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Technology evolution of the photovoltaic industry: Learning from history and recent progress

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Abstract

This paper reports on the latest advances in crystalline Si cells and modules in the industry and explores the dynamics shaping the silicon PV industry. First, we report on the recent efficiency improvements of passivated emitter and rear cell (PERC) and tunnel oxide passivated contact (TOPCon) cells on 210 mm wafers. At Trina Solar, the best batch average cell efficiency (total area) reached 23.61% for PERC and 25.04% for industrial-TOPCon (i-TOPCon). As far as we know, these are the highest values achieved on 210 mm wafers. The best champion efficiency for PERC and i-TOPCon is 24.5% and 25.42%, respectively, as independently confirmed by the National Institute of Metrology of China in Beijing and ISFH CalTech in Hamelin. We have developed modules with power outputs of up to 660 W by using 66 pieces of these 210 mm cells with 12-busbar technology in mass production. Besides, the aperture efficiency of the best laboratory PERC module fabricated by Trina Solar is 23.03%, which was independently confirmed by TÜV Rheinland. As far as we know, this is the first commercially sized PERC module with an aperture efficiency of 23% and a power output of over 600 W. Second, we have examined the technological development in the PV industry and summarise some empirical results. A look at the historical data shows that an increase in wafer area of at least 50% is required for a wafer size to become a new industry standard that lasts for 10 years. We find that it typically took about 3 years for the average efficiency of a cell in mass production to reach the efficiency of the champion cell produced in the industrial laboratory. We apply the empirical Goetzberger equation to analyse the module efficiency of c-Si and thin-film technologies. Based on our previous work, we update the selling price and manufacturing cost of PV modules and their learning curves. If we restrict the module price learning curve to the years starting in 2015, we find a short-term learning rate (LR) of about 40%, while the overall LR since 1970 is about 24%. A strong LR is driven by collaboration among industrial players and clustering of the industry, as well as standardisation of the technology, the supply chain, and final product design, which lead to fast equipment development and fast increase in capacity of supply chain. We propose an empirical law to describe the recent evolution of equipment LR, which shows that the throughput of tool increases 100% in every 3 years, so that the investment in cell production lines has decreased by 50% every 3 years since

2015. Finally, we quantify the material consumption and carbon footprint of PV plants today and for the expansion of PV to terawatt (TW) levels. Besides replacing silver fingers with copper and aluminium, saving copper cables in utilities and low-carbon mining of materials are the most effective carbon reduction measures in the PV supply chain.

KEYWORDS

efficiency, evolution, industrial, manufacturing cost, power, size

1 | INTRODUCTION

The photovoltaic industry has achieved an impressive growth at an average annual growth rate of 30%–40% from 2000 to 2021. A global new installation of 170 GW (AC) was reached in the year 2021, with an annual installation of 54.8 GW in China,[1] while production was estimated to be greater than 200 GW_{DC}. A cumulative installation of 1 TW of PV systems was achieved in 2022. In average over the last 50 years, the annual production and cumulative installation of PV modules have doubled every 3 years. This significant development is driven not only by the policies of local governments but also mostly by the fast reduction of levelised cost of electricity (LCOE) of PV power plants comparing to other energy sources.

The efficiency of silicon wafer-based commercial photovoltaic (PV) modules has been rapidly improving over the past decades with an average annual growth of 0.3–0.4$\%_{abs}$.[2] This is due to the continue of technology evolution of solar cells. Today, PERC (passivated emitter and rear cell), which was first developed in 1989,[3] dominates with an average efficiency of 23.5% in mass production. The next main stream cell technology will be solar cells with passivating contacts, possibly including heterojuncti (HJT)[4] and tunnel oxide passivated contact (TOPCon),[5] which will improve the cell efficiency to over 25%. For solar cells, great changes take place in terms of not only the cell structures but also the sizes. From 2014 to 2019, various solar cells with dimensions from 156.75 to 166 mm came to market with rapid size evolutions. This creates non-standardisation created chaos and loss to the whole PV community. During the past decade, the manufacturing cost of PV modules drops dramatically. All these contribute to the reduction of LCOE and make PV very competitive in the field of energy.

In this paper, we examine the deeper causes and the dynamics of PV production growth and price development as we have access to detailed data of the PV industry in China.

2 | INITIAL WORK ON PERC AND i-TOPCon

The scientists and engineers in the State Key Laboratory of PV Science and Technology (SKL) in Trina Solar started the R&D of PERC cells[3] in 2010 and fabricated world record efficiencies from 21.4% (2014), 22.1% (2015) to 22.6% (2016)[6–8] on 156 mm monocrystalline wafers. They transferred the PERC technology from laboratory to mass production in 2015.

In 2015, the R&D group in SKL started the study of thin SiO_x/poly-Si (n^+) structures with an industrial process flow leading to the industrial-TOPCon (i-TOPCon) cell.[9] We demonstrated a champion efficiency of 23.1%, which was independently confirmed by JET Japan[10] in 2018 and later a champion efficiency of 24.58%[11] in 2019. In 2018, we started to transfer the technology from the SKL to an 8-year-old manufacturing factory, which was used to fabricate conventional multi-crystalline silicon (mc-Si) cells with full-area Al back surface field (Al-BSF) in Trina Changzhou. It was a challenge to transfer the new technology from lab to fab, and it was even more challenging to transfer it to an old factory by keeping (1) as much equipment as possible from the previous mc-Si lines and (2) these tools at the same positions without moving to extend the lifetime of these tools and facility and to minimise the capital investment. After careful considerations, the R&D team successfully kept most of the tools, like previous Tempress $POCl_3$ diffusion furnaces, remote PECVD SiN_x:H tools from Roth&Rau, and the previous screen printers from Baccini, and only introduced new tools like a low pressure chemical vapor deposition (LPCVD). The upgrading of this workshop to i-TOPCon started from Q3 2018 with wafer size of 158.75 mm. The new i-TOPCon technology was very successful from the beginning and resulted in an average efficiency of over 23.5%.[12] The i-TOPCon and modules were installed in 500 MW PV power plants near the cities of Changzhi and Tongchuang in northwest China, with the support from the Super Top Runner Project from the Chinese government.

