Photovoltaic Advancements

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1. Introduction

The last deep dive I did on photovoltaic (PV) technology was about a year and a half ago with the following post:

Photovoltaic plus Storage: This was a two-part series, and part 1 was on new technologies for utility-scale PV, utility-scale storage, PV plus storage systems, and the evolution of their missions. Part 2 describes recent major U.S. PV and storage projects and some new twists on residential PV plus storage.

https://www.energycentral.com/c/cp/photovoltaic-plus-storage-%E2%80%93-part-1-technology

https://www.energycentral.com/c/cp/photovoltaic-plus-storage-%E2%80%93-part-2-projects

However PV technology is has been advancing rapidly since the above-linked post, and it's time for an update.

2. Photovoltaic Generation Systems

Most technologies advance over time, providing more functions or value for a given product purchase-price.

The most extreme example of this is Moore's Law. This is named after Gordon Moore, the co-founder of Fairchild Semiconductor and CEO and co-founder of Intel, who in 1965 forecast a doubling every year in the number of components per integrated circuit and projected this rate of growth would continue for at least another decade. In 1975, looking forward to the next decade, he revised the forecast to doubling every two years. While His prediction held since 1975 and has since become known as a "law." [1]

Moore's prediction has been used in the semiconductor industry to guide long-term planning and to set targets for research and development, thus functioning a bit like a self-fulfilling prophecy. Advancements in digital electronics, such as the reduction in quality-adjusted microprocessor prices, the increase in memory capacity (RAM and flash), the improvement of sensors, and even the number and size of pixels in digital cameras, are strongly linked to Moore's law. These step changes in digital electronics have been a driving force of technological and social change, productivity, and economic growth…

I will not delve into Moore's Law further, as that is not the subject at hand.

The subject of this section is photovoltaic generation systems (hereafter PV systems). As with products whose prices are driven by Moore's law, PV systems are a combination of different types of components with different price-reduction speeds. Overall PV systems have experienced rapid price declines in the last 10 years. This can be seen from the charts below from the source here.[2]

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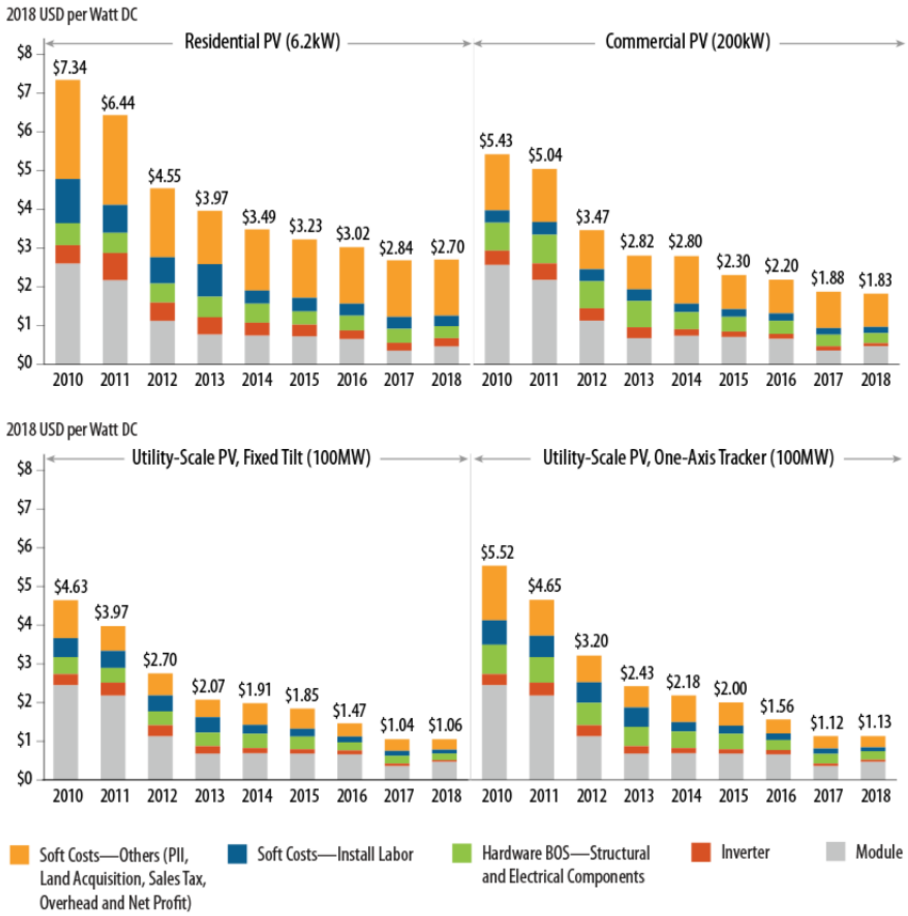
[1] Wikipedia Article on Moore's law, https://en.wikipedia.org/wiki/Moore%27s_law

