Basics and growth of photovoltaic efficiencies: Extrapolating the potential of various solar cell technologies

by.

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1 - Solar Cell - Preface:

Solar cells absorb energy from sunlight and turn it directly into electricity. Due to the vast amount of energy the sun emits via photons daily, there is massive potential for solar cells to take over as the main source of energy. Due to this potential, many institutions, governments, and private investors are investing heavily in the research of photovoltaic technology leading to a rising efficiency percentage for photo-conversion, or the conversion of light into electricity. A group of solar cells can be combined to create a solar panel like the Silicon-based panel shown below in Figure 1.

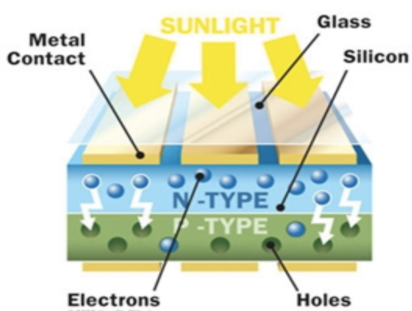

Figure 1. Composition of a Silicon solar panel with protective glass layer over the semi-conductive layers: n-type and p-type as sunlight rays hit the panel (Source: Turner, 2017)

Silicon photovoltaic cells, like the one illustrated above, work by absorbing the sun's rays that penetrate through a glass film onto the semi-conductive n-type and p-type layers. Adding an impure atom to the semiconductors increases the conductivity; this process is known as doping (Acton, 2013). For the n-type semiconductor, doping occurs with atoms holding more electrons than Silicon bringing in free-moving electrons into the semiconductor. For the p-type semiconductor, doping occurs with atoms holding fewer electrons than Silicon, resulting in mobile positive charges known as holes. As a n-type semiconductor and a p-type semiconductor are joined, they form a p-n junction, where electrons and holes sometimes travel across the junction leaving behind immobile positive and negative charges respectively. After it travels across the junction, the drifting electron diffuses into a hole, and the drifting hole diffuses into an electron after it goes across the junction (Dittrich, 2015). The motionless positive and negative charges that get left behind create an electric field on the boundary of the p-n junction. As sunlight hits the p-n junction, an electron gets detached in the electric field. This creates an electron and a hole that can both move dynamically. These dynamic-moving charges move back towards their original semi-conductor (electrons move towards n-type and holes move towards p-type), which creates a charge gradient known as the voltage (Dittrich, 2015). This motion of the charges results in the external energy that can be used to power electric appliances. Photovoltaic cells rely on this charge gradient for solar energy production, so research in photoconversion efficiency is essential for maximizing the energy harvested from the sun.

2 - Why Are Solar Cells Important?

The rise of solar cells mitigates the dangers of fossil fuel emission by minimizing the reliance on coal and oil as energy sources. Along the equator, the sun irradiates the surface from directly overhead at the equinoxes. On the other hand, near the equator, trade winds flowing in opposite directions meet and dissipate, leading to calm winds that limit the usefulness of wind turbines in this part of the world. Therefore, construction of solar panels near the equator could serve as a solution for the increasing demand in energy, especially when combined with turbines at other latitudes with higher wind speeds. As fossil fuel sources decline, many countries shift towards Silicon-based solar electricity as their primary energy resource.

3 - The Beginning of the Solar Revolution and the World's Reliance on Solar Energy,

Photovoltaic cells arose in the late 1950s as a research tool. Photovoltaic cells were later improved in the 1960s and 1970s to actually power small appliances for commercial uses and satellites orbiting the Earth (Bellis, 2017). Today, solar cells have expanded from single crystalline photovoltaic cells to contain a broader range of compounds and minerals such as Gallium Arsenide and Perovskite. Throughout the world, the reliance on photovoltaic cells is increasing and currently, China is leading the research with the most capacity for solar cells (Table 1). However, Germany has the highest energy allowance per capita because they became one of the first countries to execute solar financial incentives, like the feed-in tariff system that gives photovoltaic developers long-term contracts (around 10-25 years) with clients priced per kilowatt-hour (Couture et al., 2010).

TABLE 1: TOP 10 COUNTRIES FOR INSTALLATIONS AND TOTAL INSTALLED CAPACITY IN 2015

TOP 10 COUNTRIES IN 2015 FOR ANNUAL INSTALLED CAPACITY			TOP 10 COUNTRIES IN 2015 FOR CUMULATIVE INSTALLED CAPACITY		
1	China	15,2 GW	1	China	43,5 GW
2	Japan	11 GW	2	Germany	39,7 GW
3	USA	7,3 GW	3	Japan	34,4 GW
4	UK	3,5 GW	4	USA	25,6 GW
5	India	2 GW	5	Italy	18,9 GW
6	Germany	1,5 GW	6	UK	8,8 GW
7	Korea	1 GW	7	France	6,6 GW
8	Australia	0,9 GW	8	Spain	5,4 GW
9	France	0,9 GW	9	Australia	5,1 GW
10	Canada	0,6 GW	10	India	5 GW

©Snapshot of Global PV Markets – IEA PVPS

Table 1. Amount of solar capacity installed by country based on ten highest capacities (Source: Masson et al., 2016)

In the Middle East, Saudi Arabia is investing in solar cell research programs, like growing the first hybrid, Perovskite, monocrystalline films by collapsing bubbles that trigger single crystal growth in the film; energy gets lost in the boundaries between these crystals (Peng et al., 2016). Therefore, this monocrystalline film process prevents bubbles from growing that result in energy loss making polycrystalline films better. Figure 3 is an estimated projection of how much photovoltaic energy will be produced by different countries or regions in the future. Naturally, renewable energy sources like photovoltaics are expected to become more impactful and common, especially because various regions are investing in generating electricity through photovoltaic sources.