However, it became more and more difficult to operate the refurbished i-TOPCon factory due to two main reasons: (1) The cost of PERC cells dropped significantly; and (2) the efficiency of PERC cells improved continuously with bigger wafer size of 166 mm, causing the power of PERC modules higher than i-TOPCon modules with 158.75 mm cells. After 2 years, the factory was shut down in 2020, as it cannot be upgraded to the size of 166 mm.

3 | RECENT PROGRESS

To the best of our knowledge, an average efficiency of 23.5% in the refurbished factory was one of the highest efficiencies reported in 2019. However, the shutdown of the refurbished i-TOPCon factory taught us a lesson that the efficiency is not the only parameter that matters, but so does the wafer size, the manufacturing throughput, yield, and cost. Therefore, Trina started an investment of new PERC cell lines in 2021 with 35 GW annual capacity, and PERC modules with 50 GW, based on 210 mm (G12) wafers, and a new 210 mm i-TOPCon cell factory with a capacity of 8 GW in 2022.

The cell structures of PERC and i-TOPCon are as usual and illustrated in Figure 1. Their process flow is listed in Table 1. For PERC cells, the selective emitter is fabricated using laser doping because the etch-back technology has previously proven to introduce contaminants via the ink that stuck to the corners of the etched area. For i-TOPCon cells, the poly-Si is either deposited as an intrinsic layer by LPCVD followed by a phosphorus diffusion or deposited as a phosphorus-doped layer by plasma enhanced chemical vapor deposition (PECVD).

Table 2 summarises the latest progress of PERC and i-TOPCon cells and modules from Trina Solar. The results of the champion PERC and i-TOPCon cell were independently confirmed by National Institute of Metrology of China in Beijing and the ISFH CalTech in Hamelin, respectively. The batches in the usual production lines were measured inhouse with reference cells calibrated by third parties. To the best of our knowledge, this is the highest efficiency reported to date on 210 mm wafers.

Table 3 lists the reported best module efficiency of 23.03%, which was independently confirmed by TÜV Rheinland and TÜV NORD, together with a total power over 600 W. The measurement was done on aperture area. To the best of our knowledge, this is the first time that an aperture efficiency above 23% for a commercially available 600 W PERC module was reported. The module consists of 66 pieces of 210 mm PERC cells with an average cell efficiency of 23.6%. Each cell was cut into three pieces with multi-wires to reduce resistance loss.

Although good results with both PERC and i-TOPCon cells and modules were achieved, still some open questions remain. Will we have a bigger size than 210 mm in the future, and when? How can a new technology go from laboratory to mass production and become a new mainstream? Why are old factories so difficult to maintain, even with the help of latest technology? With these questions in mind, we look from a historical point of view and try to find industrial empirical laws that govern the PV industry.

4 | MODELS AND METHODOLOGIES

4.1 | Efficiency model

Goetzberger et al in 2002[13] introduced an empirical fit η (t) to efficiency values of champion laboratory cells over time:

$$\eta(t) = \eta_L \left[1 - \exp\left(\frac{a_0 - a}{c}\right)\right] \quad (1)$$

where η_L is the practical efficiency limit, a_0 is the virtual starting year of the technology development, a is the calendar year, and c is a

TABLE 1 Process flow of PERC and i-TOPCon cells in Trina's manufacturing lines

	PERC	i-TOPCon
1	Saw-damage etch and texturing	Saw-damage etch and texturing
2	Phosphorus diffusion	Boron diffusion
3	Laser doping of n++	Inline rearboro silicate glass (BSG) removal
4	Thermal oxidation	Thermal or plasma assisted tunnel oxide
5	Inline rear phosphosilicate glass (PSG) removal and cleaning	Poly-Si (*i*) by LPCVD or poly-Si (*n*) by PECVD
6	Thermal oxidation in tube	Phosphorus diffusion or annealing
7	Deposition of rear passivation	PSG removal and cleaning
8	Front SiNx deposition in tube	Deposition of rear passivation
9	Rear laser ablation for BSF	Deposition of front passivation
10	Rear Ag and Al printing	Rear Ag printing
11	Front Ag printing	Front Ag printing
12	Firing	Firing
13	Hydrogenation	Hydrogenation
14	I–V measurement	I–V measurement

Abbreviations: BSF, back surface field; i-TOPCon, industrial-tunnel oxide passivated contact; PERC, passivated emitter and rear cell.

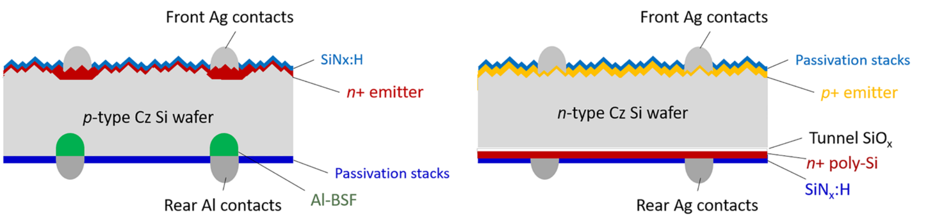

FIGURE 1 Cross session schematic of passivated emitter and rear cell (PERC) (left) and industrial-tunnel oxide passivated contact (i-TOPCon) (right) bifacial cell based on Cz silicon substrate with front and rear screen-printed contacts. Al-BSF, Al back surface field

TABLE 2 Summary of latest progress of PERC and i-TOPCon cells in the laboratory and in mass production

Cell	Data type	Wafer size (mm)	V_{oc} (mV)	J_{sc} (mA/cm^2)	*FF* (%)	Efficiency (%)
PERC	Best batch average (1000 pcs)	210	695.9	41.38	81.99	23.61 (t)
PERC	Best lab champion[b]	210	699.4	41.20	84.9	24.5 (t)
i-TOPCon	Best batch average (1000 pcs)	210	717.8	41.85	83.36	25.04 (t)
i-TOPCon	Best lab champion[a]	156.75	725.0	42.08	83.30	25.42 (da)

Abbreviations: da, designated illumination area; i-TOPCon, industrial-tunnel oxide passivated contact; PERC, passivated emitter and rear cell; t, total area.
[a]Independently confirmed by ISFH CalTech with aperture area of 226.62 cm^2.
[b]Independently confirmed by the National Institute of Metrology of China with multi-busbar.