[2] National Renewable Energy Laboratory, Energy Analysis, Solar Installed System Cost Analysis, https://www.nrel.gov/analysis/solar-installed-system-cost.html



Note that “PII” in the above soft costs is Permit, Inspection and Interconnection. BOS is Balance of System. Recently there have been significant advancements that have or will result in decreased costs for PV Systems. These are described in the subsections below.

2.1. Modules

At most of the above scales a PV system has very similar architectures. Most PV cells are fabricated from silicon wafers. The cells are then mounted in a frame that ranges in length and width from roughly 65” x 39” to 78” x 39”. When a frame, cells and other components are assembled it is commonly called a module (also a solar panel). Modules are normally connected in series into a string. The use of the series-string architecture minimizes the current, and thus the size of the wiring needed. All of the strings in a project (or major section of a very large project) is called an array.

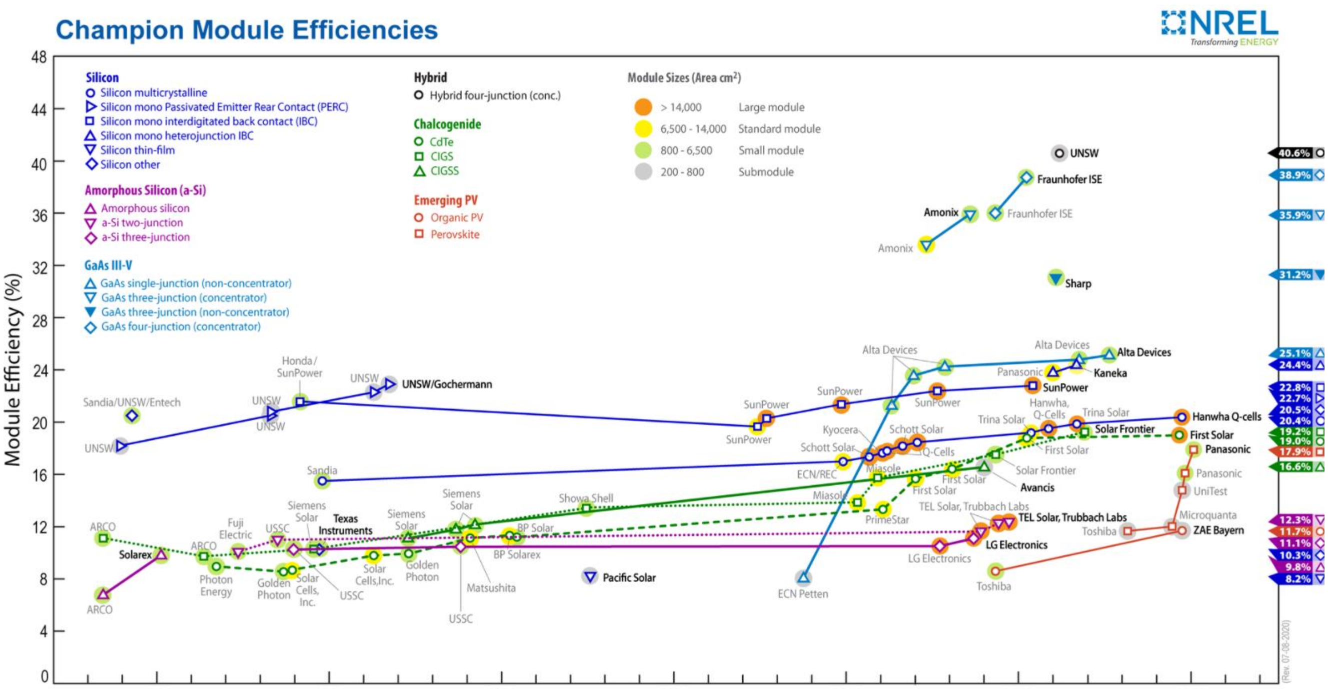
A year or two ago the standard output for a state-of-the-art solar module was around 450 watts. Now the industry standard module output is between 500 and 550 watts. Also, in a recent SNEC PV POWER EXPO in China, *JA Solar exhibited a module with an output of 810W, alongside Tongwei which had a 780W module on show… it is anticipated that it will be a while yet before these particular products hit the shelves.*[3]

