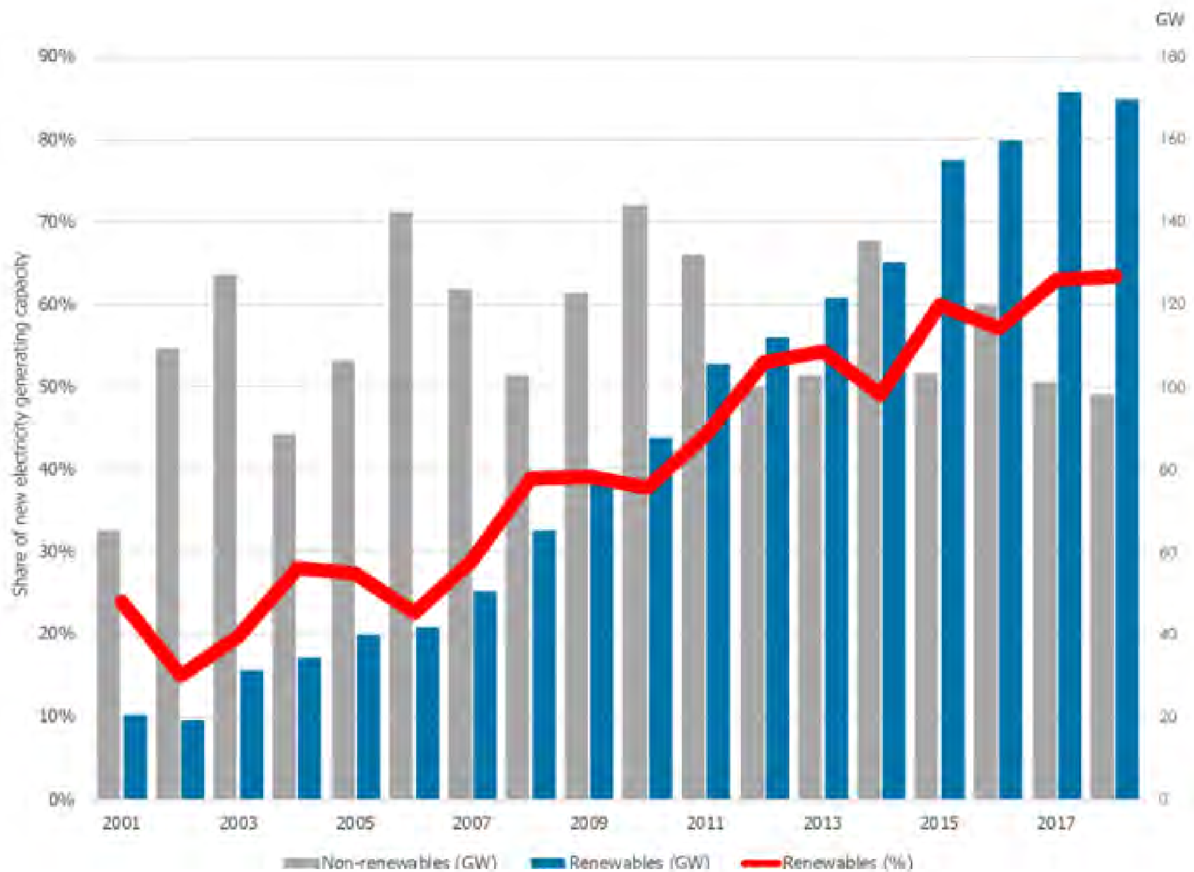
The Future

- Renewables are taking over



https://www.irena.org/newsroom/pressreleases/2019/Apr/Renewable-Energy-Now-Accounts-for-a-Third-of-Global-Power-Capacity