TABLE 3 The latest progress of PERC module production at Trina Solar

	Cell	Data type	Wafer size (mm)	V_{oc} (V)	I_{sc} (A)	*FF* (%)	Efficiency (%)	Power (W_p)
Module	PERC	Best lab champion[a]	210	45.86	18.104	80.2	23.03 (ap)	665.7

Abbreviations: ap, aperture area; PERC, passivated emitter and rear cell.
[a]Aperture efficiency, independently by TÜV Rheinland Shanghai.

parameter which is related to the development speed. The equation is based on the observation that a technology would (1) develop quickly at the early phase and (2) gradually approach its practical efficiency limitation. We adopted this fit to industrial cells and modules,[2] where we applied the Shockley–Queisser[14] efficiency limitation as the theoretical efficiency limit for solar cell.

4.2 | Learning curve model

Under ideal circumstances, the manufacturing costs of an item tend to decrease with cumulative production. This ideal trend can be expressed with the well-known experience curve C_t, a power function of the form:

$$C_t = C_0 \left(\frac{q_t}{q_0}\right)^{-b} \tag{2}$$

where C_0 is the cost at a reference time, q and q_0 represent the time dependent cumulative production at time t and at the reference time, respectively. The key parameter is the slope b, called learning coefficient: the higher the b, the stronger is the cost decay. However, a more useful indicator is the percentage of change in cost during a doubling of experience, called learning rate $LR = 1 - 2^{-b}$. The higher the LR is, the faster is the cost decrease with cumulative production.

5 | RESULTS AND DISCUSSION

5.1 | The cell size evolution

First of all, we investigated the historical evolution of cell size n. In 1983, Alsema et al reported a wafer size of 100 mm,[15] while in 1994, various dimensions of 104,[16] 155, and 125 mm[17] were reported. The last one became the industrial standard with an increasement of wafer

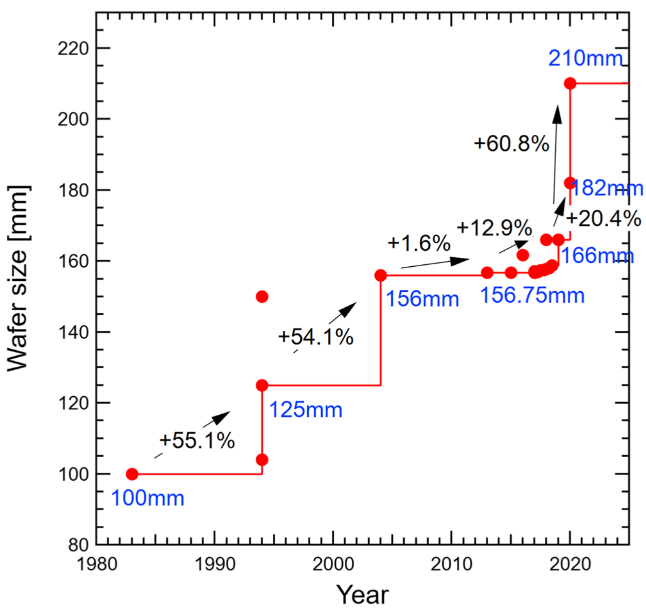

FIGURE 2 Wafer size over time. The symbols represent the size proposed for the first time, while the line is a guide for the eyes. Note that several sizes have existed simultaneously. The numbers are the area increasement comparing to the previous size.

area of 55.1% over 100 mm. In 2004, the dimension of 156 mm was proposed to the PV industry[18] with an increase of area of 54.1% compared to 125 mm, as illustrated in Figure 2. It seems that evolution of wafer size follows a certain regular trend: We propose an empirical "50%-10 years" empirical law for wafer size evolution, meaning that the wafer size can become a long term industrial standard only if the wafer area increases more than 50% and that a new dimension of wafer will remain a standard about every 10 years. In 2013, the industry adopted the size of 156.75 mm with an area increase of only 1.63% over 156 mm. In the following 5 years, various sizes like

156.85, 157, 157.3, 157.5, 157.75, 158, 158.75, …, 161.7 mm appear in the market as shown in Figure 2. This caused difficulties in the whole industry, not only in the supply chain but also in cost reduction. In 2018, Canadian solar introduced the size of 166 mm,[19] soon followed by Longi.[20] However, with the area increase of only 12.9%, 166 mm lasted for only 2 years and was soon replaced by 210 mm (with area increase of 60.8%) and by 182 mm (area increase of 20.4%). It seems to us that the size of 210 mm agrees well with the "50%-10 years" empirical law. This is why we proposed the 210 mm to the PV community, and we believe that the 210 mm standard may last for the next 5 to 10 years for the whole industry. Going to 210 mm wafers took a few months to have the fabrication tools developed, homogeneity reaching acceptable standards, and the manufacturing yield reaching above 98%. The new standard turned out to be more difficult for calibration labs. The cell calibration was an issue for quite some time for the calibration labs to accept to change to 210 mm size.

