The Effect of Structural Modifications on the Efficiency of Thin-Film Tandem Solar Cells

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Abstract

The effect of thin film tandem solar cells on the efficiency of photovoltaic solar technology was analyzed to discover whether they hold higher efficiencies of electrical energy production compared to silicon solar cells. Peer-reviewed articles that reported efficiencies and other variables on different types of cells were collected to conduct a statistical analysis test. Results showed that thin film tandem cells are not more efficient than silicon cells. These findings signify that silicon cells may be more beneficial than other types of cells when considering the amount of electricity generated, cost of electricity, and environmental impact.

Keywords: solar cells, photovoltaics, tandem cell, power conversion efficiency

Energy Generation

Electricity generation is a common concern for the general public as wide-used sources of fossil fuels become depleted. These sources include oil, coal, and petroleum and they have generated sufficient electricity for public use since the Second Industrial Revolution in the late 1880s. Yet because there is only so much oil, coal, and petroleum available in the Earth, as these sources of energy are not sustainable (Hoekstra et al., 2014). Globally, coal makes up 416.3 gigawatts (GW), or 31.4% of electricity capacity produced out of the 1326.7 GW of generating capacity since 2000 (Davis et al., 2010). Yet the dependence on fossil fuels used to create electricity is not decreasing despite their unsustainability. This poses an issue to the future of energy production.

Another issue with fossil fuels is their negative impact on society. For instance, coal working has caused the death of over 200,000 coal workers since 1995 due to pneumoconiosis, a disease in the lungs that destroys the lung cells (Epstein et al., 2011). Furthermore, health and climate in major cities of the United States are negatively affected by carbon emissions from fossil fuels, since the United States makes up 20.7% of carbon dioxide released worldwide (Streets, 2015). The demand for energy also poses an issue because industrial cities lack access to sufficient renewable energy, hence the use of fossil fuels for energy though the health of animals and humans is inhibited as a result (Chu et al., 2012). Conventional sources of energy like fossil fuels are not viable for the well-being of animals and people on Earth and need to be replaced.

Renewable Energy

With the side effects of fossil fuel burning, environmentalists and researchers alike are turning to renewable energy, or energy that is replenished through natural resources. Renewable energy is more sustainable than fossil fuels and has been shown to not emit greenhouse gases, helping the environment (Twidell et al., 2015). In fact, different state governments are passing legislation for renewable energy. For example, California has passed a law to run on 100% renewable energy by the year 2045 (Luke et al., 2017). This is just one example of how institutions are implementing programs to slowly transition into a system that is beneficial to nature.

Different types of renewable energy used today include hydropower, wind power, biomass fuel, and geothermal energy. Yet, solar power has the potential to be one of the best-utilized energy sources out of all energy sources with high capacities due to its dependence on the Sun, which is more reliable than other components of weather (Park et al., 2009). Despite previous studies showing semiconductors used in solar cells can release harmful elements to the environment, solar power is still safer than other methods of electricity generation, for instance, nuclear energy because of the risks associated with radiation containment (Mekhilef et al., 2011).

Photovoltaics

Photovoltaics is described as the process of converting solar irradiation to electrical energy using solar cell technology. Solar energy became popular in recent years due to the abundant and sustainable energy the sun emits. The independence of solar energy from material energy sources allows it to be a clean and renewable energy source. The United States energy market is made of 7-8% solar energy but is projected to grow to 40% by 2050 due to progress in researching and improving cells (Kabir et al., 2017). Because solar energy is predicted to experience a large increase in usage, methods are being developed to research the best type of solar cells.

One limitation to solar energy is that panels can be expensive initially, on average costing $35,967 (Ali & Hossain, 2017; Dastrup et al., 2011). The high price for purchase and installation of photovoltaic technology often detracts customers. Therefore, methods should be implemented to reduce the cost of solar energy to make them available to consumers. These methods could include decreasing the cost of the manufacturing process, reducing the cost of materials, and increasing the efficiency of the cells.