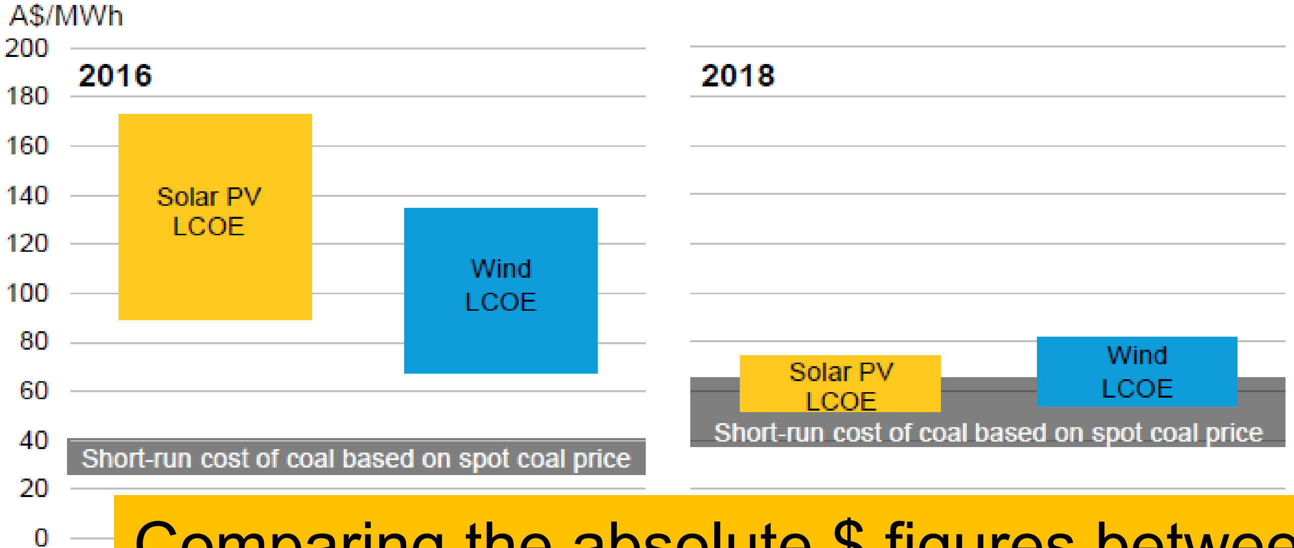
Stats:

- Total of 170 GW renewable generation capacity added in 2018
- 49 GW Wind
- 94 GW Solar

Capacity Factors not accounted in this chart

New wind & solar are now cheaper than *operating* some coal plants in Australia

Short-run cost of coal versus levelized cost of electricity of new build wind and solar in Australia



Comparing the absolute $ figures between this and previous slides may be confusing. This is because they change so rapidly, renewables going down, others going up!

Source: Blo… …e and a range of 6000kCal thermal spot prices at Ne…

BloombergNEF

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Options for a future electricity system
- High Voltage DC Transmission

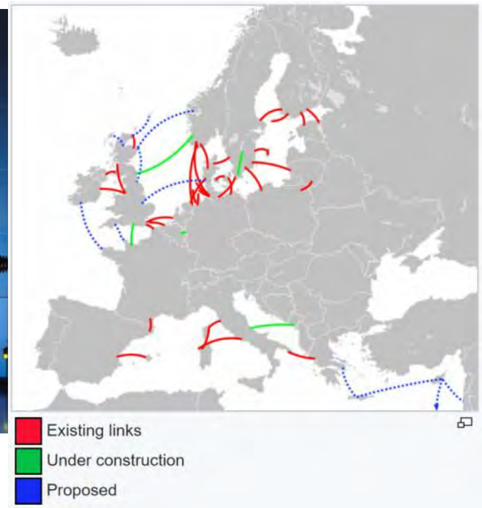


ABB wins orders of over $300 million for world's first 1,100 kV UHVDC power link in China

Press release | Zurich, Switzerland | 2016-07-19

ABB transformers and other key equipment to enable Changji-Guquan link to transmit 12,000 megawatts of electricity over 3,000 kilometers at 1.1 million volts, setting new world records on voltage level, transmission capacity and distance

https://new.abb.com/news/detail/13922/abb-wins-orders-of-over-300-million-for-worlds-first-1100-kv-uhvdc-power-link-in-china

- *Up to 1.1MV DC transmission*
- *Only ~10% loss over 3000 km*
- *Up to several GW capacity*

