A Brief History of Silicon Solar Cell Efficiency Developments

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1. THE NEED FOR EFFICIENCY

As the work toward creating a viable terrestrial energy source got underway in 1973, terrestrial module efficiencies were in the 5 to 6 percent range. It was understood that higher efficiency would be needed, but this raises the question "how much efficiency is actually required?" The parallel question of how to get there is, of course, the purpose of this review, but that will be treated later.

Clearly, the required efficiency must be greater than that needed to generate sufficient electricity production value to cover the manufacturing cost of the cell and module, plus the installation and other system costs. Most early work concentrated on the cell cost, as these were very high and in need of serious reduction. Cell cost swamped all other costs so little effort was focused on non-cell cost. When considering the widespread use of terrestrial photovoltaics (PV) as a power generator, the question of required costs of various elements of a PV system became germane. There is a close relation in the value of a PV module versus its efficiency. But what is that relation?

The long haul to forecast and reduce non-module costs receives less attention than the highly tracked module cost, with its impressive learning curve, but is equally important as we shall see. (See [1, p. 4] for an up-to-date module learning curve. Module prices in constant dollars have decreased 600 fold over the period 1976 to 2022.) A large early effort to get a more rigorous estimate of potential costs was performed by the General Electric Company in 1978 under contract to the Electric Power Research Institute (EPRI today) [2]. The effort described in this report was extensive and looked at the value created by utility ownership of PV plants. This is a complex issue because a PV plant's output as well as the utility load demand varies over time. It depends on the location of the plant as well as the details of the utility's generation mix. General Electric performed a detailed engineering design of all the plant elements including site preparation, racking structure installation, wiring, etc. Most of these elements were similar enough to other construction projects that it was possible to get a reasonable idea of their costs. They estimated that the area related balance-of-system cost would be \$16/m^2 and the cost to laminate solar cells into modules would also be \$16/m^2. The cell cost, c_{cell}, was left as a variable. The result appears in Figure 1. Note: the required cost is the cost at which the plant will financially break even from the utility owner's perspective. It was assumed that with sufficient development and production volume, the cell cost could be as low as \$40/m^2 and the efficiency 12 percent. As seen in Figure 1, this is higher than the cost for economic breakeven, even in the most favorable case. Also shown was the then-current cost of \$2000/m^2. Based on the results in Figure 1, General Electric recommended a research and development effort to bring cell cost to \$20/m^2 with an efficiency of 14 to 18 percent. They estimated that the raw material cost in the cell would be \$10/m^2, so the cell would cost twice material cost. Thus, an early estimate for the required cell efficiency was 14 percent minimum. Again, about a factor of 100 in cell cost reduction on an area basis (\$2,000/m^2 versus \$20/m^2), along with an increase in cell efficiency from the 1978 commercially available efficiency of around 12 percent to over 14 percent, was required to envision large-scale use. Note the Figure 1 implies that a cell that is free must have an efficiency in the 10 to 13 percent range just to cover the non-cell costs.

Other cost projections quickly followed. For example, the American Physical Society conducted a workshop in 1979 titled *Study Group on Solar Photovoltaic Energy Conversion* [3]. After surveying the available literature, they concluded that a reasonable number for $c_{a,BOS}$ was \$20/m^2. This would be \$72/m^2 in 2022 dollars. Because of the importance of the balance-of-system (BOS), or non-module, costs, these attempts continued. Selected results appear in Table 1.

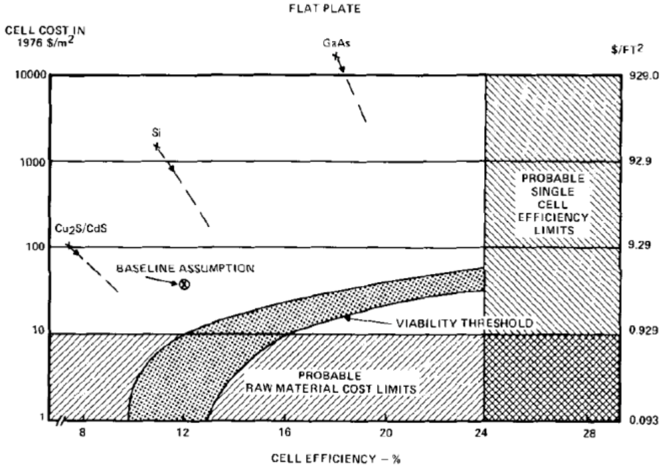

Figure 1: Required cell cost versus cell efficiency for a utility scale PV plant as computed in 1978 [2, pp. I-12]. The region labeled "variability threshold" is the required cell cost versus efficiency range over the assumed locations. The "probable raw material cost limits" region refers to cell material cost.

