Journal & Proceedings of the Royal Society of New South Wales, vol. 155, part 2, 2022, pp. 168–181. ISSN 0035-9173/22/020168-14

Silicon solar cells to power the future

2022 Millennium Technology Prize Lecture

Martin A. Green

School of Photovoltaic and Renewable Energy Engineering
UNSW Sydney, Australia

Email: m.green@unsw.edu.au

Introduction

It's a great honour to have been announced as the winner of the 2022 Millennium Technology Prize for my work on accelerating the development and uptake of silicon solar cells. In my lecture, I'd like to give an overview of our work and outline how such work has now positioned solar to play a major role in climate change mitigation. The images on my cover slide (Fig. 1) show the iconic Sydney Opera House, also the building where my research labs are located at the University of New South Wales (now UNSW Sydney), solar powered, of course, and our Solar Industrial Research Facility where we undertake technology transfer to industry.[1]

Figure 1: Sydney Opera House; UNSW Tyree Energy Technology Building (TETB); UNSW Solar Industrial Research Facility (SIRF).

My talk is divided into three sections. First, I'll talk about technology, then costs and, finally, recent market drivers that are sustaining very rapid present expansion of solar uptake. So, hopefully, there is something interesting in my talk for everyone.

Technology

Operation

First, technology. Figure 2(a) shows the cell operating principles — cells are very much 20th-century devices, essentially quantum converters, relying on the 20th-century developments in quantum mechanics to understand their operation. Photons in sunlight with sufficient energy enter the cell, giving up their energy by exciting electrons from silicon atomic bonds, creating electrons in excited states and leaving vacancies or holes in the bonds, that act as positive charge carriers. Without any other features, the excited electrons would just relax back to their initial states and nothing useful would happen. What is required is an electronic asymmetry to give a directional flow to the electrons and holes. This is where what is called a "positive-negative junction" or "p-n junction" comes into play, with such junctions one of the most important building blocks in microelectronics.

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[1] In October 2022, Martin Green won the Millennium Technology Prize, Finland's top technology award. This is his acceptance speech. Presentation of actual lecture can be found at https://millenniumprize.org/events/award-ceremony-2022/. Lecture was extemporised so text is the intended lecture, also including some information additional to what the allocated presentation time allowed and excluding some of the visual material actually presented.

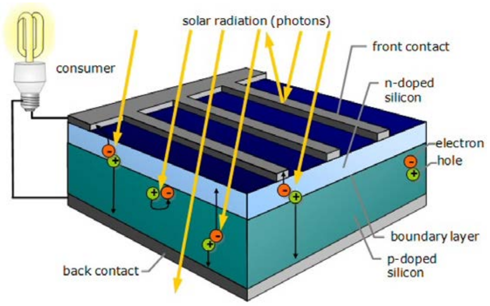


Figure 2(a) Operating principles of a solar cell (Quaschning, 2019).

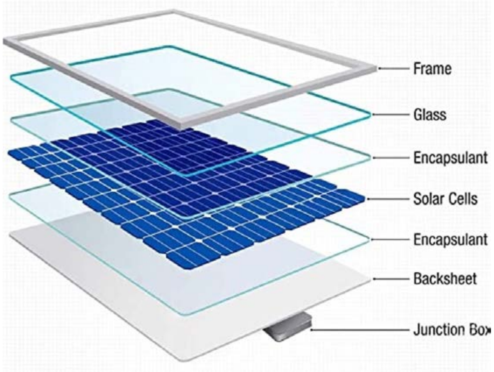


Figure 2(b) Solar cell encapsulation into a solar module (DuPont, 2016).

This junction was actually discovered and named when the first silicon solar cell was accidentally made in the early 1940s. Serendipitously, a piece of relatively pure silicon was prepared that generated a voltage when illuminated by a torch, with a clear junction between the region that showed a positive voltage and the region showing a more negative voltage. Working out what caused this ultimately led to the microelectronics revolution.

It was found that the different properties were due to small quantities of trace impurities in the silicon. Silicon comes from Group IV of the old periodic table. Elements from Group V have more electrons available, making it easy for electrons to move through silicon when such impurities are present, forming "negative" or "n-type" regions. Elements from Group III have fewer electrons, or more holes, so holes can easily move through silicon when these impurities are present, forming the "p-type" regions. So, in a cell as in Fig. 2(a), with the n-type region uppermost, electrons can readily flow to the top and holes to the back.