5.2 | The cell efficiency evolution

The closer cell efficiency comes to practical efficiency limits, the more it becomes influenced by spatial inhomogeneities and by the recombination at the cell's edge, both lowering *FF*. With bigger wafer size, it is therefore harder to improve efficiency because the wafers need to be cut in halves for module use, and inhomogeneities increase. Figure 3 shows the cell efficiencies in production lines for PERC and i-TOPCon cells in Trina with wafer sizes of 156.75, 158.75, 166, and 210 mm, over time. In general, both PERC and i-TOPCon show an annual efficiency improvement of 0.4%–0.5% abs., which is very similar to Fertig et al.[21] The efficiency of 210 mm is lower at the beginning; however, it took only half a year to reach the same efficiency level of small cells. By comparing the efficiency of champion lab cell and production, we have observed an empirical "3 years" trend that it normally takes 3 years for the average efficiency of cells in production to reach the efficiency level of champion industrial lab.

5.3 | The module power evolution

Figure 4 plots the power of single commercial modules over time. From 2011 to 2015, both mono and multi existed, with approximative 40% and 60% market share respectively, and it was hard for mono to dominate in the market because the power of mono modules was only 2–5 W higher than multi. The mono standard BSF modules were replaced by PERC mono in 2015 with a power improvement of 30 W. From 2015 to 2019, as the power of mono PERC module was about 10% higher than multi BSF module, the market share of multi shrunk rapidly. It was not until in 2019 that the application of 166 mm wafer with mono PERC contributes to a power over 420 W. This is about 130 W (30%) higher than that of multi standard BSF modules with 158.75 mm cell size, which caused multicrystalline Si cells to almost disappear in 2020. Since 2020, the module power has increased rapidly from 400+ to 550 W, which could be achieved by both 182 and 210 mm big cells. Soon, 600 and 660 W modules using 210 mm cells appear, leading the module power to the 600+ W era.

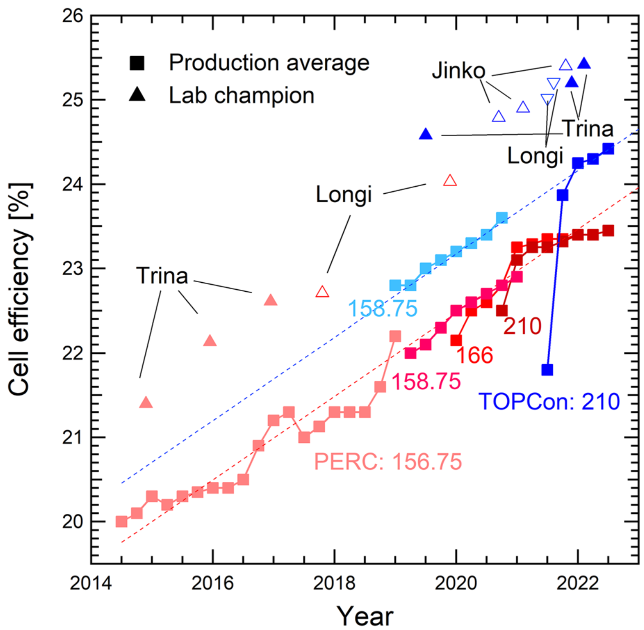

FIGURE 3 Cell efficiency of passivated emitter and rear cell (PERC) (red) and tunnel oxide passivated contact (TOPCon) (blue) cells with various wafer sizes in three labs (triangle) and production lines from Trina (square) over time

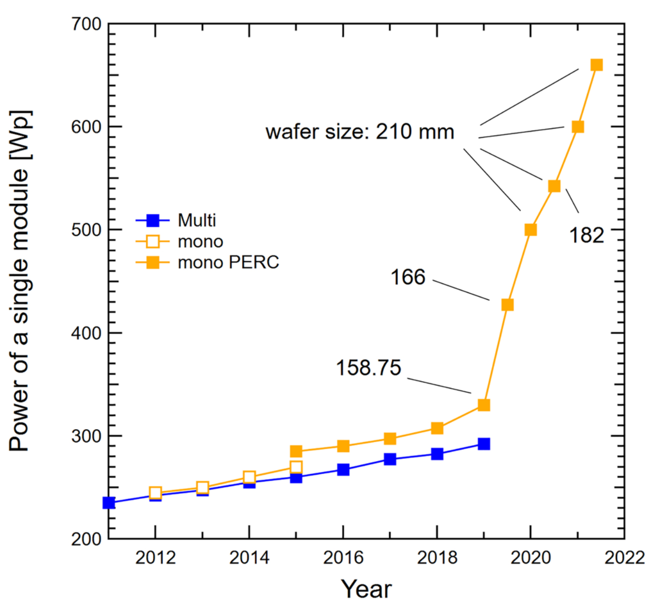

FIGURE 4 Typical average power of single modules for multi (blue), mono (yellow, empty square) and mono passivated emitter and rear cell (PERC) (yellow, solid square) over time in the industry

5.4 | The module efficiency evolution

Figure 5 plots the module efficiency for PERC and *n*-type technologies (passivated emitter, rear totally cell [PERT], TOPCon, HJT, and interdigitated back contact [IBC]). The module efficiencies have been routinely collected from datasheets of the websites from the various manufacturers. They represent the mass-produced products, not the products with the highest efficiencies, and may have a time lag depending on how often the websites are updated. As a general observation, cells with advanced structures have better efficiency. However, the rapid technology improvement in solar cells (also seen in Figure 3) enables today's PERC modules to have higher efficiency than some *n*-type variants like PERT, HJT, and TOPCon modules that were manufactured in old factories. This observation does not support the expectations that if a module consists of advanced cells, say HJT, then it will have higher module efficiency than a PERC module. As the efficiency of every cell technology improves over time, any new cell technology needs to compete in cost, LCOE, and efficiency against the fast moving target of the mainstream technology. This shows how important is the pace of efficiency improvement.