	$C_{a,BOS}$	Type	Reference	Organization
	$/m^2			
1972	670	Estimated	[25]	NASA
1978	73	Projected	[35]	GE
1979	72	Projected	[36]	APS
1981	147	Projected	[37]	Sandia
1983	80	Projected	[38]	Sandia
1984	143	JPL Goal	[39, p. 51]	JPL
1984	612	Actual	[39, p. 58]	SMUD 1 MW
1984	137	Projected	[40]	Black & Veatch
2022	50	Actual, Global	[41, p. 47]	IRENA
2022	61	Actual, USA	[42, p. 101]	FgISE

Table 1: Selected area-related BOS costs adjusted to 2022 US dollars using the consumer price index, https://www.bls.gov/cpi/. "Estimated" means that the result was based on simple estimates. "Projected" means that the result was based on detailed cost modeling for a large power plant, and "Actual" means the result observed in actual construction.

As a result of the early calculations, it became apparent that module efficiencies well over 12 percent would be required. Thus, the Federal PV program changed the module efficiency goal from an original 10 percent in 1975 to 15 percent in 1980. This was 17 percent at the cell level [4, p. 35]. Of course, the projected numbers in Table 2 were just hoped-for possibilities in the period 1978 through 1984, but they provided hope that one day PV could become a cost-effective large-scale source of electricity.

Today, many large PV plants have been constructed that supply grid power economically, so we have actual results to go by. Today's large power plants are being built with area-related BOS costs in the $50 (global average) to $61/m^2 (US average) range. The early projections in Table 2 were remarkably accurate. Note that the actual cost for one of the early large plants, the Sacramento Municipal Utility District 1 MW plant in 1984, was $612, which is tenfold the current costs. This can be attributed to a classic learning, albeit with a lower learning rate compared to modules, as would be expected due to the more classical construction nature of the BOS components (steel, concrete, copper, etc.). In the period 1984 to 2022 PV module prices declined nearly 100-fold, from $20/W to around $0.23/W, which is fortunate as they needed such a decline to make PV competitive with fossil fuel electricity. The tenfold decrease in BOS costs should not be dismissed, however. Without that improvement PV today would not be competitive.

A more recent calculation (2016) along the same line as the 1978 GE study is shown in Figure 2 [5]. Note that the base case calls for a 20 percent efficient module costing $0.40/W, which is $80/m^2. This would translate to $21/m^2 in 1978 dollars. GE calculated module lamination would cost $16/m^2 and cells might be as low as $20/m^2 giving $36/m^2 panel cost [2]. This is certainly not too far off given the 40-year time difference. Perhaps even more remarkably, the results of [5] reveal that the module must have over 12 percent efficiency to have positive value, which is well within the 10 to 13 percent range calculated by GE 45 years ago [2].

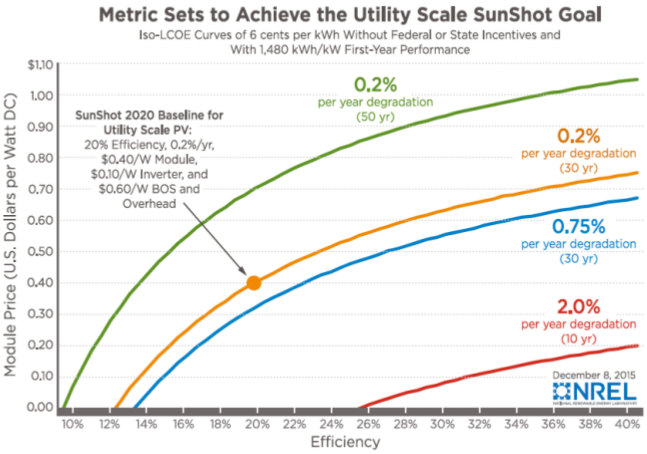

Figure 2: Required module cost versus efficiency to achieve $0.06/kWh LCOE.