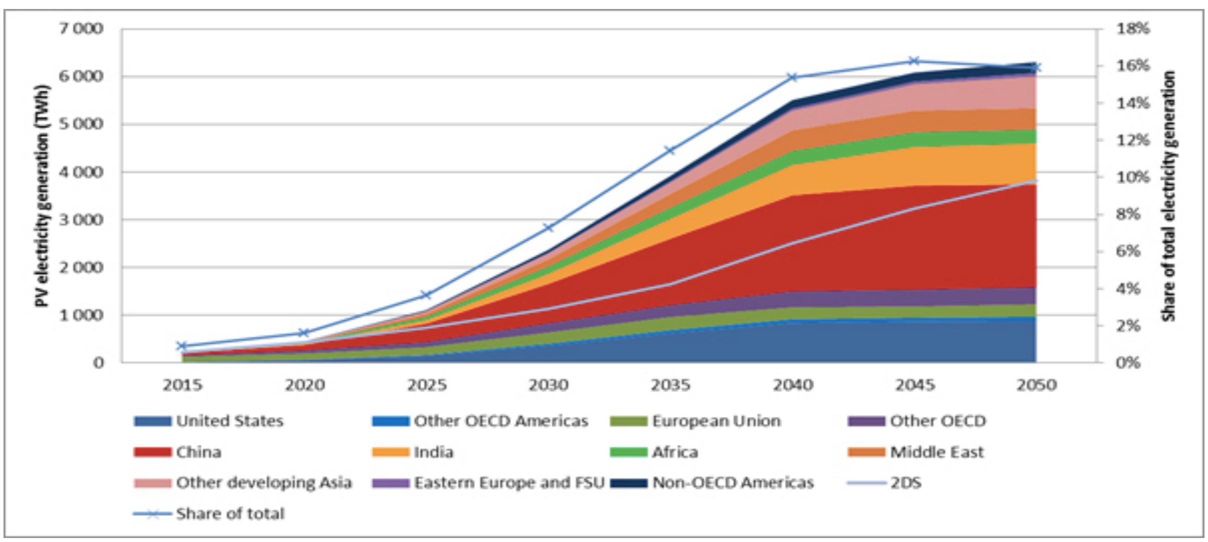

Figure 3. Future projection of photovoltaic electricity generation (in terawatt hours) for various regions of the world. (Source: IEA, 2014)

Based on the solar capacity installed (Table 1) and the rise in photovoltaic electricity generated by different countries (Figure 3), solar energy seems very promising. However, there are some environmental impacts.

4.1 - Drawbacks of Solar Energy – The Lake Effect:

One drawback of solar energy is the "lake effect" whereby birds fly down towards solar panels because they see what they think the familiar is the familiarheat color as the panels reflect the sky's blue light (Kagan et al., 2014). The annual number of bird deaths in the US alone is between 37,800 to 138,600 due to both collision-related deaths, such as the "lake effect", and solar-flux related deaths, which involves heat from the panel's reflected light harming the birds. But this latter type has only been seen at solar farms with power-tower or concentrating solar power (CSP) technologies (Walston et al., 2016). This mortality count is smaller compared to the 365 million to 988 million birds that are killed by windows and buildings in the US annually (Walston et al., 2016). Consequently, only a small percentage of national bird deaths annually are from solar farms suggesting that this is only a minor drawback.

4.2 - Drawbacks of Solar Energy - Habitat Conversion:

Habitat destruction is a major dilemma associated with building more solar farms. Even in the desert, there are many wild native species facing habitat loss through massive solar panel developmental projects. For example, burrows carved by desert tortoises underground provide a habitat for many other animal species (Lovich & Ennen, 2011). These burrows might become obstructed if massive solar panel farms are developed. One solution to this problem is to locate solar panels at locations where they are compatible with other uses. For example, UCSC's Arboretum houses solar panels along the roofs of greenhouses lined with LR305 (Lumogen Red 305) embedded in acrylic plastic, which increase the luminescent absorption of the solar panels to that of greater wavelengths of light (Loik et al., in review).

Figure 4. Photographs of solar greenhouse greenhouses with Luminogen Red 305 at the Arboretum at University of California Santa Cruz (Source: Glenn Alers, in review)

Even though the yield of the tomatoes were not remarkably different from the yield of the tomatoes grown under normal light conditions (Loik et al., in review), the greenhouses still provide an integrated photovoltaic electric generator that could simultaneously produce energy and crops similar to a system that incorporates solar photovoltaic with batteries in households.