5.5 | Manufacturing cost

We reported the cost learning curves study in a previous publication, indicating that the LR of c-Si was 24%[12] with updated data from International Technology Roadmap for Photovoltaic (ITRPV)[22] in the entire range shown in Figure 6. However, starting from 2015, after the bump created by the silicon feedstock supply constraint, we notice a steeper learning curve of c-Si with a LR of 40%, which lead to a price of 0.2$/W in 2020. Contributions for this stronger price decline come mostly from collaboration of partners of a clustered PV industry essentially in China, the rapid development of the domestic Chinese equipment industry (as will be shown in Figure 7), a cheaper supply chain, leading to a fast scaling up of the PV industry and its supply chain, and the rapid introduction of new technology like PERC, leading to the scaling effect of price decay. Started from 2020, the rapid increase of cell and module manufacturing capacity leads to relative shortage of the supply of silicon feedstock and the other materials that the price of raw materials like poly-Si feedstock increases rapidly. There always will be "bumps" in the learning curve created by temporary supply constraints, followed by "dips" to recover, but we believe that the decrease in manufacturing cost will continue with a LR greater than 24%.

5.6 | The evolution of manufacturing equipment

We empirically see that the throughput of cell manufacturing tools has generally followed in a similar manner, reaching in 2022 up to 12,000 wafers per hour for some specific tools. We also have been observing the investment of PERC lines shown in red in Figure 7. The CAPEX following an exponential decay has dropped dramatically by

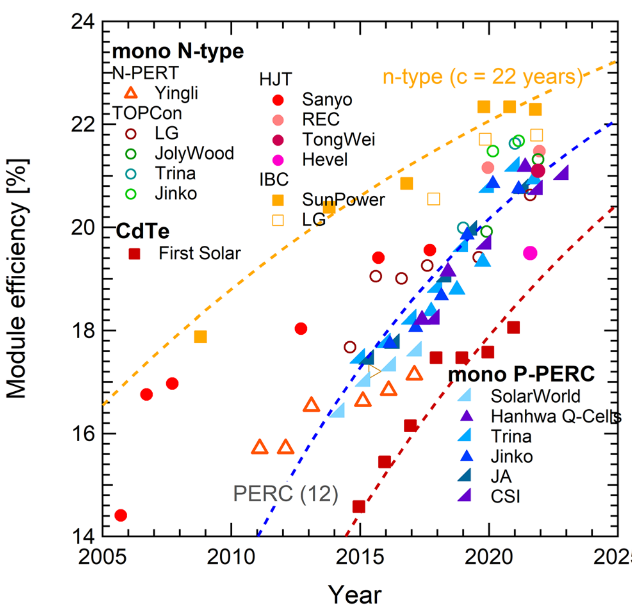

FIGURE 5 Module efficiency for various cell designs. The symbols are module efficiency of the commercial modules, taken from datasheets of various manufacturers for their fastest selling products, not their highest efficiencies. The curves are parameterised with the Goetzberger Equation 1. PERC, passivated emitter and rear cell; TOPCon, tunnel oxide passivated contact

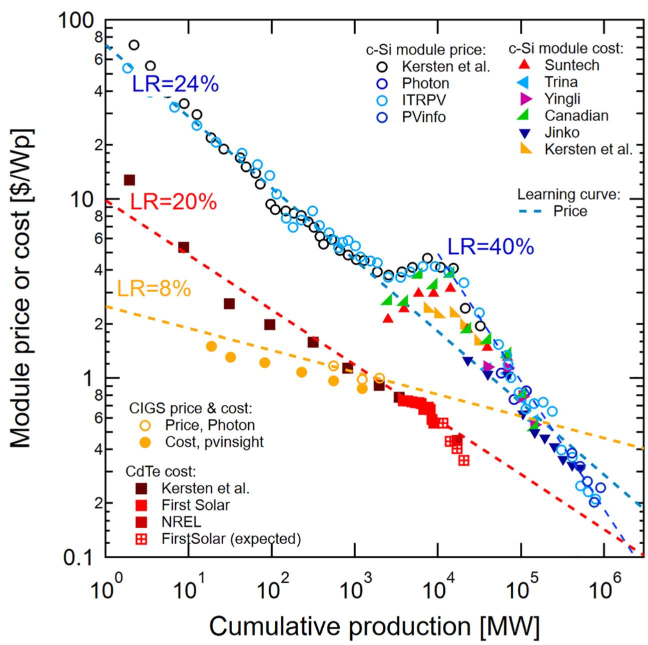

FIGURE 6 Module selling price or fabrication cost as a function of cumulative production, with data from Chen et al.[2] The dash lines are the fittings with learning curves. LR, learning rate

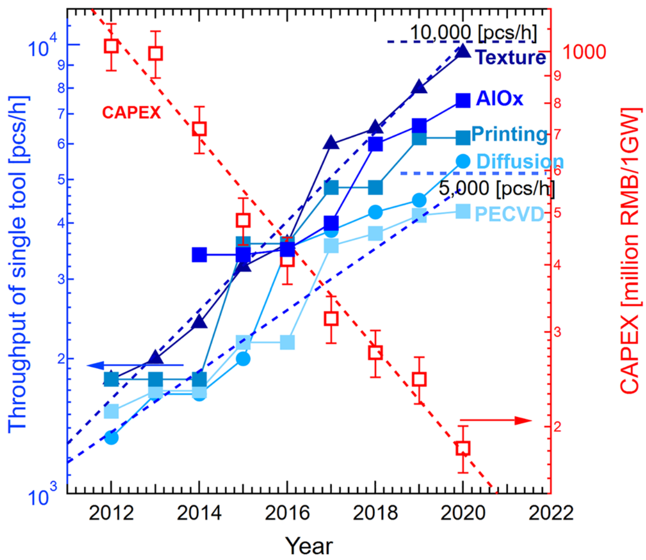

FIGURE 7 The historical throughput of a single tool (left axis, blue) and the capital expenditure (CAPEX) of equipment for a 1 GW factory of passivated emitter and rear cell (PERC) cells (right axis, red) over time. The curves are a guide to the eyes.