Figure 2 also reveals the large impact of module degradation rate. Note that modules that degrade 2 percent per year must over 25 percent efficiency just to have positive value. In fact, such a module would have to have 40 percent efficiency, and cost the same on an area basis, to compete. So, there would be no point. Conversely, a 50-year module can cost almost twice a 30-year one.

2. HISTORIC IMPACT OF EFFICIENCY

The NREL record laboratory cell efficiency chart is well known and can be found at https://www.nrel.gov/pv/cell-efficiency.html. Of more importance to the market and system deployment are commercially available module efficiencies. The efficiency of commercially available cells and modules lag those laboratory cell records, of course. These are shown in Figure 3, where the highest module efficiencies available from leading manufacturers are shown. The remarkable and inexorable upward trend is evident. Note that the actual average efficiencies are somewhat lower than the manufacturers data as plotted because of over reporting, especially in the early years, as well as the fact that the highest efficiency bin usually had limited availability. This detail does not modify the overall picture, however. Details of the various cell structures and process flows are covered in [6] and [7].

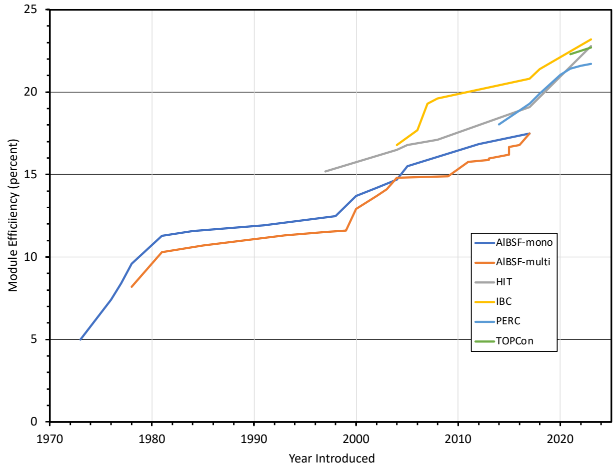

Figure 3: Historic module efficiency versus year of introduction for various commercially available silicon cell technologies. The modules with the highest commercially available efficiency are plotted. Data is from Photon International, company data sheets, conference publications, and JPL reports.

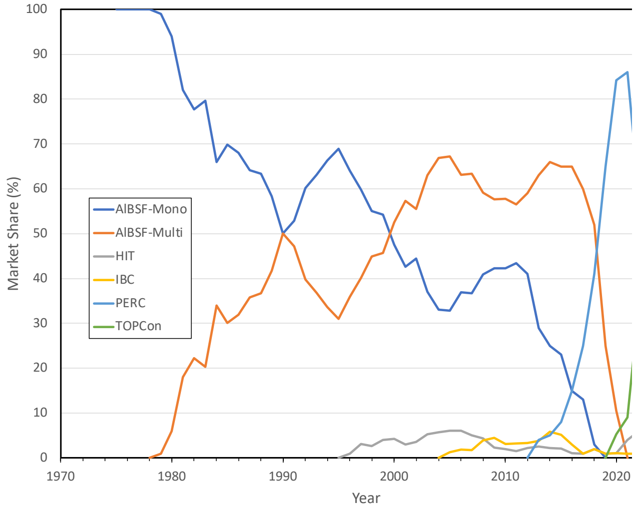

Figure 4: Market share versus cell technology. Data from ITRPV, Solar Flare, and PV Magazine.