4.3 - Drawbacks – Battery and Energy Storage:

Storing solar energy electricity involves making a battery that can pose many environmental risks. Currently, a household system that consists of photovoltaic panels powering a battery merged with a heat and power plant results in 35 – 100% less environmental impacts than that of a system where electricity is received from the grid, or transported through a power line, and where heat is generated from a gas boiler (Balcombe et al., 2015). However, this system requires more maintenance because batteries decay 42 times faster as a result of Antimony (Sb) being present in the battery (Balcombe et al., 2015). Therefore, creating a sustainable battery is difficult because an essential element used in the construction of the battery decays very rapidly. Also, mining and refining rare elements like Cerium and Neodymium results in substantial water and energy usage, and the final material results in only about 30 – 70% of the ore (Haque et al., 2014). Since this energy-intensive mining and refining process yields only about half of the ore, then more efficient means of producing battery storage is required for batteries to become more sustainable. Recent research shows a new battery made from aluminum, graphite, and urea, which is found in mammal urine (Angell et al., 2016). This battery can reduce the cost of energy storage because of the relatively high abundance of these materials on Earth. The availability of the materials makes these batteries about 100 times cheaper than current technologies. These batteries do not require rare earth elements, so the process results in less water and energy usage. Incorporating these batteries would serve as a sustainable solution to having external storage of electricity, but the amount of energy stored by the battery is dependent on the efficiency rate of the photovoltaic cell.

5 - Determining Efficiency Percentages:

Solar energy efficiency percentages are based on the solar radiation intercepted in a particular area and the type of photovoltaic cell. While the type of photovoltaic cell controls the conductivity and the range of wavelengths of energy that can be absorbed by the cell, the solar radiation concentration is based on how much sunlight irradiates an area. For example, the sun's rays hit the equator directly overhead while there is less concentration of sunlight hitting the Earth north and south of the equator (Figure 5). Solar radiation concentration levels are also a factor of weather patterns because the percentage of the sky blocked by clouds directly determines how much solar radiation can be converted into solar power.

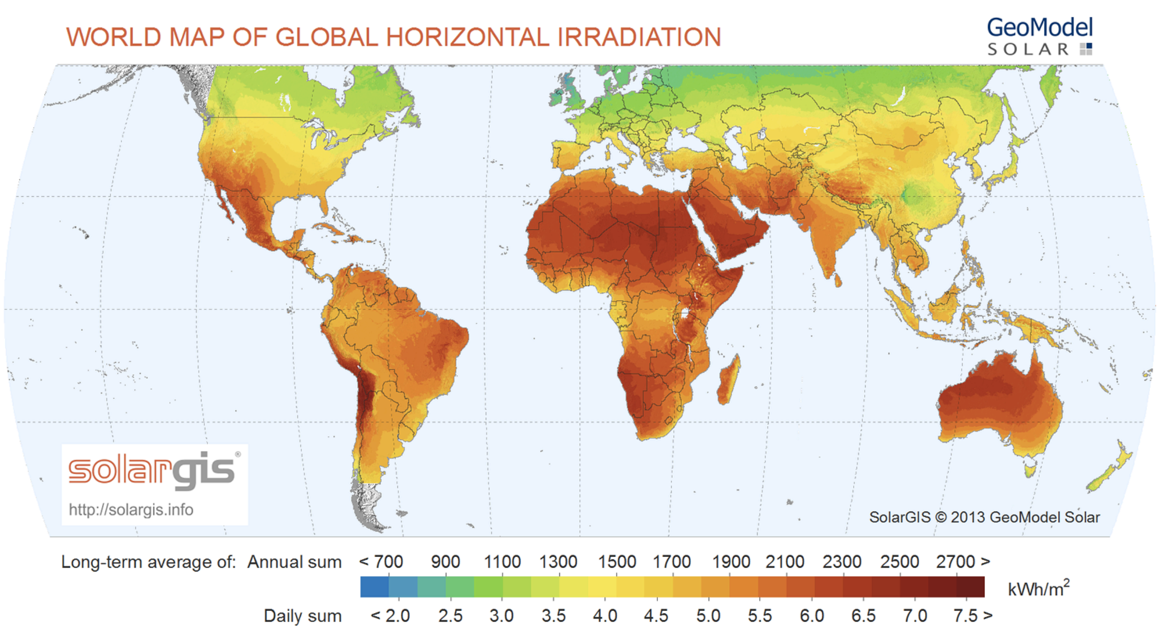

Figure 5. Global map of solar irradiation levels based on latitude and longitude. (Source: SolarGIS, 2013)

For example, if there is 50% cloud cover, then there will be 50% solar radiation (Sharma et al., 2010). Simultaneously, solar radiation concentration levels are also determined by the time of the year (Figure 6).

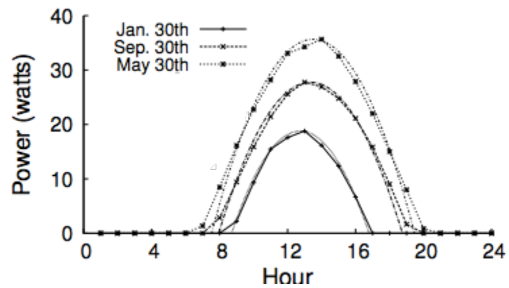

Figure 6. Solar power generated throughout 24-hour time period using the same photovoltaic model and weather station in Massachusetts throughout different months where May 30th represents a date close to the summer solstice, Jan 30th represents a date close to the winter solstice, and Sept 30th represents a date between the solstices. (Source: Sharma et al., 2010)

The highest amount of solar power is generated during the months of May, June, and July and the least amount is generated during the months of November, December, and January for regions in the northern hemisphere. The opposite case holds true for regions in the southern hemisphere. Combining the amount of solar power generated in the northern hemisphere during the summer solstice with solar add-ons, such as thin-film technologies and bi-facial panels, could maximize net energy yields.