Factors Affecting Efficiency of Solar Cells

The solar cell functions by using photons emitted from the sun to create an electron-hole pair, or an exciton. This is created when a photon, a quantum particle of light, strikes the material of the cell, separating an electron from the atom and leaving a positive charge. The electron from the n-material travels to the p material of the cell, through what is known as the p-n junction. When the electron and the hole separate, the electrons travel through a wire to the hole to neutralize the material, generating a current which is then converted into electrical energy (Zweibel, 1990).

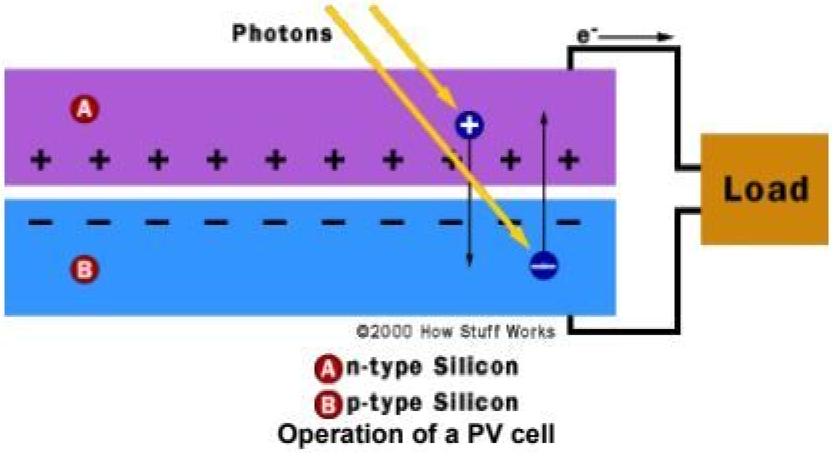

Figure 1. Diagram of electron-hole pair creating an electrical current (Zweibel et al., 1990). The electron is forced to the n-type silicon of the cell, creating a positive charge in the p-type silicon. The electron travels through the circuit to reach equilibrium in the p-type silicon, generating a current.

One aspect of a cell that affects efficiency is the Shockley Queisser Limit, known as the bandgap of a solar cell. The bandgap is measured in electron volts (eV) and measures the amount of energy each photon needs to create an exciton. If a photon does not have the required bandgap, that energy is not converted. Furthermore, if a photon has more than the amount of energy required, it will create the exciton but the remaining energy will disperse (Miller et al., 2012). These factors contribute to a loss in energy, known as the blue-loss of a cell. Finding a bandgap where the most energy can be converted is crucial to the efficiency of the cell. Most bandgaps produce the best efficiency of around 1.4 electron volts (eV) (Beckman et al., 1991).

Open circuit voltage (V_{oc}), another factor affecting efficiency, is the measure of the voltage across the cell when the closed circuit current (J_{sc}) is zero. The voltage is a measure of the energy, in volts (V), that the photons have in the cell after they are absorbed. The V_{oc} increases when higher energy electron-hole pairs are produced with a higher bandgap (Elumalai et al., 2015). The V_{oc} can be used to calculate the blue-loss of a cell. This voltage is what is transferred to an external circuit to generate electricity.

The closed circuit current (J_{sc}) is a measure of density in the cell, in units of milliamperes (mA) per cm^2. It is affected by the area of the solar cell, the number of photons, the angle of light, reflection properties, and the lifetime of the cell (Beckman et al., 1991). The J_{sc} is important in knowing how many photons the cell has absorbed as the more photons there are, the less energy each photon has. Both V_{oc} and J_{sc} are crucial to efficiency as there needs be a balance between the energy of the photons that strike the cell and how many photons strike in the cell.

The fill factor (FF) of a cell is the ratio of power converted of the cell to the product of the V_{oc} and J_{sc}, or theoretical power that the cell would output. FF is a measure of how much power the cell is outputting versus how much it would output in a perfect environment, therefore measuring how much the outside environment affects the conversion energy of the cell (Qi et al., 2014). When graphing J_{sc} versus V_{oc} in a J-V graph, the FF is a measure of how square-like the J-V curve is.