[3] Liam Stoker, PVTECH, “Is solar ready for the high-power era?” , Sep 29, 2020, https://www.pv-tech.org/editors-blog/is-solar-ready-for-the-high-power-era

The following are major improvements that module manufacturers have made in the last couple of years.

Wafer Form Factor: The oldest silicon wafers that were used to fabricate PV cells had an M0 form factor, and a couple of years ago, these had evolved to an M2 form factor. Recent designs use M6 wafers, and near-future designs will probably use M12 form factors. The form factor controls the size, shape, number of cells per module and the light-absorbing area per cell. Recent / future cell designs have a surface closer to a true square which would give a larger area per module. Older designs have the wafer-edges clipped more since these are sliced from cylindrical silicon ingots. Ingot size has increased from 200 mm diameter (M0) to 223 mm diameter (M6).

Cell Technology: All of the technologies in large percentage of modules currently made are monocrystalline silicon (mono).[4] The primary two new cell technologies that are pushing PV module efficiencies to the mid-20% range are passivated emitter rear cell (PERC) and integrated-back contact (IBC). See the NREL Graph below.



Reported timeline of champion solar module energy conversion efficiencies since 1988 (National Renewable Energy Laboratory)

PERC Technology was covered in depth in the earlier “Photovoltaic plus Storage – Part 1, Technology”, which is linked in the Introduction. The following is a summary.

PERC cells require two additional production steps vs. a conventional cell: first, a rear passivation film is applied. Then, either lasers or chemicals are used to open up tiny pockets in the film through which the rear conducting layer can contact the silicon above the passivation layer.

[4] Allied Market Research, “Crystalline Silicon PV Market by Type”, https://www.alliedmarketresearch.com/crystalline-silicon-photovoltaic-pv-market

The above technique enables the efficiency of the solar cell to be improved in four ways:

- By minimizing surface recombination by charge-carrying electrons
- By more efficiently capturing longer wavelengths (red light) generated electrons near the back surface
- By Increasing Internal Reflectivity (mainly at the rear surface) to capture more light.
- By reflecting light with wavelengths that are too long to be converted to electrons back out the front, thus reducing cell-heating by this light

IBC cells collect more light. Most PV cells (including PERC) use both front and rear contacts. The front contacts reduce the surface area of the cell that can absorb light. IBC cells put both sets of contacts on the back, which eliminates shading from contacts on the front.