6 - Developing Solar Add-ons:

New solar add-ons are being developed that contribute to the energy yield of the cell and the net energy yielded per surface area. Recently, Dibyashree Koushik and her team at Einhoven

University of Technology have constructed ultra-thin aluminum-oxide films that significantly boost the yield of perovskite solar cells by 3%. These films work by providing a barrier that protects the photovoltaic cell against harmful, humid weather conditions and rust (Koushik et al., 2016). This reduces external problems that could damage the conductivity of the cell. New research from Singapore's Agency for Science Technology (Alagappan and Png, 2016) shows that it is possible to trap light using the crystal structure of merged lattices. Combining lattices of closely identical periods induces light entrapment by looping the light beam once it has entered the lattice (Alagappan and Png, 2016). This leads to a higher energy yield because less light escapes from the cell. Another new solar application is a bifacial solar cell, illustrated in Figure 7 below, which has the ability to absorb sunlight normally as well as being able to absorb light reflected from a surface set parallel to the ground toward the back of the panel (Hoare et al., 2015). New research (Yusufoglu et al., 2014) shows that at optimal angles, placing the bifacial panel’s lower edge 2 meters above the ground rather than close to the ground at optimum tilt angles increases annual energy yield by 30%. This 2-meter displacement reduces the shadow cast on the light-reflecting surface because the panels can’t obstruct as much sunlight if they are further off the ground. This results in more direct sunlight irradiating the light-reflecting surface.

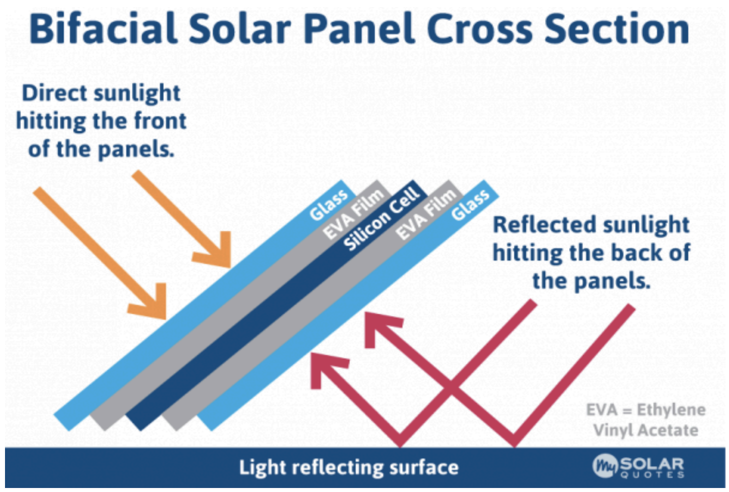

Figure 7. Composition of a bifacial solar panel angled from a light reflecting surface set on the ground. (Source: Kristy Hoare et al., 2015)

7 - Economic Cost and Theoretical Limits to Performance:

The cost per Watt ratio for various photovoltaic modules is rapidly decreasing, as shown in Figure 8, because cells are getting closer to the ideal theoretical efficiency of X% (Figure 9). However, producing a solar cell that has an efficiency percentage close to the maximum theoretical efficiency possible requires a lot of preparation, material, and energy, which incur a high cost. The flexible Copper Indium Gallium Selenide (CIGS) modules are better in the long term than their rigid counterparts because they could eventually lead to lower production cost as they use roll-to-roll processing, where electronic devices are implemented onto a flexible substrate as the machine unrolls the substrate (Chirila et al., 2011). Since, Perovskite research has only recently emerged, the module price is not shown on this graph.

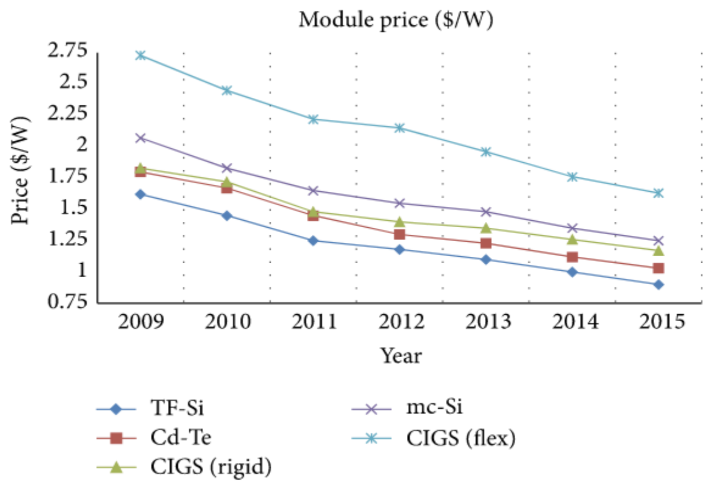

Figure 8. Cost (in dollars) per watt from 2009-2015 of various cell module technologies, where TF-Si represents thin-film Silicon modules, mc-Si represents multi-crystalline Silicon modules, Cd-Te is Cadmium Telluride, CIGS (flex) represents flexible Copper Indium Gallium Sulfate modules, while the rigid CIGS version represents an un-bendable form (Source: Cengiz et al., 2015)

Table 2 shows the theoretical maximum efficiency of various solar cell types. Perovskite and Gallium Arsenide solar cells are amongst the highest efficient, so more research is expected to develop for those photovoltaic modules in the future.