Referring to Figures 3 and 4 we see an interesting dance among competing technologies. In the mid nineteen seventies the only available technology was based on Czochralski wafers, and these enjoyed 100 percent market share. These modules are referred to as AlBSF-Mono to distinguish them from other monocrystalline cell types introduced later. (AlBSF refers to aluminum back surface field). The efficiency of mono-crystalline modules rapidly increased from 5 percent in 1973 to around 11 to 12 percent in 1980. This period is distinguished by the rapid transition from space cell designs to cells made specifically for terrestrial use. These changes included the use of larger cells, often the whole round wafer, texturing, and screen-printed metallization. This became the standard approach by 1980. The need to improve efficiency drove a transition from round cells to semi-square cells so that the cells covered a larger portion of the module area. Semisquare cells were made from round ingots with some material removed at the edges giving a square shape with rounded corners. At that point (1980) AlBSF-mono module efficiencies pretty much stagnated for 20 years until 2000. What small increases there were came from improved process control, reduced metal linewidths, and other manufacturing improvements. There was, on the contrary, a huge reduction in the manufacturing cost of conventional AlBSF cells. Module prices decreased 10-fold from 1980 to 2000 [8]. The manufacturing improvements that allowed this reduction are covered in the literature [9, 10]. Much of this cost reduction effort in the US was sponsored by the DOE PVMaT program, which was equally influential as the JPL LSA project [11].

Cells made of multi-crystalline cast silicon were introduced in 1978 by Solarex. Modules made of multi-crystalline silicon had lower cell efficiency due to carrier recombination at grain boundaries; however, they made up for some of this loss by being square and hence had a larger cell coverage fraction. Referring to Figure 3 it is seen that these modules maintained roughly a one percentage point lower efficiency compared to mono-crystalline over the following years. By avoiding the Czochralski ingot growth step, however, multi-crystalline modules enjoyed a cost advantage. As a result, mono-crystalline AlBSF modules slowly lost market share to multi-crystalline, and pretty much disappeared by 2018 (Figure 4.)

As seen in Figure 4, module efficiency had stagnated in the 12 percent range for almost 20 years. Starting in 1998, new higher-efficiency technologies started to be introduced which dramatically improved performance by doubling the module efficiency. This journey is the subject of this paper.

3. THE SEARCH FOR HIGHER EFFICIENCY

With the establishment by 1975 of the aluminum back-surface field solar cell (AlBSF) technology as the dominant silicon cell standard, effort got underway to find a path to higher efficiency. The AlBSF cell design limited module efficiency to 12 percent or so, and as seen in Section 1, 12 percent efficiency was less than that required to meet system cost goals. The AlBSF cell appeared rather well developed and mature, however, so the question was, “how to improve upon it?” At first this effort involved two key aspects: 1) the use of float-zone silicon wafers, and 2) more complex cell designs and structures. It was known that cells made of Czochralski silicon were limited by the rather low minority carrier lifetime in finished cells. Therefore, float zone wafers were used in most high-efficiency laboratory cells. Float-zone ingot growth avoided the impurities introduced from the quartz crucibles used in Czochralski growth. This was done by means of melting and re-crystallizing a polycrystalline silicon rod using induction heating, but it was much more expensive. The more complex cell structures were usually made with photolithographic patterning which provided finer patterns than available with screen printing. It was also much more expensive. Laboratory cells were typically much smaller than commercial cells; several square centimeters versus hundreds of square centimeters. Thus, initially laboratory record cells were just that, laboratory cells. The industry was often dismissive of the value and utility of such laboratory cells. Researchers justified it by saying "it is important to explore where one can go with silicon." We shall see that the seeds of the modern high efficiency cells germinated in this effort to produce record laboratory cells. This has enabled the explosive growth of the industry to continue beyond 2000. (i.e, there was great utility in the research effort.)

The University of New South Wales (UNSW) photovoltaic group, under the leadership of Prof. Martin Green, was a leader in this effort. They held the silicon non-concentrator cell efficiency records from 1983 until 2014, except for two record cells from the Stanford group in 1986 and 1988. From these efforts the concept of localized, or point contacts emerged. An example is the PERC cell mentioned in Section 2. A history of PERC cell development is covered in [12].

The author's group at Stanford University also researched new cell designs. The Stanford approach was different, however, in that initially we worked on silicon cell development for thermophotovoltaic (TPV) systems [13]. A TPV converter is a direct conversion heat engine that uses a photovoltaic cell to convert thermal radiation from an adjacent radiating surface into electric energy [14]. In the proposed solar-electric system, concentrating mirrors are focused on a TPV converter that operates at high power density and potentially high efficiency. This project will be described more fully in the next section, but one result was the development of a new type of silicon cell, the point-contact IBC cell, that evolved to mitigate some of the issues limiting TPV conversion efficiency.