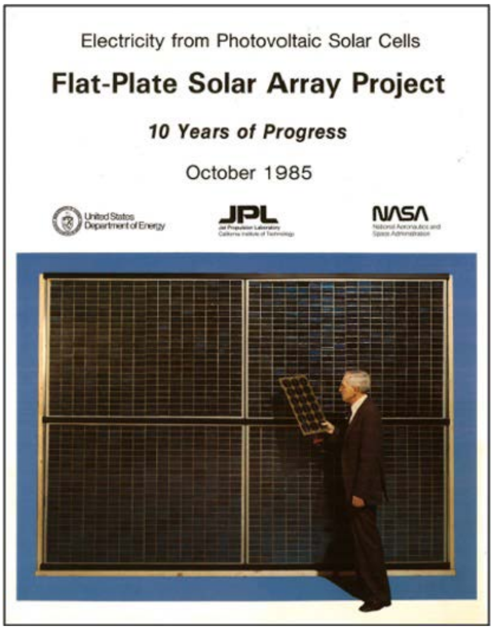
Without any electrical connection between the top and the bottom contacts to the cell under illuminated by light, you would measure a voltage difference between the top and bottom called the "open-circuit voltage," something that I will talk about later. But, if you connect an electrical circuit between the top and back, such as the light bulb shown, electrons will flow through the circuit around to the back of the cell, where they will meet up with holes and complete the cycle.

There are no moving parts involved or inherent wear-out mechanisms, so the cells are very reliable. The cells are now made very thin and can be mechanically fragile, so are packaged into a solar module with a strengthened glass cover sheet and aluminium frame, providing mechanical support, with a tough back cover laminated to the module rear providing electrical and chemical protection. Modules are very reliable, with manufacturers now warranting them for between 25 to 40 years.

First efficient cells

The first efficient silicon solar cells were made in 1953. Perhaps very appropriately, given the important role solar cells now seem likely to play in our energy future, this made front-page news in the *New York Times* in April 1954 — "Vast power of the sun is tapped by battery using sand ingredient."

Figure 3(a) Vanguard 1 satellite launched in March 1958 (Image: Wikimedia Commons).



Electricity from Photovoltaic Solar Cells

Flat-Plate Solar Array Project

10 Years of Progress

October 1985

United States Department of Energy

JPL

NASA

Figure 3(b) Tenth-year progress report on the Flat-Plate Solar Array Project started in January 1975 (Christensen, 1985).

There was excitement about possible uses, such as providing energy for a family as shown in the drawings accompanying the press release, but the cells were then far too expensive for any such use to be feasible.

Fortunately, the cells almost immediately found an application where cost was not a big issue: in space. Proponents were successful in having cells flown on the second US satellite, Vanguard 1, in 1958. These worked very well, too well in fact, since there was no "off-switch" and the signals they powered clogged up airwaves for the next six years. However, this showed the cells were ideal for powering communication satellites, pioneered by Telstar in 1962. Bell Labs were given the job of developing reliable solar cells for this mission, developing an improved design that became the workhorse for the industry, known as the conventional space cell (Smith et al., 1963).

Project Independence

Things might have stopped there, except for the 1973 Arab-Israeli war that sparked an oil crisis, in the US in particular. President Nixon launched "Project Independence" in late 1973 to wean the US from foreign oil. Crucially for subsequent developments, solar was selected as a candidate for doing this, leading to the "Flat-Plate Solar Array Project" that ran for 10 years from 1975 (Christensen, 1985), specifically aimed at substantially reducing the cost of solar cells. Massive progress was made such as in the area of module packaging, which evolved dramatically over this period through a series of "block purchases" targeting ongoing improvements. The designs resulting from this period remain in force right up to the present.

The program also consolidated then recent improvements in cell design and fabrication. Space cell researchers found they could etch the cell surface to produce the tiny pyramids shown in Fig. 4(a), greatly reducing reflection and improving cell performance substantially. At about the same time, a very simple way of making the contacts to the cell was suggested by screen-printing the patterned metal contacts as a paste, much like printing patterns onto a T-shirt, then heating to high temperatures to solidify. At the rear, an aluminium paste was used that introduced p-type aluminium dopants into the silicon at the high temperatures involved, further improving cell performance. The "aluminium back surface field" cell was a very advanced design for the era and was so successful that it remained the dominant commercial technology for the next 40 years.

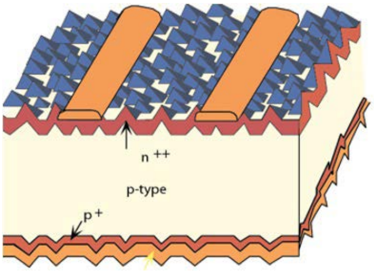


Figure 4(a) The "aluminium back surface field" (Al-BSF) solar cell that was a combination of the pyramidally textured "black cell" developed by COMSAT Laboratories in 1974 (Alison et al., 1974) with "screen-printed" contacts (Ralph,1975). The "back surface field" refers to the heavily doped p+ region at the cell rear that helps prevent electrons from reaching the rear contact.