Photovoltaic Cell Type	Theoretical Efficiency	Source
Amorphous Silicon (Single)	22%	(Crandall, 1995)
Thin-Film Cadmium Telluride	28 - 30%	(Mohamed, 2013)
Single Crystal Silicon (non-concentrated)	29%	(Blakers, 2013)
Copper Indium Gallium Selenide	30%	(Niki, 2008)
Perovskite	31%	(Sha, 2015)
Gallium Arsenide (concentrated)	33%	(Sha, 2015)

Table 2. Table of various photovoltaic technologies and their maximum theoretical efficiencies ordered from least to most efficient type

8 - Future Projections of Cost and Efficiency:

In general, the costs of most photovoltaic modules are expected to drop as photo-conversion efficiency percentages increase within the next 20 years [Cengiz et al., 2017]. Figure 9 is a graphic extrapolation of rising efficiency percentages based on the ideal theoretical percentage efficiencies and the estimated extent of research conducted into each technology. The initial data for this graph was sourced from the NREL (Best-Research Cell Efficiency). The ideal theoretical percentage efficiencies were taken from various sources (including Chen, 2015). These theoretical percentages are fixed because they represent a maximum efficiency that is based on the optimum band gap of the photovoltaic cell (See beginning of Section 9.3) and the total solar irradiation causing electron and hole pairing (Shockey and Queisser, 1961). Some solar cells are not included due to inadequate research or because of limited research. According to Figure 9, the photo-conversion efficiency of Perovskite is expected to grow faster than any other photovoltaic type because current research revolves largely on Perovskite.