The TPV system proved too complex to be practical, mainly due to the high solar concentration required (>10,000X) and the high radiator temperature (>2100 K). The radiating element tended to sublime onto the surface of the cell and was dispensed with in the late 1970s. Thereafter we focused on having the incident light hit the IBC cells directly, i.e, on concentrator cells. Efficiency was still the most important metric, because the system had to produce enough energy to pay for the concentration apparatus, which was usually comprised of Fresnel lenses or reflective parabolic dishes mounted on 2-axis trackers. This allowed for more complex cells designs and processes, such as the interdigitated back-surface contact (IBC) cell discussed in Section 1. The cost of float-zone silicon was not an issue either. The Stanford group's IBC cells, and cells built to its design, held the efficiency record for silicon concentrator cells continuously since these results were tabulated by NREL, starting at 26.8 percent in 1986 and going to 27.6 percent in 2007. This was a pyrrhic victory in that concentrators were never able to compete with flat-plate modules in the market. The IBC cells, however, did make into SunPower Corporation's flat-plate modules.

As discussed in the following sections, all modern high-efficiency flat-plate modules incorporate features developed in these early laboratory efforts at the UNSW and Stanford. So intriguingly, both approaches, laboratory one-sun cells and concentrator cells, led to the same result, high efficiency one-sun cells. This was quite an amazing journey.

4. THE STANFORD TPV PROJECT

In 1974 the author, then at Stanford University, began investigating how to make PV cost effective for terrestrial applications. After considering the non-module costs, BOS cost in today's vernacular, he became convinced that higher efficiency was needed than the 10 percent or so available at the time. It was not obvious how to do this, however. He came across the TPV idea in a paper by Wedlock [14]. As mentioned, it involved illuminating a PV cell with blackbody radiation from a hot radiating element. Photons of an energy not efficiently used by the cell could be reflected back to the radiator and get another chance to come back at the right energy. An idealized TPV converter had been shown to be a reversible heat engine and thus would have the Carnot efficiency operating between the radiator and cell temperature [15]. This was over 80 percent at the anticipated radiator temperatures. That seemed promising. EPRI had come to the same conclusion regarding the need for efficiency, and began supporting the Stanford TPV effort in 1976 [16].

The method chosen for recycling below-bandgap photons was to have them pass through the cell, reflect off a mirror on the backside, and thereby return to the radiator to be reabsorbed. Modeling had indicated that the back reflectance must be over 98 percent (an absorptance of less that 0.02) to get high enough recycling efficiency because most of the radiation was below bandgap. Initial experiments showed that the standard aluminum back surface contact was too absorptive. He therefore conceived of the idea of having small, localized contact regions distributed across the back and front. The region between contact points was covered with a silver mirror which gave sufficient reflectivity. A cross-section of the cell is shown in Figure 5 from 1977 [17]. The base is undoped to get high lifetime, hopefully, and low free-carrier absorption for the below bandgap photons. Contact was made through 10 μm stripe openings in the passivating SiO_2 layer. The top grid was in the form of a silver screen with linewidths of 20 μm on 120 μm centers.

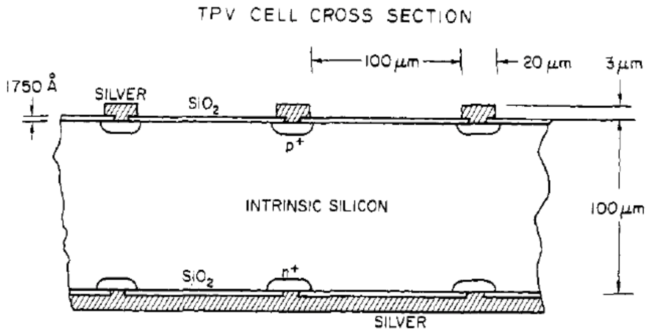

Figure 5: TPV cell cross-section showing localized contact points on front and back [17].