Options for a future electricity system
- High Voltage DC Transmission

SUN CABLE

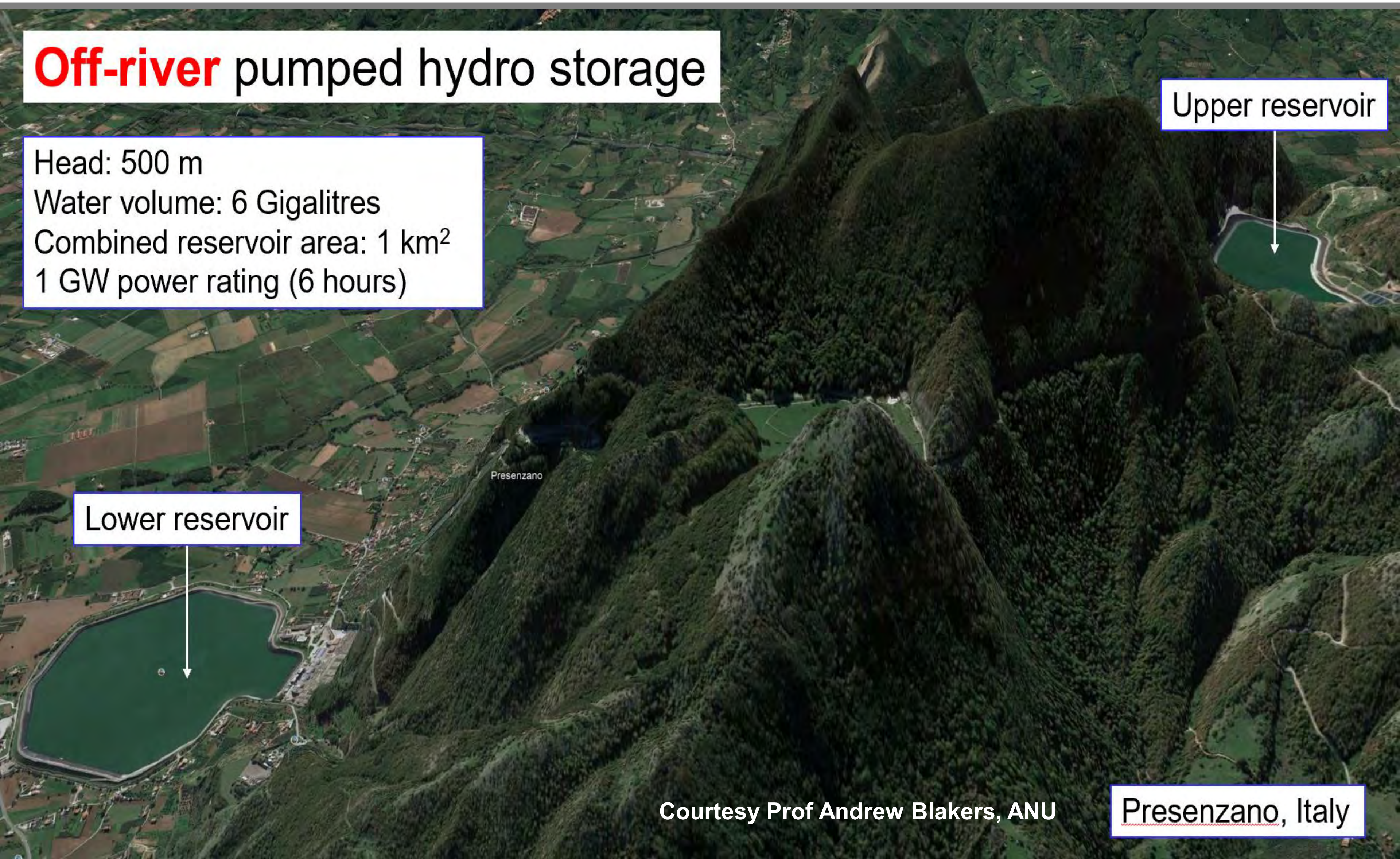
https://www.suncable.sg/

3GW	3800	15000	1/5
of Energy	Kilometres of HVDC Cable	Hectares of Solar Arrays	of Singapore's Electricity Supply

- *Singapore relies on imported Gas for 95% of its electricity*
- *15 Hectare Solar Array near Tennant Creek*
- *HVDC cable from Australia to Singapore*
- *Currently still in planning phase*