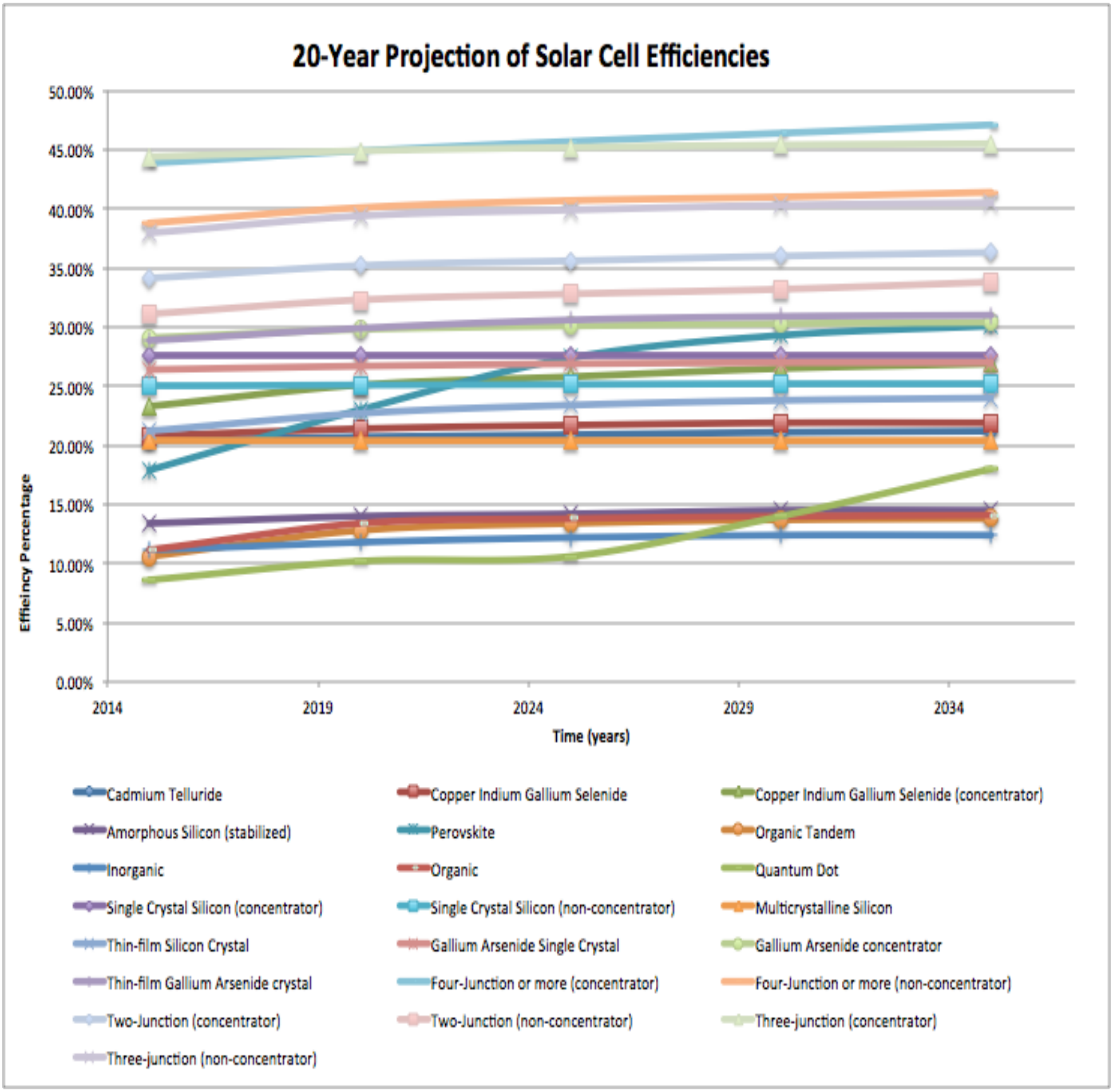

Figure 9. Future projection over a 20-year period illustrating the rising photo-conversion efficiency of various photovoltaic technologies

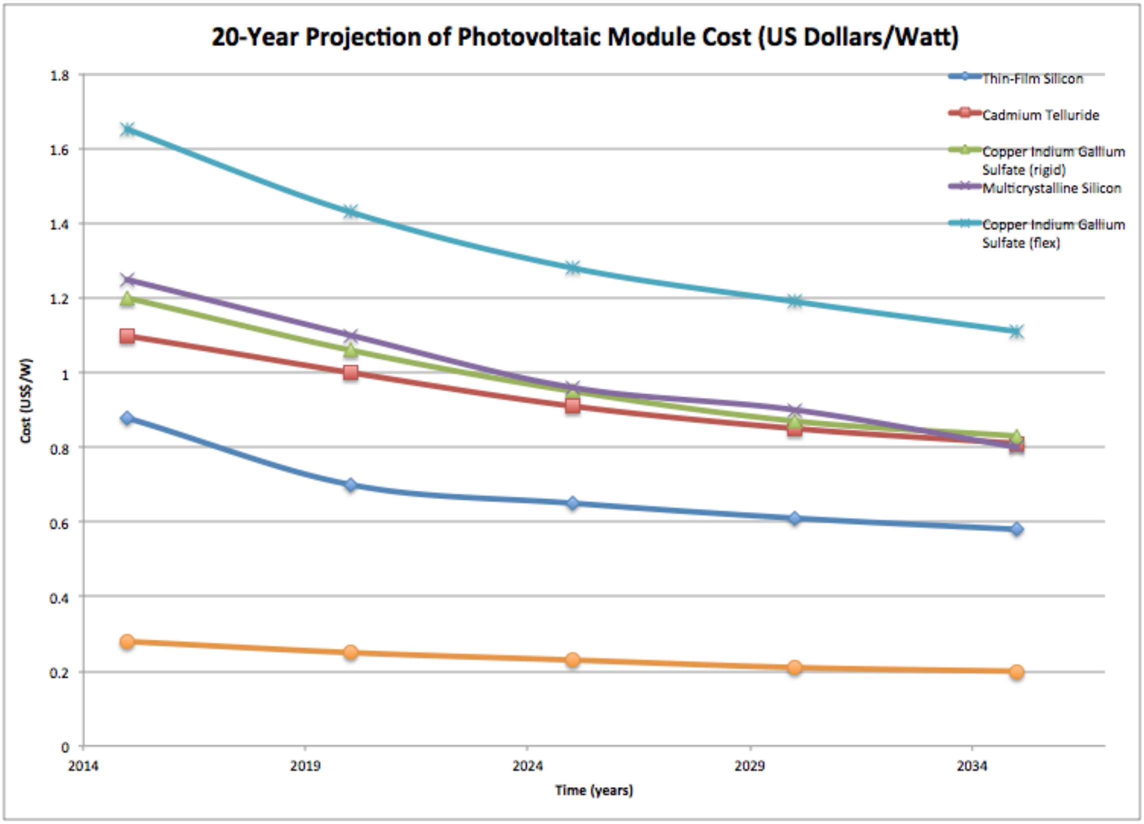

Figure 10. Future projection for the price of photovoltaic modules over a 20 year period estimated based on the abundance of materials and the energy cost of each technology.

As shown in Figure 10, the price of Perovskite is not expected to decrease much because it is already very cheap (about $0.27 US per Watt) (Cai et al., 2016).

9.1 - Photovoltaic Cells - Silicon

Pure crystalline Silicon photovoltaic cells are not applicable models of solar cells because pure Silicon has to go through a lot of processing before it is ready to be utilized as a solar cell (Bharam, 2012). As Figure 11 shows, the energy band gap between the conduction and the valence band in Silicon photovoltaics decreases as temperature rises, allowing photons that were lower in electrovolts to be absorbed. This results in a higher energy yield, which explains why pure Silicon needs to be heated before it can become an efficient solar cell.