The TPV efficiency[1] for the first cells was measured at 12 percent, far below expectations of over 30 percent plus. Part of this poor performance was due to a low minority carrier lifetime of 10 μs. The starting float-zone wafer was specified to have a 1 ms lifetime, and that was the needed value according to cell modeling. This started an on-going effort to improve carrier lifetime in finished devices. It was found that the low lifetime came from process induced metal contamination, which occurred during the high-temperature oxidation and diffusion steps. The effort to eliminate this initiated what we called the "lifetime wars."

The first cells also suffered from high parasitic absorptance of 0.35. This was found to come partially from a 200 Å titanium layer between the silver and SideO_2 which was required to obtain good adhesion. The contact regions also had a high absorptance of 0.443. The rather high contact coverage fraction of 16 percent caused them to contribute 0.07 to the absorpance. Improved lifetime and back reflectance enhanced the TPV efficiency to 26 percent [18]. To further reduce parasitic absorptance it was decided in 1980 to reduce the contact coverage fraction by replacing the line contacts with points [19]. The change is shown in Figure 6.

This increased the TPV efficiency to 29 percent. It was found that the top metal grid introduced an anomalous parasitic absoption that was found to come from a combination diffraction of the infrared light to beyond the critical angle, as well as the difficult-to-eliminate multiple bounce from light exiting the cell. Therefore, to get sufficiently low absorption it was found necessary to place both contacts on the backside in the form of an interdigitated backside contact (IBC) cell. This structure had been explored by Schwartz and Lammert at Purdue, also for TPV applications but using germanium as the absorber. We married the local contact concept with the IBC cell. The device became known as the point-contact cell. Its structure is shown in Figure 7 [20, 21].

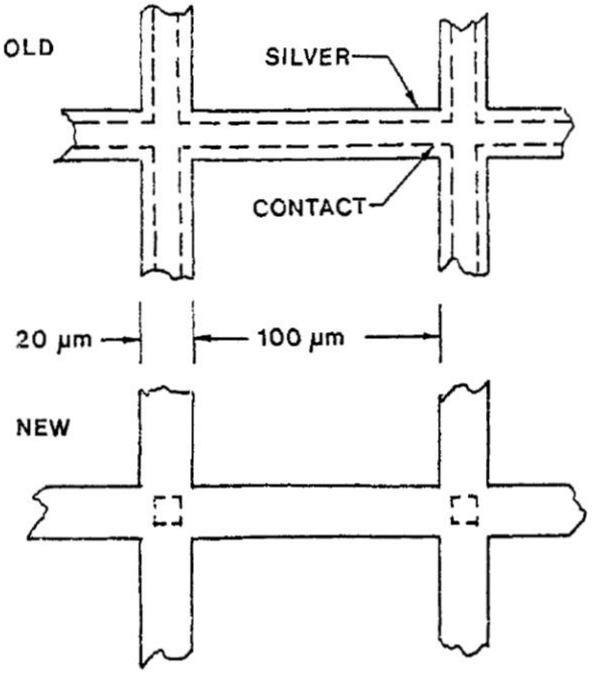

Figure 6: Change from line (old) to point contacts (new) for the cell shown in Figure 5 [19].

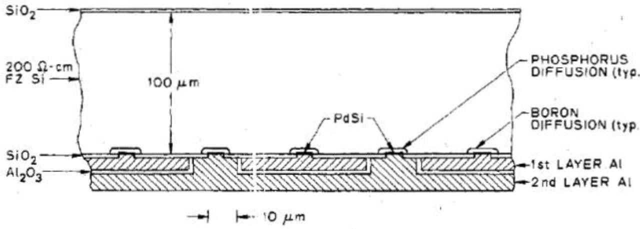

Figure 7: Cross-section of the point contact cell [21].

As the IBC point-contact cell was being developed it became clear that the TPV efficiency would never be sufficiently high to overcome the additional complexity of a TPV system. It was thus decided to eliminate the radiator and focus sunlight directly on the cell; i.e., use it as a concentrator cell. The first cells had an efficiency of 20 percent at a concentration of 88 suns. This was a record silicon concentrator cell at the time (1983) and would have resulted in a lower cost system compared to using the 29 percent TPV cell. The point-contact cell continued to improve, eventually reaching over 27 percent efficiency by 1986 [22].

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[1] The TPV efficiency is defined as the ratio of electrical output power divided by the total absorbed power.

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