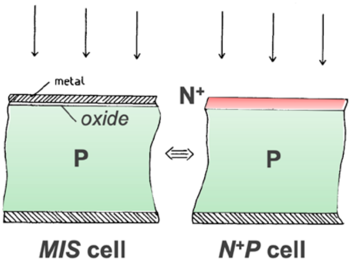


Figure 4(b) The metal-oxide-semiconductor (left) studied in the author's thesis when the normally insulating oxide layer was sufficiently thin to allow quantum mechanical tunnelling between the metal and semiconductor. With appropriate choice of the metal, this was shown to give identical properties to an ideal p-n junction diode (right).

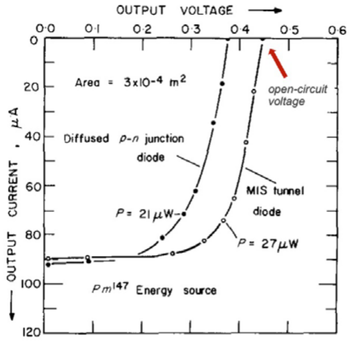


Figure 4(c) The author's cells outperformed the best p-n junction cells being made for a McMaster University project to develop long-life pacemaker batteries based on the betavoltaic effect, using high-energy electrons from a radioisotope instead of photons as the excitation. Notable is the very high open-circuit voltage demonstrated (over 650mV at solar intensities!) (Shewchun et al., 1972).

Tunneling contacts

Meanwhile, I was working on my PhD in Canada at McMaster University, where I had won a scholarship from Australia. My research (Green, 1974) involved a common microelectronic structure, the metal-oxide-semiconductor structure shown in Fig. 4(b), but I investigated it when the normally thick insulating oxide was thin enough to allow electrons to pass through it by quantum-mechanical tunnelling. One major result I found was that, when designed correctly, the device could replicate the properties of an ideal p-n junction diode. This made it of interest for solar cells although McMaster was better set up for nuclear work, having its own reactor. My thesis supervisor had a project to develop a pacemaker battery using electrons from a radioisotope, rather than photons, to illuminate a p-n junction. My devices worked much better than the p-n junctions being developed by other students for the project. Particularly notable is the very high open-circuit voltage shown in Fig. 4(c), a reliable measure of p-n junction quality. This was my first successful experimental foray into energy conversion (Shewchun et al., 1972).

Early years at UNSW

On returning to Australia, I started the solar group at UNSW in late 1974. By 1976 my first PhD student, Bruce Godfrey, and I were getting good results in applying my thesis structure to solar energy conversion, with us both shown at work in Fig. 5(a). Fortunately for us, NASA had launched a program to improve silicon cell efficiency by increasing the open-circuit voltage and, despite our then very modest facilities apparent in the figure, we were able to beat all NASA subcontractors in terms of the voltages demonstrated, as shown in Fig. 5(b). This brought our work to international attention, with our small team receiving an invitation to present a plenary paper at the 14th IEEE PV Specialists Conference in San Diego (Green et al., 1980), then by far the most important international conference series in photovoltaics. This international endorsement of our work helped me raise the funding needed to put together the larger team and facilities to develop the other cell features required for an assault upon the cell efficiency record, particularly highly conductive, fine linewidth plated metallisation fingers and double layer antireflection coatings. The late Erik Keller, an experienced engineer supported by one of my grants, did a superb job in both areas.

Figure 5(a) Martin Green (left) and Bruce Godfrey getting last-minute results for the 12th IEEE PV Specialists Conference in Baton Rouge in 1976 (Green et al., 1976).

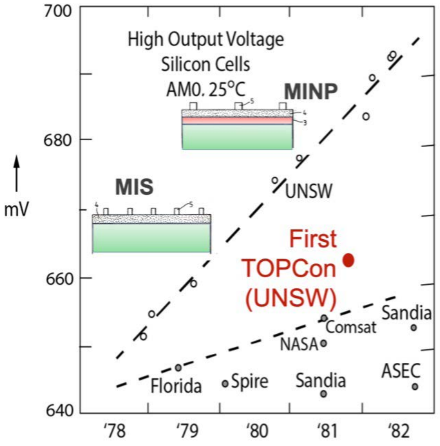


Figure 5(b) Highest reported silicon cell open-circuit voltage over the 1978–1982 period, showing how UNSW outperformed NASA and NASA subcontractors.