- *Australia has the chance to become a Renewable Energy Superpower*

Options for a future electricity system
- Pumped Hydro Storage



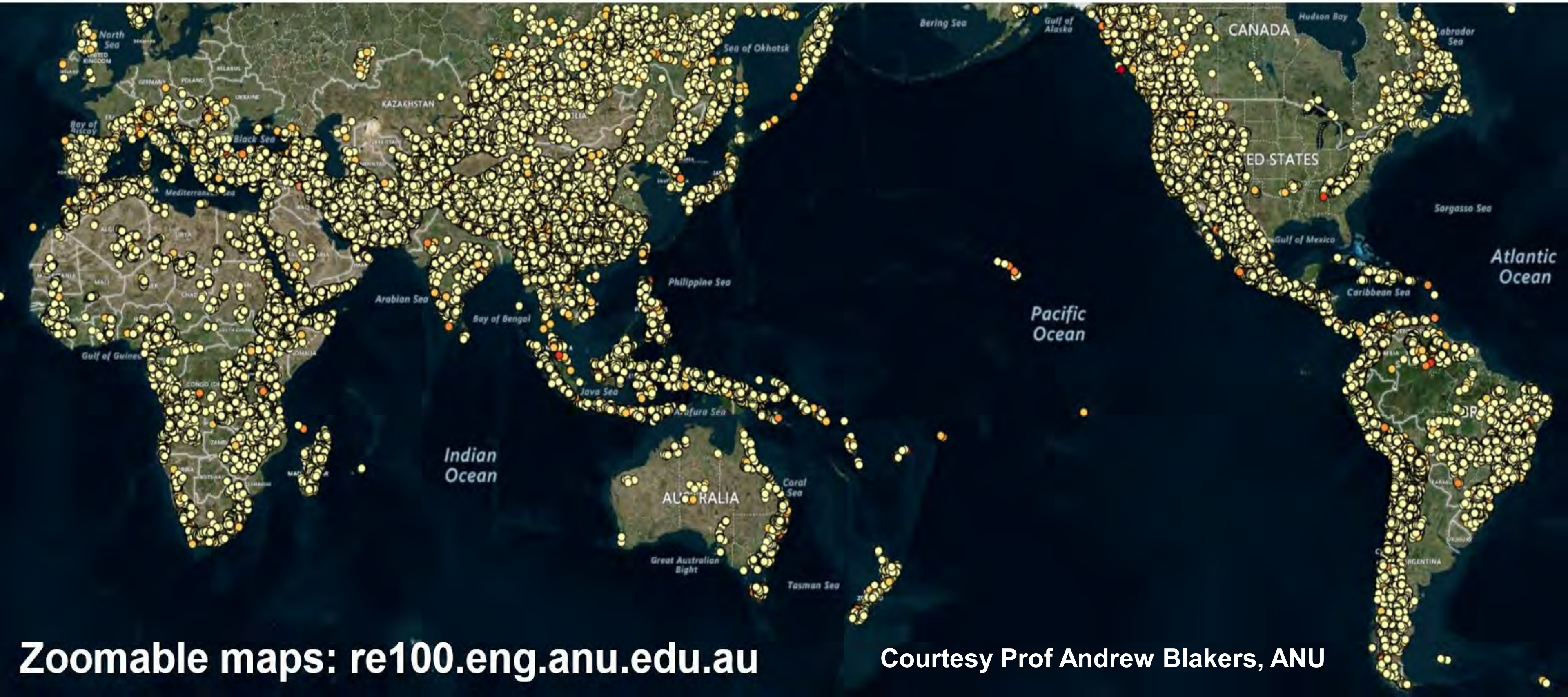
Options for a future electricity system
- Pumped Hydro Storage

Australian National University

Global off-river pumped hydro atlas (ANU)

