Global annual net new generation capacity

PV has rapid exponential growth

PV and wind are variable

Negligible growth in annual net new deployment
PV learning curve – rapidly reducing prices
Silicon PV: 95% of PV market

Source: Fraunhofer ISE
Silicon incumbency

- Silicon abundance
- Moderate cost
- Non-toxicity
- High and stable cell efficiency
- Simplicity (mono-elemental semiconductor)
- Physical toughness
- Highly advanced knowledge of silicon materials & devices
- Share investment with the electronics industry
- Extensive and sophisticated supply chains
- Large-scale investment in mass production
- Deep understanding of silicon PV technology and markets
- Thousands of silicon specialists: scientists, engineers, technicians
Increasing cell efficiency

- Cells are a decreasing fraction of the PV value chain
- Improved cell efficiency leverages nearly the whole PV value chain
  → Strong drivers for higher cell efficiency
Worldwide market shares for PV technologies
PERC in 2017

- PV: 40% of annual global net new capacity additions
  - Wind, fossil, hydro, nuclear and others = 60%
- PERC: 22% of PV production
  - 9% of global net capacity additions
- PERC abates 0.1% of global greenhouse emissions
- PERC cumulative sales: $21 billion
PERC: projected fraction in 2020 of global annual net new capacity additions

Cumulative PERC module sales to 2020 ~ AUD$70 billion
PERC abatement of global emissions ~ 0.7%
PERC cells: 1988-2018
1988-2008: some things changed

Shipments (MW)

- **Wind**
  - 1988: 200
  - 2018: 50,000

- **PV**
  - 1988: 50
  - 2018: 98,000
1988-2008: some things changed

- **Wind Shipments (MW)**: 200 in 1988, 50,000 in 2018
- **PV Shipments (MW)**: 98,000 in 2018
1988-2018: some things stayed the same

- Silicon still dominates PV
- BSF cells still important
- Module design similar
Large PV systems

in 1988
0.1 to 5 MW →
in 2018
50-500 MW
Wind generators
1988 - 2018

50-100 kW → 2-10 MW
1984: 18%

PESC silicon solar cell

- First reported 18% efficient cell
- Untextured
- DLAR
- Al alloyed on rear
- Voc = 643 mV

Blakers, Green, Jiqun, Keller, Wenham, Godfrey, Szpitalak, Willison

18% Efficient Terrestrial Silicon Solar Cell (Edl Vol. 5, pp. 12-13, 1984)
1984: 19%

MINP silicon solar cell
- First reported 19% efficient cell
- Untextured
- DLAR
- Al alloyed on rear
- Voc = 653 mV

Green, Blakers, Jiqun, Keller, Wenham
1986: 20%

- First reported 20% cell
- Micro grooves
- DLAR
- Al alloyed on rear
- SERI: 20.9%
- Voc = 661 mV

Blakers & Green
What next?

• Rear alloyed Al maintains high lifetime (by gettering) at the cost of poor surface passivation
  – Introduce chlorine to furnaces and eliminate alloying

• Rear alloyed Al is a poor reflector
  – Replace with un-alloyed Al mirror atop a dielectric

• Microgrooves are not very effective for light trapping
  – Introduce inverted pyramid texturing

• Thermal oxide is very effective for surface passivation
  – Oxidise 99% of both surfaces

• Metal contacts have high recombination rate
  – Restrict contact area on both surfaces
1988-89: PERC cells

- 22%-23% efficient cells reported
- Inverted pyramids
- Al point-contact on rear
- Voc ~ 700mV

**Blakers, Wang, Milne, Zhao, Dai, Green**

22.6% Efficient Silicon Solar Cells (4th PVSEC Sydney, Feb 1989)

**Blakers, Wang, Milne, Zhao, Green**

22.8% Efficient Silicon Solar Cell (APL Vol. 55, pp. 1363-1365, 1989)

**Blakers, Zhao, Wang, Milne, Dai, Green**

23% efficient silicon solar cell (8th PVSEC, Freiburg, Sept 1989)
Other PERC developments in 1988

• Aluminium alloy into the rear contacts
  – Dominant commercial implementation today

• Boron diffusions into the rear surface
  1. Full area (PERT)
  2. Only in the contacts (PERL)

• Selective phosphorus diffusions on the front
• n-type PERC with MIS contacts
• Alnealing oxide
• Test structures (Voc = 705 mV)
Back contact solar cells

- IBC cells developed at the same time as PERC, with similar efficiencies, and share many features:
  - Small-area metal contacts (both polarities on the rear)
  - Dielectric passivation of both cell surfaces
  - High-lifetime wafer processing
  - Rear surface reflectors
- Fruitful exchange of ideas between labs
- SunPower stemmed from the Swanson IBC group at Stanford University

Common PERC configurations developed in 1988

**Simple PERC**
- Phosphorus-doped emitter
- Undoped point contact
- Passivating dielectric
- Aluminium

**Commercial PERC**
- Phosphorus-doped emitter
- Local aluminium alloy
- Passivating dielectric
- Aluminium

**PERT**
- Phosphorus-doped emitter
- Sheet boron-doping
- Passivating dielectric
- Aluminium

**PERL**
- Phosphorus-doped emitter
- Local boron-doping
- Passivating dielectric
- Aluminium
Later PERC lab cells at UNSW

• PERL/PERT lab cells from UNSW in the 1990s reached 24-25%
  – Silicon cell efficiency record remained at UNSW until recently
• Improvements:
  – Better boron diffusions
  – Better light trapping
  – Improved reflection control
  – High minority carrier lifetimes

Zhao, Wang, Altermatt, Wenham, Green
24% efficient PERL silicon solar cell: Recent improvements in high efficiency silicon cell research”, SEMSC Vol 41–42, 87-99 (1996)

Zhao, Wang, Green
24·5% Efficiency silicon PERT cells on MCZ substrates and 24·7% efficiency PERL cells on FZ substrates”, PiP 7, 471-474 (1999)
Commercial PERC

• Commercial PERC is similar to Al-BSF allowing rapid transition
• 25-year gap between 1988 and PERC commercialisation
• Key technical differences from 1988 lab-PERC:
  – Negatively charged Al₂O₃ on undoped rear surface with SiN cap (not SiO₂)
  – Screen-printed front & rear metal (not evaporated)
  – Laser rear contact openings (not photolithography)
  – Single-sided Phos-diffusion
  – Al-alloy (not boron)

High efficiency cell team incl. PERC

Mike Willison
Ted Szpitalak
Stuart Wenham
Andrew Blakers
Jianhua Zhao
Martin Green

+ Ximing Dai
Bruce Godfrey
Shi Jiqun
Erik Keller
Adele Milne
Aihua Wang
Conclusions

• PERC is having a large global impact
  – 9% of net new generation capacity additions in 2017
  – Cumulative sales to 2017 of A$21 billion
  – Much larger numbers in the future! (extrapolation is always fraught)
    • Extrapolated to 2025: PERC global emissions abatement ~ 4%
    • PERC cumulative sales ~ several hundred $billion

• Parallel development of IBC cells (Stanford) led to fruitful exchange of knowledge

• 12 people contributed substantially to the UNSW high efficiency cell program
  – Including 6 people who made substantial contributions to the development of the PERC cell
Thank you!
http://re100.eng.anu.edu.au