Meanwhile, our voltage lead had been further improved when my 2nd PhD student, Andrew Blakers, and I serendipitously discovered that combining our tunnelling structures with a lightly doped p-n junction gave better results than tunnelling alone. I coined the acronym “MINP cell” (metal-insulator-NP junction cell) for the resulting devices (Green et al., 1981).

Since the metals being used reacted with the oxide at high temperatures, we realised these structures would not be suitable for use with the screen-printing process used in manufacturing. To demonstrate compatibility of the tunnelling approach, we fabricated devices (Fig. 6) with the metal replaced by heavily doped polycrystalline silicon that acts nearly like a metal but does not react with its underlying oxide even at high temperatures. This structure successfully demonstrated record voltages, outside our group at least, and is now being used commercially in "TOPCon" cells.

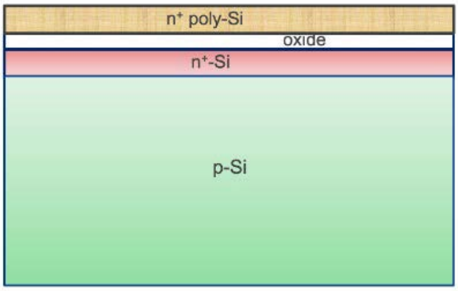


Figure 6: MINP cell fabricated in 1981 with the metal layer replaced by a thin heavily doped polycrystalline silicon layer (Green and Blakers, 1983; Green, 1987; Green, 1995). This approach has reportedly since been used commercially by SunPower and Tetrasun and now, more widely, in "TOPCon" cells.

With our large voltage lead, we were well-placed to improve cell conversion efficiency. Success came in September 1983 with the tunnelling structure shown in the insert of Fig. 7(a) producing a cell confirmed as 18.7% efficient (18.1% by present standards), the first record for a group outside the US (Green et al., 1984a). The photo shows the team involved, with my second and third PhD students, Andrew Blakers and Stuart Wenham, behind me as well as Jiqun Shi, a visiting scholar from China, and grant-supported engineers, Erik Keller and Ted Szpitalak at the front. This was the first of 18 world records we set over the next 30-years, improving certified cell performance by over 50% over this period as shown in Fig. 7(b) (Green, 2009).

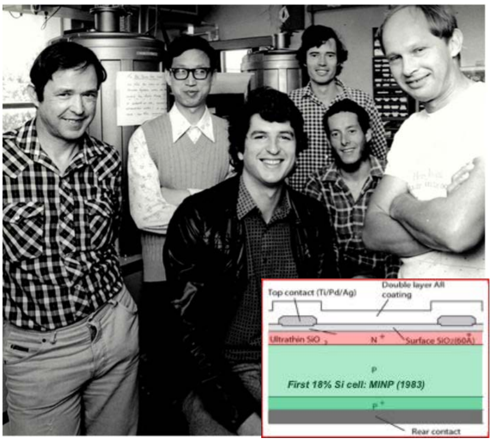


Figure 7(a) Team producing the first 18% efficient silicon solar cell in 1983. Left to right: Erik Keller, Jiqun Shi, Martin Green, Stuart Wenham, Andrew Blakers and Ted Szpitalak. The insert shows the MINP cell structure used.

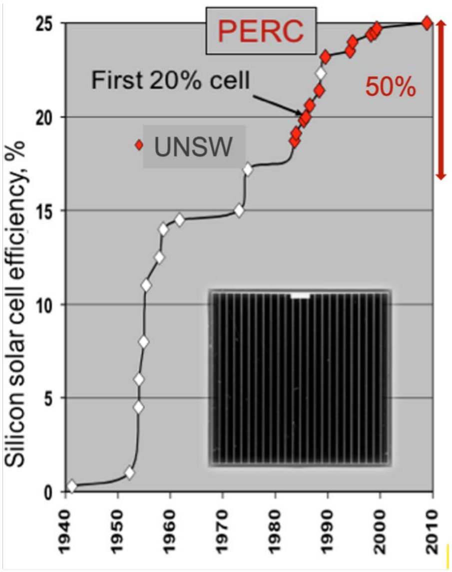


Figure 7(b) History of silicon solar cell efficiency evolution showing UNSW impact over a 30-year period, improving the highest confirmed efficiency by more than 50% in relative terms. Highlights include producing the first 20% cell in 2005 and the first record PERC cell in 1989, eventually achieving 25% efficiency. The insert shows the physical appearance of the 2cm x 2cm cell setting the team's first record.