616,000 off-river sites (60°N to 56°S), all outside national parks & urban areas

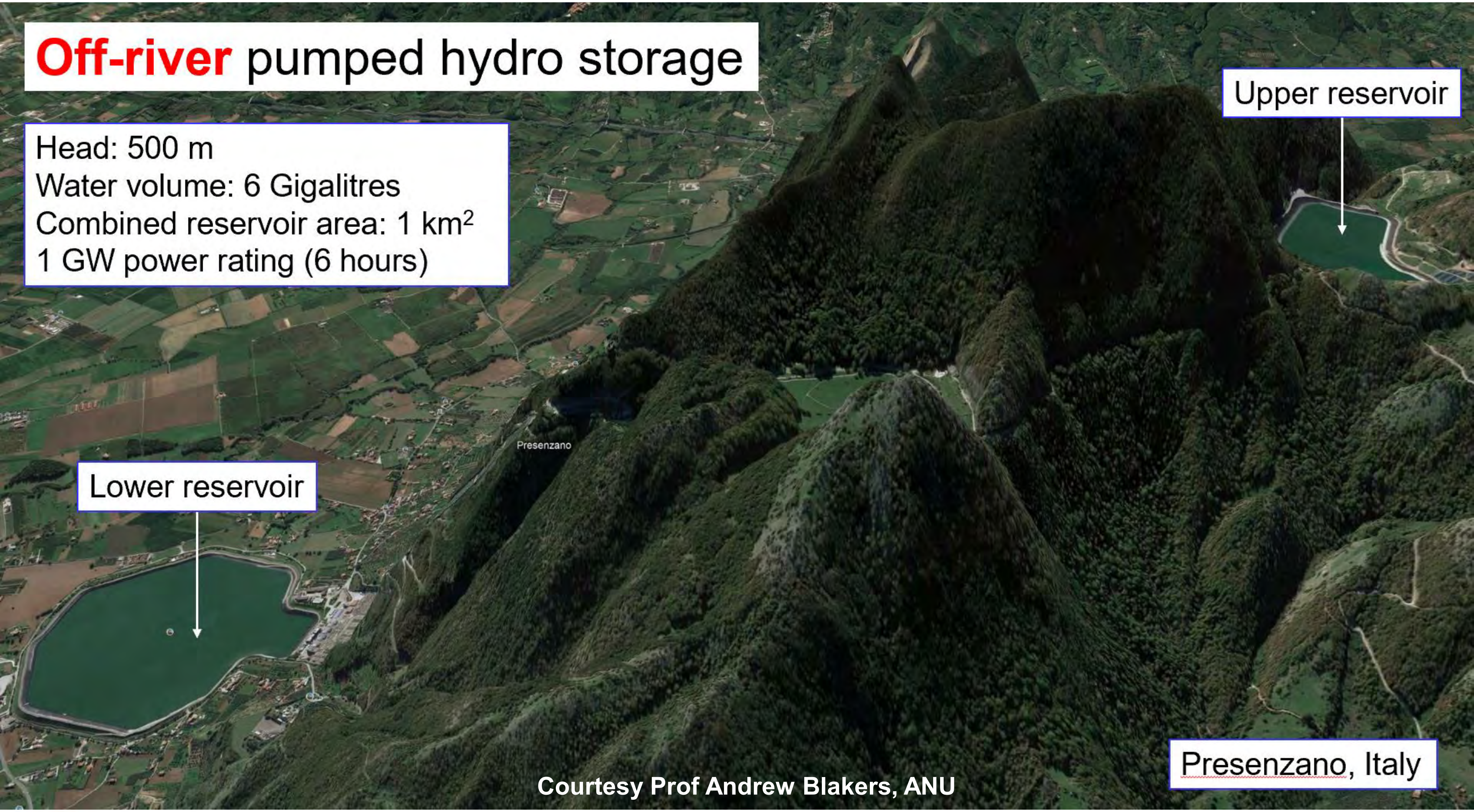
23 million Gigawatt-hours (1 million GW * 23 hours)



Zoomable maps: re100.eng.anu.edu.au

Courtesy Prof Andrew Blakers, ANU

Options for a future electricity system
- Pumped Hydro Storage



Options for a future electricity system
- Pumped Hydro Storage

China set for 40 GW of pumped hydro storage next year

The showpiece 3.6 GW Fengning county project which will offer grid services and back-up power at the 2022 Winter Olympics is part of a 31.15 GW construction pipeline of projects, many of which are set to come into service next year.

The storage capacity of pumped hydro projects like this one at Shoalhaven in Australia could hit 40 GW in China next year.