Bifacial Technology: Conventional PV modules are monofacial, meaning that their electrical power output is a function of the direct and diffuse radiation captured on the front side of the module only. By contrast, bifacial modules convert light captured on both the front and back sides of the modules into electrical power (see the picture below). Bifacial design improves PV system energy capture—dramatically in some cases. However it impacts mechanical components that support and position the module (next subsection), and also ground-surface treatments. *"Results and studies have shown that bifacial modules can produce additional power between 10-20% over monofacial panels. If conditions are optimized and single axis trackers adopted, the additional power can be as high as 30-40%."*[5]

2.2. Trackers

These are part of the "Hardware Balance of System (BOS)" in the price charts at the beginning of this section, albeit the only active hardware, and the only hardware that contributes to the output of an array. The trackers' job is to keep the modules pointed (more or less) directly at the sun throughout the day by continually adjusting the modules tilt. The most accurate trackers are two-axis trackers, but these or rarely used for most types of modules. Single-axis trackers are not nearly as accurate, but offer the most increased output for the price for most types of modules. Also, many projects still use "fixed-tilt" mounting. That is, they don't use trackers.

[5] Nick Lusson, PV Magazine, "Bifacial modules: The challenges and advantages", Aug 19, 2020, https://www.pv-magazine.com/2020/08/19/bifacial-modules-the-challenges-and-advantages/

2020 will be the first year when the tracker market's value will surpass the value of the fixed-tilt market. Between 2022 and 2025, global annual solar installations will average 135 gigawatts. Meanwhile, the global tracker market will see a 45 percent increase in installations from 2020-2025.[6]

Most current tracker technologies require each string (and thus a large majority of the associated arrays) to be on a reasonably flat surface. But this limits the topology of sites that can be considered for a project, and/or requires earth-moving operations to flatten the surface.

The latest tracker and their controls allow more flexible operation, to allow different strings/rows or even portions of strings to be positioned independently, thus facilitating arrays that are not on a completely flat surface, and reducing site-preparation costs.

Another consideration is whether the modules used are monofacial or bifacial. In the case of the latter, the tracker will need to position the modules for the most combined output from the front and back surface throughout the day.

In the past some sites were not acceptable for PV arrays because of high winds that were beyond the ability of the tracker or mounting system (for fixed-tilt) to correctly operate / withstand. Currently some trackers/support systems are specifically designed for high wind.

The results of all of the above advanced trackers are:

- The highest energy production from a given module design,
- Arrays can be integrated into sites that were previously off-limits, and
- A given project may require minimal site preparation

2.3. Inverters

First of all there are at least two distinct types of solar projects. The first type is used for distributed energy resources (DER) – typically owned by residential or small commercial utility customers. And then there are the utility-scale and large commercial & industrial projects. Both of these use inverters, and both of these are in the midst of a change in functionality and technology. However the specifics will probably be a bit different.

A week before I posted this paper, I posted another that delves into DER projects, and specifically into smart inverters. This is linked below.

https://energycentral.com/c/cp/connections-future

The above linked paper delves into the specifications and regulations for DER smart inverters, but I believe these specs. and regs. will be different for the utility-scale and large C&I projects. The good news is that the functional requirements for these two types of smart inverters are very similar. These are summarized below.

- Anti-islanding protection – use of low/high frequency and voltage ride-through to prevent unintentional islanding
- Low and high voltage ride-through – requiring inverters to stay connected and adapt to low/high voltage fluctuations

[6] Ravi Manghani and Chloe Holden, Greentech Media (gtm), "How Tracker Technology Is Expanding the Footprint for Solar", Sep 28, 2020, https://www.greentechmedia.com/articles/read/how-tracker-technology-is-expandingthefootprint-for-solar?utm_medium=email&utm_source=Daily&utm_campaign=GTMDaily

- Low and high frequency ride-through - requiring inverters to stay connected and adapt to low/high frequency fluctuations
- Dynamic Volt-VAR Operation – requiring inverters consume and/or produce reactive power to help optimize grid voltage (note that this frequently reduces real power, so the project developer will need to be paid a premium for this service).
- Ramp rates – ramp rate of increasing/decreasing their output power to smooth the transitions from one output level to another
- Fixed power factor – setting of power factor of inverters (inject or absorb VARs)
- Soft start reconnection – ability to use random timing when inverters reconnect after disconnection to reduce effect on the grid