Meanwhile, I had been studying what efficiency we might ultimately expect from silicon and what cell design features would be required. In the same journal issue where our first record was published, I also published the results of this study (Green, 1984b). Key findings were that silicon was capable of energy conversion efficiency closer to 30% than the 20% value previously thought a practical limit, with 25% estimated as a feasible target. My work also showed that we needed to eliminate the "aluminium back surface field" that was such an important part of commercial cell design to reach such efficiencies.

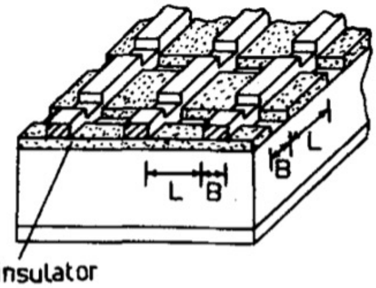


Figure 8(a) Low area contacting approach used to verify the high voltage potential of PESC solar cells (Green, 1975).

When Stuart Wenham and I were giving the record MINP cells their final anneal, we found that higher annealing temperatures than we expected gave best results. We postulated that the metal may have been penetrating the oxide in small area filaments. I had earlier suggested such small area contacts as a way of reducing the detrimental effects of metal contact recombination (Green, 1975). So Andrew tested out a structure I had suggested in my earlier work, shown in Fig. 8(a), and it worked well, giving us a second way of getting high voltage with the advantage that it simplified cell processing. This gave us our second world record in December 1983 with a cell confirmed as 19.1% efficient (18.4% by present standards) (Green et al., 1984a).

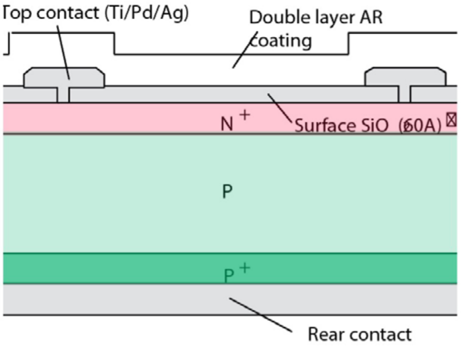


Figure 8(b) PESC cell confirmed as 19.1% efficient in December 1983 (Green et al., 1984a).

I named this the "passivated emitter solar cell" or PESC cell shown in Fig. 8 (b), where emitter refers to the top of the cell. Based on this development, my theoretical paper and earlier experimental work I had supervised on increasing cell rear reflection, I drew my first diagram of a cell design improving upon the "aluminium back surface field" towards the end of 1983, including the drawing in Fig. 8(c) in two reports released in early 1984. I quite naturally named this the "passivated emitter and rear cell" or PERC cell, since this development fixed up both top and rear of the cell.

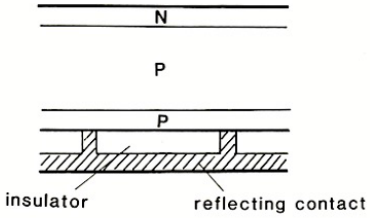


Figure 8(c) First drawing of PERC solar cell emphasising rear contact design (Green, 1984b; Green et al., 1984c).

Another idea mentioned in the two reports, texturing the top surface, was more readily implemented. By including this, we achieved the landmark 20% efficiency in 1985, long regarded as the "four-minute mile" of photovoltaics. The very happy team contributing to this achievement is shown in the first photo in Fig. 9 with myself surrounded by six PhD students and two grant-supported engineers. The observant might detect a certain gender imbalance. This was soon partly rectified by the addition of the late Adele Milne, who completed the first-ever PERC thesis worldwide, and Aihua Wang and Ximing Dai, who made important contributions to our lab and then to the development of the solar industry, being founders and Chief Technical Officers (CTOs) of CSUN and JA Solar, two of the companies early into manufacturing in China.

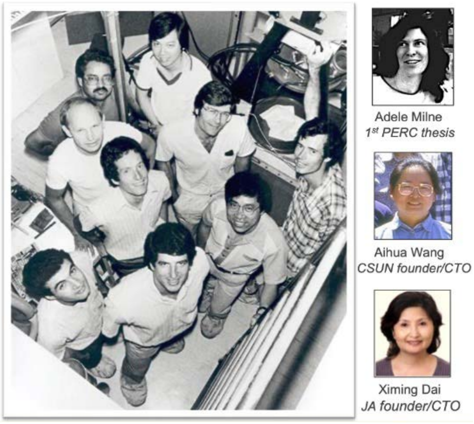


Figure 9: Team producing the first 20% efficient silicon cell in 1985 together with subsequent team members contributing to both cell efficiency improvement and to the solar industry's transformation.