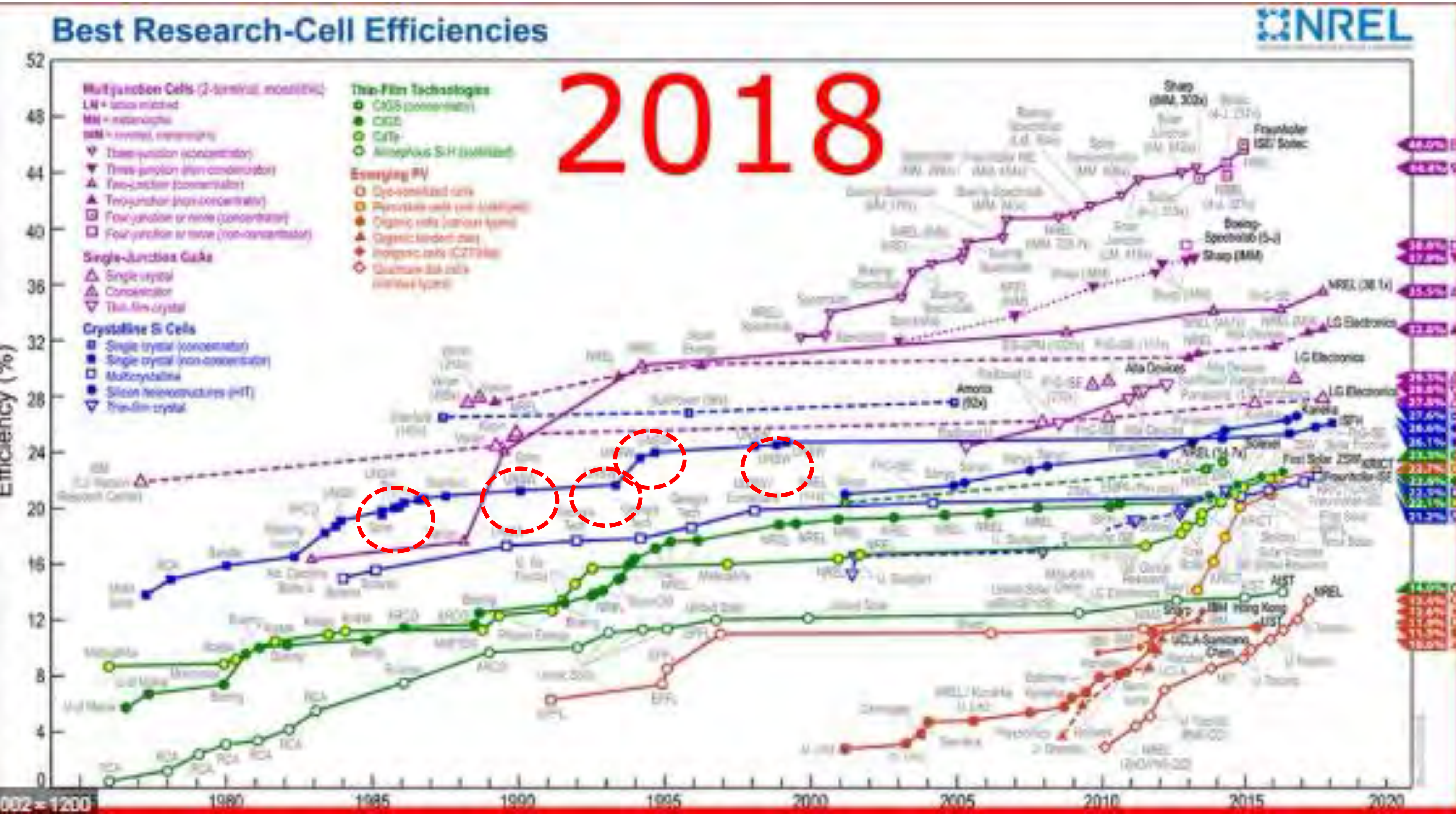
Fengning Pumped Hydro Power Station:

- ***3.6 GW*** *total generation capacity*
- ***3.424TWh*** *annual power generation*
- ***9.4GWh*** *per day or*
- *3.6GW for 2.6 hours every day*
- *Fully operational in 2023*

https://www.pv-magazine.com/2019/09/25/china-set-for-40-gw-of-pumped-hydro-storage-next-year/

UNSW PV R&D

- world record silicon solar cells



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