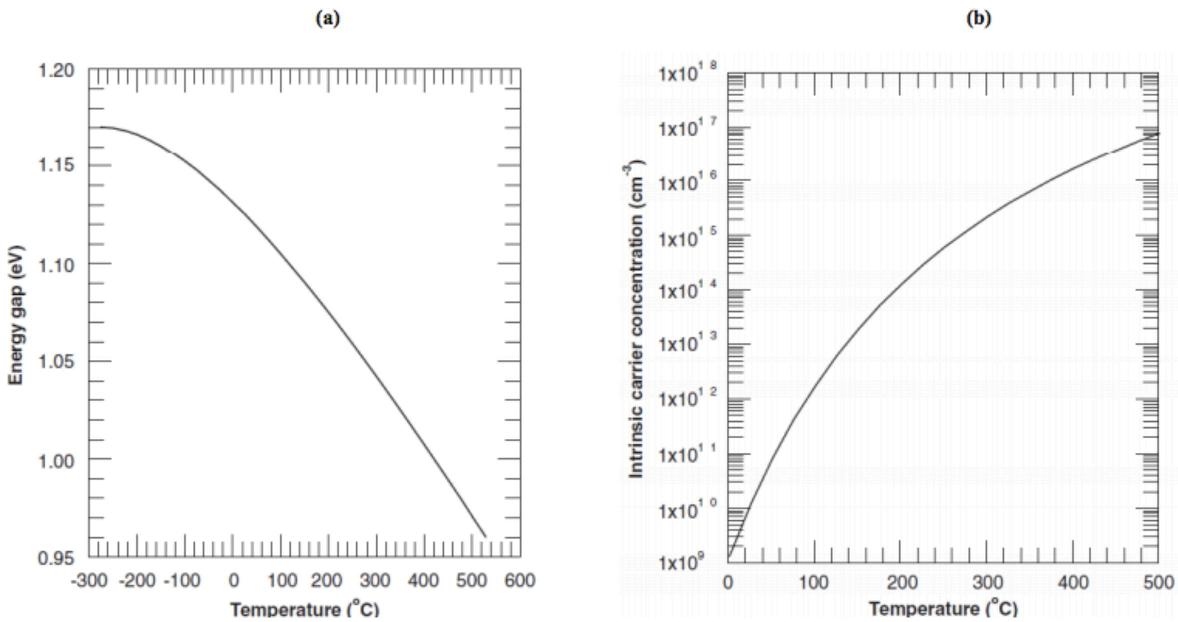

Figure 11. As temperature rises, the energy gap of the Silicon photovoltaic cell decreases which results in more carrier charges. (Source: Bharam, 2012)

As a semiconductor, silicon is also known for its fast charge carrier mobility, resulting in high charge carrier gradients (Bharam, 2012) that make the efficiency as high as 29% (Blakers et al., 2013). Another type of Silicon cell is amorphous Silicon, which yields about 7% less energy than single crystalline Silicon theoretically (Table 2) due to having a higher band gap (Bharam, 2012). One major advantage of amorphous Silicon is that it is a non-toxic material so it has minimal impact on the environment (Werner et al., 2011); Amorphous Silicon also costs significantly less due to requiring a lower temperature than single crystalline silicon (Crandall and Luft, 1995).

9.2 - Photovoltaic Cells – Copper Indium Gallium Selenide

Copper Indium Gallium Selenide as a solar cell module (CIGS) has a more complicated manufacturing process than crystalline Silicon cells (Tang, 2017). This is mainly due to the complexity of the layering of CIGS solar cells as shown in Figure 12.

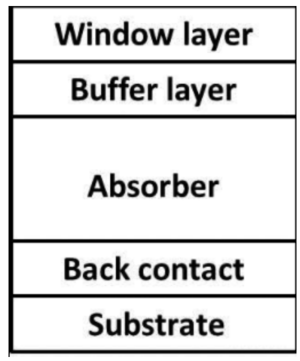

Figure 12. Composition of CIGS solar cell where the absorber layer represents the p-semiconductor, the buffer layer represents the n-semiconductor, the window layer represents the glass film, and the back contact and substrate represent the back of the cell. (Source: Tang, 2017)

The buffer layer and the absorber layer together represent the p-n junction where doping occurs, thereby creating the photoelectric current flow. Buffer layers strengthen the open circuit voltage, or the electrical potential, between the window layer and the absorption layer, and also prevent the degradation of the neighboring layers as a result of stress (Roedern, Von, and Bauer, 1999). One common form of a buffer layer application in CIGS solar cells is CdS, which has a band gap of 2.4 eV (Tang, 2017), or a 2.4-electrovolt difference in energy between the top of the valence band and the base of the conduction band that determines the cell's conductivity.