The emphasis was then placed on implementing PERC. Using a process developed by Andrew Blakers, Jianhua Zhao made the first efficient PERC in September 1988 with 21.8% efficiency confirmed (21.2% by present standards). This would have been a world record except that Stanford University reported a 22.3% efficient cell at about the same time using a sophisticated approach with both contacts on the rear (22.5% by present standards!). This put pressure on us to regain our record. Andrew got closer with 22.2% confirmed in February 1989 (21.6% by present standards), when he left for Germany to take up a Humboldt Fellowship. Jianhua then became our processing leader with Aihua Wang fabricating a certified 22.8% cell by adding two extra high-efficiency features, regaining our record (although this result was later recalibrated to 22.2%, a lower value than Stanford's!). I quickly wrote a paper reporting this result giving the honour of first authorship to Andrew, despite his absence, to recognise his 10 years of lab contributions (Blakers et al., 1989). The structure reported retained the simplified design suggested by Andrew but, with Jianhua now our processing leader, the originally conceived rear doping was soon implemented with efficiency steadily increasing to our 25% target, confirmed in 2008 (Green, 2009). Stanford's 6-month or so interruption to our run of efficiency records was the only one over 31 years.

Since 2014, three other cell technologies have exceeded the 25% mark (Fig. 10). The second one in Fig. 10(b) labelled TOPCon reverts to use of the tunnelling polysilicon contacts our team demonstrated back in 1981. The third, the heterojunction (HJT) cell, is based on a junction between thin layers of silicon in amorphous form and the normal crystalline material. Citing our earlier work, it was initially found that inserting a thin oxide layer between the thin amorphous layer and the crystalline material improved performance (Morikawa et al., 1990) but a thin layer of undoped amorphous silicon was then found to do an even better job (Taguchi et al., 1990). The fourth structure, the "interdigitated back contact" (IBC) cell is the oldest of all the structures (Lammert and Schwartz, 1977), but is also linked to our early work since now using either HJT, TOPCon or mixed TOPCon/PERC approaches for the back contacts.

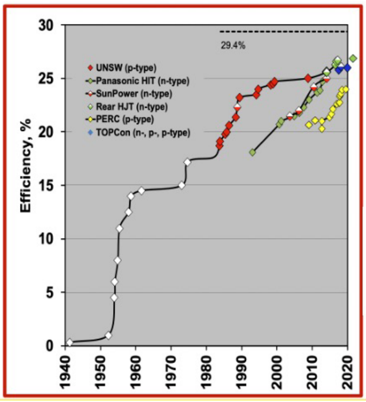


Figure 10(a) Recent developments in silicon solar cell efficiency.

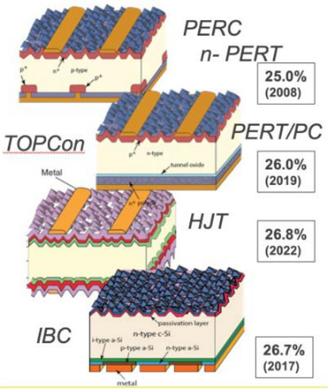


Figure 10(b) PERC cell diagram together with those of the other three silicon cell structures that have exceeded 25% cell efficiency since 2014. The present record efficiency is 26.8%, obtained in October 2022.

However, when it comes to production, PERC now completely dominates. Figure 11 shows market share, dominated for 40 years by the "back surface field" technology, the blue and maroon regions, with the first cell demonstrated in 1975. PERC, the brown and yellow regions, began challenging after 2015, now completely dominating the market with over 90% market share in 2021.

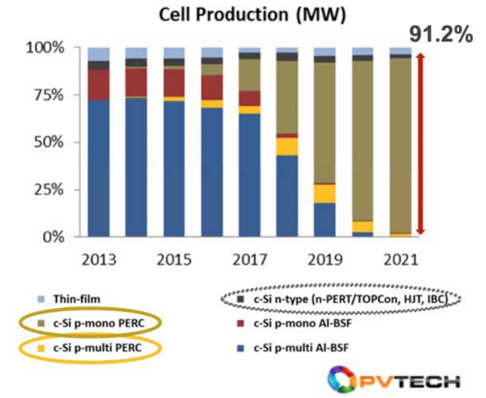


Figure 11: Share of the photovoltaic module market by different technologies (Image: PV Tech, 2022). Until 2015, the Al-BSF technology shown in Fig. 4(a) dominated the market but was then quickly displaced by PERC technology, with 91.2% share of the silicon market in 2021 (CPIA, 2022). The other high efficiency technologies presently share the small black regions of the chart, but are expected to become more important in the future.