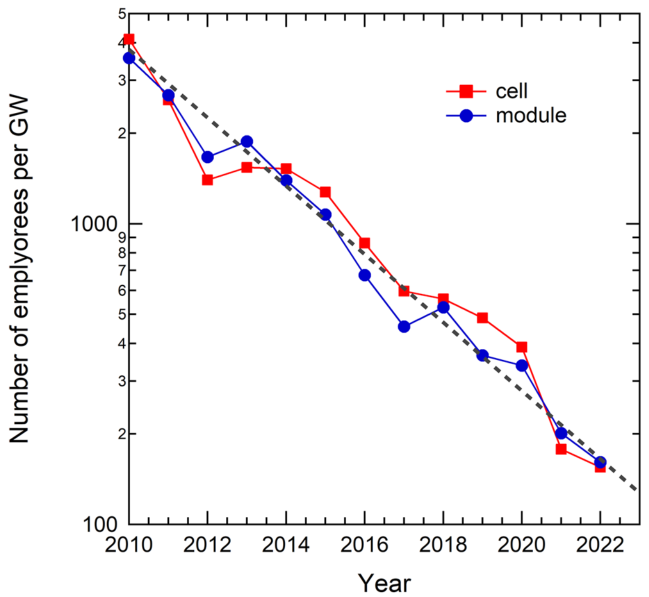

FIGURE 8 The historical number of employees at Trina Solar in cell (red) and module (blue) factory as a function of time. The grey dash curve is a guide to the eyes.

more than one order of magnitude since 2012. We propose a "50%-3 years" empirical law: that the throughput of tools doubles every 3 years and the investment in cell fab per GW drops by 50% every 3 years. The improvement of throughput of a production line reduces not only the cost of investment but also the non-material cost like number of employees, size of facilities, and number of connection points, helping the manufacturing cost of c-Si modules to drop faster. Figure 8 plots the number of employees in Trina factories per GW of cell and module production over time. During the past decade, this number decreased strongly from about 4000 people/GW in 2010 to nearly 150 people/GW in 2022 for both cell and module workshops. In general, the drop is similar to the "50%-3 years" empirical law, which is mainly due to the evolution of equipment and the introduction of automation.

6 | MATERIAL USAGE FOR SCALING UP PV

Figure 9 shows a typical 30 MW PV-utility system,[23] about 600 km west of Beijing in Inner Mongolia, built on grassland extensively farmed with goats and sheep (coordinates: N 40°42′26″, E 110°27′19″).

As the power generation itself does not cause emissions, the main environmental impacts of PV come from the mining of the necessary materials, besides the use of electricity, from a mixed generation portfolio, for cell and module production, and the use of petrol in shipping and the construction of the utility. Figure 10 shows the quantities of materials used for this PV plant.[23]

Besides concrete for fixing the mountings, the heaviest materials are 1500 t of steel for the mountings, 800 t of module glass, and almost 200 t of copper cable, 300 km long, running along the rows of modules and connecting the plant to the nearest high-voltage line. However, this power plant has a performance guarantee for 30 years and will continue to produce electricity after that,[24] with more and more modules being replaced over time, the glass being reused, and the basic structures being able to be used for longer than 100 years.

Sophisticated modelling predicts[25] that the global energy transition will require a minimum of about 63 TW of PV installations, alongside about 8 TW of wind energy plus other renewable energies and storage. We should note that predictions vary greatly with the assumptions, between 14 and 70 TW, however considerably more than 63 TW will need to be installed if inefficient energy systems are considered. The PV-utility system considered here has a capacity of only 30 MW. Power plants with total capacity of 2.25 GW have already been built, and the other 5 GW are in planning. In addition, about every house in the world would need to be powered with a rooftop PV system of 5 to 10 kW.[26] Assuming that there will be no technological improvements in the years to come, Figure 11 compares the total quantities of materials required for these systems with the amount of these materials produced worldwide in 2020.[27]

That PV needs to substitute silver with copper and aluminium is well known. The next material is glass made for PV. However, the supply chain can be expanded quickly as glass is made from abundant raw materials, mainly from quartzite mining, and it is produced in much smaller quantities than window and bottle glass.[28]

For polysilicon, PV has its own supply chain that it can expand because, similarly to glass, polysilicon is mainly extracted by mining sand.[29–31] Most silicon is produced in impure form for steel production and other applications. The amount purified for PV and electronics is 6%. Even if all global electricity were generated exclusively by

FIGURE 9 Typical 30 MW PV-utility, manufactured and constructed by Trina Solar

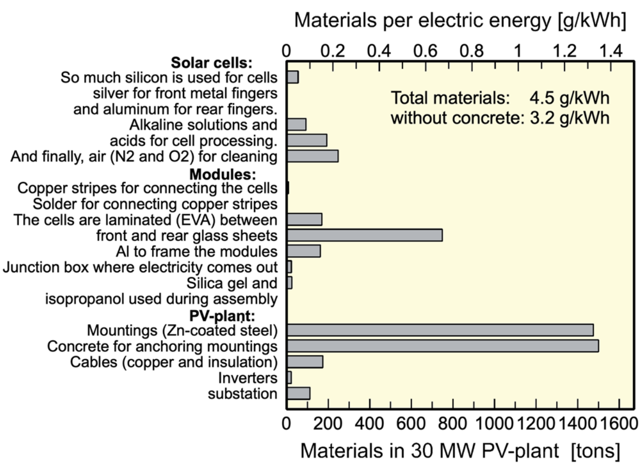

FIGURE 10 Materials used for manufacturing and constructing the 30 MW PV-utility. EVA, ethylene vinyl acetate