9.3 - Photovoltaic Cells - Cadmium Telluride

Cadmium Telluride (CdTe) serves as a leading photovoltaic cell because it has an optimum band gap of 1.5 eV, which suggests efficient photo-conversion because this band gap length is able to absorb photons above 1.5 eV, while simultaneously minimizing excess energy loss as heat to "N" if a photon is (1.5 + "N") eV before it crosses the band gap (Mathew et al., 2004). One of the major disadvantages of Cadmium Telluride is the toxic nature of the metal, Cadmium, as it contains 73 miligrams per Watt of toxic substances (Werner et al., 2011); the European Union has even banned Cadmium unless it is used in creating a photovoltaic module as of May 27th, 2011 (Werner et al., 2011). However, between the photovoltaic monocrystalline Silicon, multicrystalline Silicon, amorphous Silicon, CIGS roof-top, and Cadmium Telluride modules, Cadmium Telluride's module presented the shortest energy payback time of 0.68 years to reproduce the amount of energy that a CdTe photovoltaic module (excluding roof-top installation) costs to build (Wild-Scholten, 2013) while the other modules' energy payback times are at least a year long. Of the listed modules, Cadmium Telluride also has the lowest carbon footprint of 15.8 grams of Carbon Dioxide per kilowatt-hours followed by the CIGS rooftop module having a carbon footprint of 21.4 grams of Carbon Dioxide per kilowatt-hours (Wild-Scholten, 2013). Therefore, other than the toxic metal nature, Cadmium Telluride seems like a sustainable solar cell as it has a smaller carbon footprint and produces more energy within a shorter period of time, due to the optimal bandgap length, than other photovoltaic modules.

9.4 - Photovoltaic Cells - Perovskite:

Perovskite cells have only recently emerged, but they serve as a significantly cheaper and slightly more efficient alternative to Silicon cells. The underlying efficiency of Perovskite cells lies mainly in its crystal structure backbone, ABX_3, because the structure determines how light behaves within the cell.

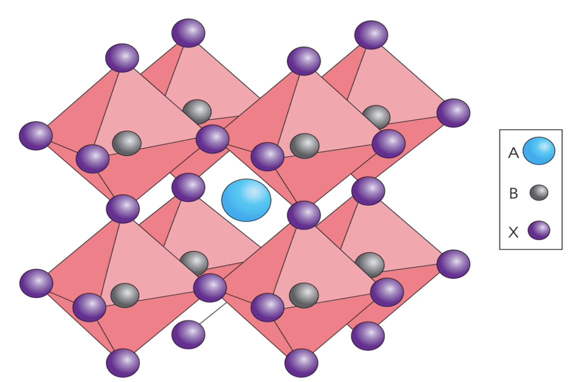

Figure 13. Crystal structure of Perovskite (ABX_3) where X portrays the faces, A depicts the body center, and B represents the edges (Source: Martin Green et al., 2014).

The structure of Perovskite (Figure 13) commonly appears in the form, $CaTiO_3$, and it also appears as a methyl-ammonium halide, where the halide is one of the members of the halogen group (Wang et al., 2016). Some methyl-ammonium halides use Iodine. Unfortunately, Iodine breaks down the methyl ammonium halide compound into Lead Iodide. This releases Iodide vapor that causes the whole solar cell to breakdown because there is high vapor pressure pushing along the walls of the semi-conductive layers (Wang et al., 2016). This Iodide vapor does not constitute a big problem because other halogen elements (such as Bromine) could be used instead. There is also a moisture problem in Perovskite cells mainly because water compounds are produced over time as the Perovskite degrades, making it increasingly difficult to absorb visible light (Hwang et al., 2015). This makes Perovskite photovoltaic cells more vulnerable to outdoor settings, thus the use of Silicon solar cells as the main photovoltaic module for residential purposes due to the low cost and durability. On the other hand, Perovskite cells are currently used in labs under safe and more stable, benign physical conditions (Hwang et al., 2015). Despite these drawbacks, Perovskite designs are still in the early stages, since molecular structures of Perovskite with bigger unit cells, or the smallest structural forms that repeat in a crystal lattice structure, are still being developed using variations of elements such as Bromine and Iodine (Green et al., 2014). The theoretical maximum efficiency for a photovoltaic cell with a purely Perovskite-based structure is around 31% (Sha et al., 2015), making it ideal for commercial use since it also utilizes low energy and cost processes to assemble (Cai et al., 2016).

9.5 - Photovoltaic Cells – Gallium Arsenide

While Silicon remains the cheapest main component to creating solar cells, Gallium Arsenide (GaAs) cells, and process photoelectric flows faster, which creates a more efficient energy conversion (Kang et al., 2017). The expensive cost of GaAs cells forces the solar industry to utilize them in special situations, such as using them for satellites and space rovers (Crisp, Pathare, and Ewell, 2004), where they are useful for more efficient-rich absorption processes. This is mainly due to light emissions being less as Mars receives less sunlight than Earth due to being farther from the sun.

10 - Conclusions:

Currently, there is a massive amount of research being invested into add-on technologies used to further enhance solar cell efficiency, such as ultra-thin film layers, to employ a yield boost or a protective layer on photovoltaic cells. As these enhanced efficiencies approach closer to the theoretical efficiency, the efficiency slowly stops increasing because the theoretical efficiency is a fixed percentage based on the optimum band gap length and the amount of concentrated irradiation. Gallium Arsenide solar cells are expected to be present in highly specialized applications due to their high cost. Regardless of their toxic nature, Cadmium Telluride photovoltaic cells create a small carbon footprint and use up little water. Therefore, research on CdTe cells is not expected to decrease in the next 20 years, although it still won't be as vibrant as the research into Perovskite applications. Silicon modules remain the most widely used photovoltaic cell because they require less maintenance than Perovskite, and silicon solar panels have existed commercially and residentially in the infrastructure before Perovskite emerged as a solar cell type. Nevertheless, the low cost and high efficiency of the Perovskite cells could designate it as the ideal photovoltaic cell within the near future.

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