Another contribution to technological uptake has been graduates from our lab. I have now supervised over 120 PhD students, but these efforts were complemented in 2000 when, anticipating the upcoming explosion of the industry, we introduced the world's first undergraduate degree program in photovoltaic engineering. With both local and international students enrolled, the program has supported the growing demand for trained engineers, particularly in Australia and China (Fig. 12).

Figure 12: The 2010 intake into the School of Photovoltaic and Renewable Engineering, the first in the world to offer an undergraduate degree in Photovoltaic Engineering. In the foreground are the inaugural and third (and current) Heads of School, Richard Corkish (left) and Alistair Sproul, both former PhD students of the author.

Costs

Historical cost decrease

That brings us to costs. Figure 13 shows a compilation of photovoltaic module costs and prices over 4 decades (Kavlak et al., 2018). Straight lines on this semilogarithmic plot represent exponential reductions, with prices reducing consistently at a compounded rate of 7%/year from 1980 to 2005. Then something happened, with price reductions markedly accelerating. Based on a “business as usual” projection with 7%/year price reduction, module prices would have been expected to reach US $1/Watt in 2020. Instead, they were 5–6 times lower, reaching prices as low as US 15 cents/Watt.

The person responsible for this was my 12th PhD student, Dr Zhengrong Shi. While working for one of our spin-off companies, he became impatient to put the knowledge gained in our labs into practice. Although by now an Australian citizen, he learnt of improved opportunities for private companies in China in the late 1990s and decided to set up cell manufacturing in China, then completely devoid of all appropriate infrastructure. The chart in Fig. 14 shows the rapid reduction in average wholesale selling price since 2008 on a linear scale due to his initiative, showing 5 distinct periods (also shown on a semilog scale since 2012 in the inset).

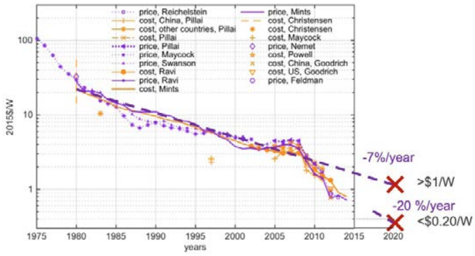


Figure 13: History of photovoltaic module prices and costs. Note the breakpoint circa 2008 (modified from Kavlak et al., 2018).

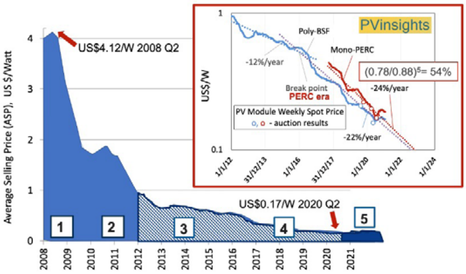


Figure 14: Module average wholesale selling price reduction since 2008 showing five distinct cost reduction periods (1: Competition between US-listed private Chinese companies; 2: Chinese state-owned companies unsuccessfully attempt to enter market; 3: Chinese government supports market development; 4: PERC enters the market and accelerates cost reduction; 5: Recent supply-constrained period). The inset shows reduction since 2012, showing how PERC reduced prices by nearly 50% compared to a “business as usual” scenario.

After rejection by several cities, the Wuxi government finally encouraged local companies to invest a total of US$6m in his initiative. With this, Zhengrong set up the first commercial cell manufacturing line in China, with help from former and current members of our team including myself, who got to cut the ribbon at the gala opening ceremony (Fig. 15). Zhengrong did well, aided by the rapidly growing market, largely due to Germany's trail-blazing feed-in tariff program, with Zhengrong investing profits into rapidly expanding his production.

Figure 15: The opening of Zhengrong's historic first production line in 2002, the first commercial solar cell manufacturing line in China (Green, 2016).

His progress was noted by US investment banks, Morgan Stanley and Goldman Sachs, looking for promising Chinese companies to list on US exchanges, given the interest in Chinese stocks in this era. They helped organise a management buy-out of the original Chinese investors, followed by listing of his company, Suntech, on the New York Stock Exchange at the end of 2005, the first private China-based company to list on this exchange. This listing was a huge success, raising $400m, the biggest tech float of 2005, making Zhengrong the "first solar billionaire" since still owning most of the company. Goldman Sachs also made at least $200m on the exercise. This created an avalanche of listings as investment banks looked for China-based solar companies to list as Suntech clones and solar companies eagerly sought such windfall investment. The first six company listings are shown in Fig.16, with UNSW-trained staff circled, either founders or recruited as CTOs to meet the investment banks' due diligence requirements. Over $7bn was raised by the 10 companies listing between 2005 and 2010, invested largely into manufacturing capacity, with 7 of these companies still presently in the top-10 worldwide, forming the backbone of the present industry. Six of these 7 had UNSW-trained staff either as founders or CTOs on listing (Green, 2016).