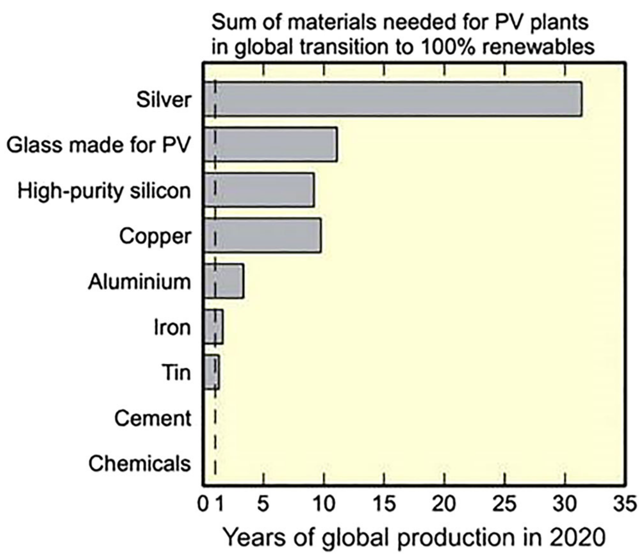

FIGURE 11 Sum of material needed for PV-utilities in a global transition to 100% renewables, compared with global materials production in 2020 Trina, assuming that there will be no technological improvements

PV by 2030, growth rates in the production of non-pure silicon would fall into historical range.[32]

Apart from silver, the only rather critical material is copper. Considering that copper is also used for power grids, electric vehicles, and wind energy, forecasts[33] estimate that copper production must be at least doubled for the next 30 years to meet this increasing demand. If not done carefully, this may significantly increase the footprint of PV. In copper mines, the purification of the ore is usually done on site, so it falls under the mining laws and not the industrial laws, and the liquid waste pollutes the environment[34] for more than a hundred years.[35,36] Therefore, it is important to keep in mind that about half of the copper mines are in regions with very low water availability, and about half are closer than 20 km to protected areas.[37] Copper mining can also have negative social impacts. As copper in economically exploitable form is not evenly distributed across the planet, more than half of the additional copper production is expected to come from Central and South America.[33,38] Positive impulses for regional economic development could not be empirically observed so far due to low labour intensity, loose ties to local suppliers, and profit outflows.[39] Social conflicts often lead to the criminalization of activists, repression, and forced displacement.[40] For all these reasons, developing technology to save copper usage in PV utilities would make PV significantly more environmentally and socially friendly.

7 | CO_2 EMISSIONS CAUSED BY PV-UTILITIES

Figure 12 shows the CO_2 emissions caused by the production and construction of the said PV plant, calculated from the bottom-up in a life-cycle analysis study. Most of these emissions come from power generation with a mixed portfolio of sources but at least two thirds from coal and from the use of petrol-powered trucks and boats. In this PV utility-scale system, the silicon was produced with hydropower; if pure coal power was used, the CO_2 emissions in the top bar of the graph would double.[41] In the course of the global energy and transport transition, all these emissions are being continuously reduced to zero.[42] Figure 12 indicates that only a small part is caused by "direct emissions," where CO_2 is released by chemical reactions in cement and silicon production and cannot be avoided by renewable electricity.

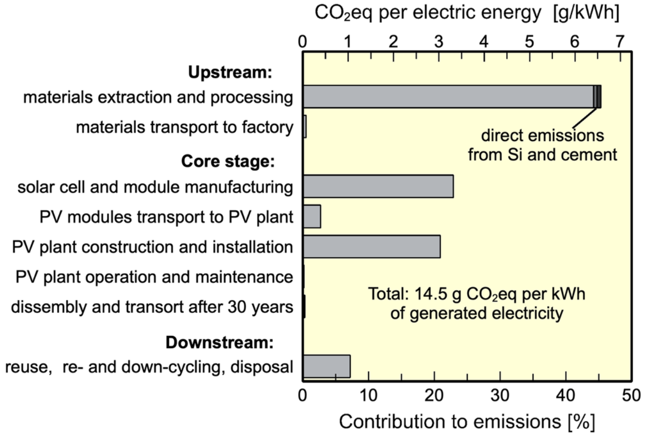

FIGURE 12 The CO_2 (eq) emissions of the PV-utility in Figure 9, as calculated from a life-cycle study.[20] The hashed area are the savings in manufacturing accomplished over the past 3 years.

The emissions add up to 14.5 g CO_2 (eq) per kWh of generated electricity, or equivalently, 535 t of CO_2 (eq) per MW of installed PV capacity.[24] To estimate the total CO_2 emissions for the global energy transition, let us again assume that there will be no technological improvements in the years to come and that 700,000 such PV-utilities will be installed. Assuming additionally that the electric power mix will linearly change to 100% renewables, the CO_2 emissions from manufacturing and building all PV systems will sum up to about 5 Gt, compared to about 43 Gt emitted globally this year alone. This means that the global deployment of PV will consume at least about 2%–3% of the remaining CO_2 budget to meet the Paris Agreement's warming target of 1.5°C. If again wealthy countries will import large amounts of PV-generated hydrogen, the global deployment of PV will cause up to 8% of the remaining carbon budget. Still, this is pure luck considering that scientists and engineers reduced PV's CO_2 emissions significantly over recent years[43]: Just 20 years ago, global PV deployment would have caused at least a quarter of the remaining CO_2 budget, see Figure 13. This shows how important R&D is for new technologies and indicates that other new technologies, such as lithium batteries, may become more environmentally friendly as well.

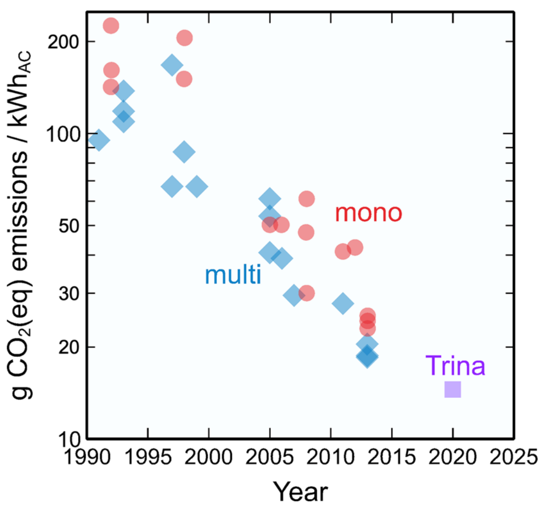

FIGURE 13 Greenhouse gas emissions from photovoltaic utilities[21] over time and comparison with a life-cycle study of the 30 MW utility system in Figure 10

The said PV system "earned back" all the energy, spent on its production and construction, within the first 20 months of its operation. In order to further reduce emissions and shorten the energy payback period, Trina Solar has reduced the consumption of fossil gas, electricity and water, and thus also CO_2 emissions in recent years,[44] as shown in Figure 14.