Figure 16: The first six of the ten Chinese-based photovoltaic companies to list on US exchanges between 2005 and 2010, triggered by Zhengrong's 2005 listing. UNSW-trained staff are circled.

The competition between these cashed-up companies caused prices to drop rapidly as they battled for market share. The strongest survived in the much lower price regime that resulted. At this stage, the Chinese government realised the huge asset it had in its solar industry and began supporting its continued growth by market development programs that have accounted for a large fraction of annual installations globally since 2012. This has had several positive outcomes, including accelerated cancellation of China's plans for new coal-fired plant and driving down solar costs to present low levels.

During this phase, cost reduction was a reasonably steady 12%/year, as seen by the fit to the blue line in the upper right graph in Fig. 14. After 2016, this rate nearly doubled to 22%/year, due to the pressure on prices as the incumbents battled to maintain market share against rapidly encroaching PERC technology. We can estimate that PERC reduced prices to 54% of what they would have been in a "business-as-usual" scenario, projected at the different rates as before.

The International Energy Agency (IEA) previously saw little role for solar in our energy future, with the situation changing completely in 2020 when the IEA recognised that solar now provides "the cheapest electricity in most countries," in fact "the cheapest electricity in history" under favourable circumstances (IEA, 2020).

Recent market drivers

Finally, I'll talk about recent market drivers, with the industry now experiencing rapidly increasing demand, with this situation expected to be maintained until at least 2030.

In its most recent roadmap for combating climate change, the IEA calls for immediate scaling-up of solar and wind rapidly over the rest of this decade. Globally we reached one terawatt of installed solar early in 2022 — the roadmap calls for 5 TW by 2030 corresponding to an average of half a terawatt/year installation, twice that expected in 2022 (IEA, 2021).

The Intergovernmental Panel on Climate Change (IPCC) also previously saw a limited role for solar, but their most recent report released in April 2022 evaluated mitigation options, their costs and their potential for impact by 2030 (IPCC, 2022). The report listed many options, with the most important of these being those that can be implemented at zero or negative cost. Such options included changing our transport fuels, but solar was found to have the most potential for reducing CO_2 emissions by 2030 at zero or negative cost, with even larger impact at small marginal cost.

Annual solar installations are expected to reach a quarter of a terawatt in 2022, doubling from 3 years earlier. Due to the factors listed, we expect the growth to be even faster over the rest of this decade, with at least two doublings by 2030, taking us up to 1 TW/year annual installation, some think by 2027. The chart in Fig. 17 that I marked up in 2015, shows the problem we face in keeping global temperature rise to reasonable levels. Despite the best efforts of the four biggest emitters, they alone appeared likely by 2030 to consume the whole allocated budget to maintain global temperature rise to 2°C. However, if installing 1 terawatt/year of solar by then, this can recover the targeted trajectory, if displacing coal from electricity generation or oil from transport.

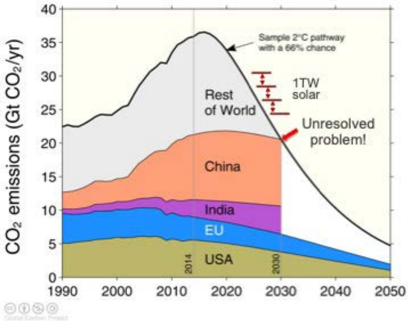


Figure 17: Historic CO_2 emissions to 2014 and a projected emissions trajectory to limit global temperature rise to 2°C (modified from Global Carbon Project, 2015).

Conclusion

In summary, we are proud that our work has positioned solar to make an immediate and major impact on climate change mitigation. Our four main contributions have been increasing silicon solar cell efficiency by 50% relative, holding the record for cell performance for 30 of the last 39 years, with several of the approaches explored during this phase now being used in commercial product. We are also proud to see the impact that our PERC cell technology has had upon recent prices and the role that our former students have played in triggering a major manufacturing transformation that now makes solar the cheapest source of electricity in history, according to the International Energy Agency. Our world-first undergraduate engineering degree program has also supplied well-trained graduates to fuel the very rapidly expanding industry.

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