This was achieved through various measures in production, for example, reusing waste heat, using cooling towers (instead of chillers) that use natural cooling in the cold season, optimising fresh air supply, reducing air conditioning, changes to the vacuum system, and building heat shields around the laminators in module production. This was

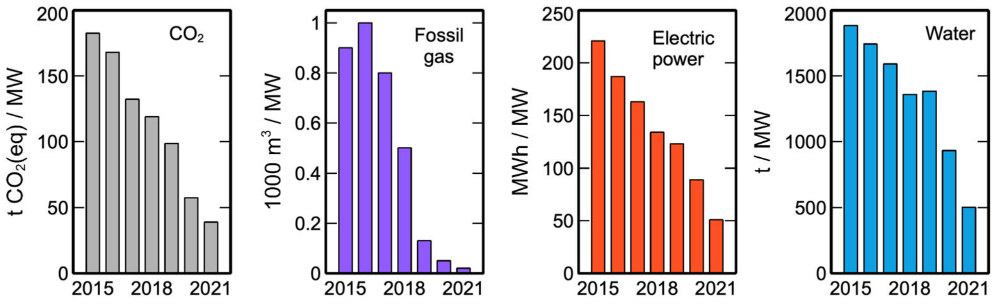

FIGURE 14 Savings of fossil gas, electricity and water consumption in cell and module manufacturing at Trina Solar, and greenhouse gas emissions calculated

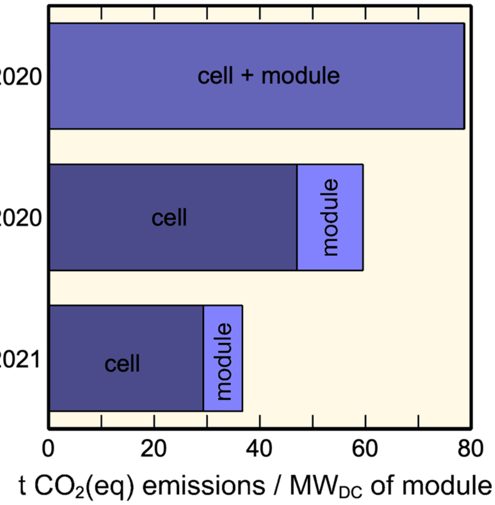

FIGURE 15 Reductions in greenhouse gas emissions in cell and module manufacturing of Trina Solar, from old to new factories

made possible mainly because the new factories were designed and built with the carbon footprint in mind, see Figure 15.

Trina Solar has joined the global Science Based Targets Initiative (SBTi)[45] in order to limit the global temperature increase by 1.5°C. To this end, an internal emission trading system was introduced for all domestic and foreign plants. In addition, an annual energy consumption target with monthly milestones and assessments was set for each division. In order to reduce secondary emissions (from the supply chain), a supplier audit and assessment process was introduced to track communication and interaction with suppliers.

8 | CONCLUSIONS

In this paper, we report the latest progress of industrial crystalline Si cells and modules, and we investigate the dynamics that shape the industry. First, we reported the efficiency PERC and TOPCon cells based on 210 mm wafers. At Trina Solar, the best batch total-area average cell efficiency reached 23.61% for PERC and 25.04% for i-TOPCon. To the best of our knowledge, these are the highest values reported on 210 mm wafers. The best champion efficiency for PERC and i-TOPCon is 24.5% and 25.42%, which is independently confirmed by the National Institute of Metrology of China and ISFH CalTech, respectively. We developed modules with up to 660 W power using 66 pieces of such 210 mm cells with 12-busbar technology. To quantify progress in module technology, we assessed that the aperture efficiency of Trina Solar's best PERC module is 23.03% as independently confirmed by TÜV Rheinland. To the best of our knowledge, this is the first commercial PERC module with 23% aperture efficiency and over 600 W power.

Second, we investigated the technology evolution across the overall PV industry and summarised several empirical discoveries. Looking at the historical data, we found several empirical constants in the evolution of the PV industry. For example, the annual PV production and cumulative installation are doubling every 3 years in average. We also found that an increase in wafer area by at least 50% has been necessary for a wafer size to become a new industrial standard that lasted for at least 10 years. We found that it usually took about 3 years for the average cell efficiency in mass production to reach the efficiency of the champion cell fabricated in the industrial laboratory, by transferring and optimising the technology from lab to production. We applied the empirical Goetzberger equation to analyse the module efficiency of c-Si and thin film technologies. Based on our previous work, we updated the sales price and manufacturing cost of PV modules, as well as their learning curves. The overall LR of silicon PV technology is greater than 24%. When restricting the module price learning curve after the supply chain constraints due to silicon feedstock limited capacity (2005–2012), in fact limiting the analysis to 2015 onwards, we observed a LR of about 40%, which leads to a 0.2 $/W module price in 2020. The strong LR is driven by a strong collaboration of partners of a clustered PV industry essentially in China, the evolution of equipment, standardisation of the technology, and the standardised supply chain. We propose an empirical law to describe the latest development of equipment learning model, that the investment of PV cell production line dropped 50% in every 3 years since 2015. Finally, we investigated the material usage for scaling up PV and the carbon footprint. The continuous development and evolution of the technology enable the PV industry and the generation of solar electricity to become more and more competitive today and in the future.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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