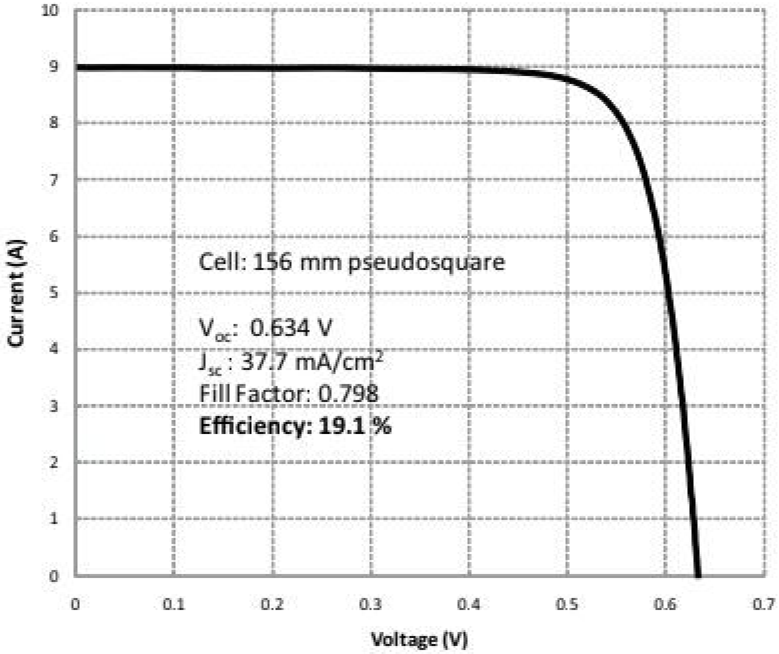

Figure 2. A graph of a J-V curve of a sample solar cell (Lee et al., 2012). FF is measured by optimizing the area of a square created by the graph of current (J_{sc}) versus the voltage (V_{oc}). FF plays a crucial role in the efficiency of electricity generation of a solar cell.

Power conversion efficiency (PCE) is the ratio of output of energy by the cell to the input of energy by the photons that strike the cell. PCE is the measure of how efficient a solar cell is in terms of how much electrical energy it is generating from solar energy (Barnett et al., 2009).

Types of Solar Cells

Silicon Solar Cells

Silicon solar cells make up 90% of the global market of photovoltaics (Jean et al., 2015). They are advantageous because silicon is abundant in nature, extremely durable, and widely used throughout electronics, allowing it to have been developed extensively (Yoshikawa et al., 2017). There are two major types of silicon solar cells: monocrystalline, or crystalline, and polycrystalline, or multicrystalline. The difference between these two silicon cells is in the fabrication method and the structure. Monocrystalline cells are fabricated through submerging a structured monocrystalline piece into the melted silicon, allowing it crystallize. Once the metal has cooled, it is cut into rectangular blocks and then cut into the sheets which form solar cells. Contrastingly, polycrystalline is melted and cools in molds rather than crystallizing the metal (Tagçjollu et al., 2016). As a result, two different structures are formed: one in which there is a uniform structure of crystal throughout and the other which has varying crystal structures.

Monocrystalline solar cells have an optimal bandgap of 1.3-1.4 eV (Jean et al., 2015). These crystalline solar cells make up 35% of the market (ITRPV, 2014). One weakness of crystalline solar cells is its indirect bandgap, a non-fixed bandgap, which leads to decreased absorption of light and forces the cell to be thicker. Moreover, the production process uses high amounts of silicon, making it less desirable due to inefficient material use. These cells still generate efficiencies of 25.6%, costing $0.38 per watt at peak production (W_p) (Mrinalini et al., 2019; Rohatgi et al., 2010; Saga et al., 2010).

Polycrystalline cells often have a bandgap of 1.1 eV (Benick et al., 2017). These cells consist of 55% of the solar cell market, making them the most sold type of solar cell (ITRPV, 2014). Weaknesses of polycrystalline solar cells are similar to those of monocrystalline cells. Multicrystalline cells generate electricity at a cost of \$0.34 per W_p at 21.5% efficiency (Saga et al., 2010).

Tandem Solar Cells and Thin Film Cells

Tandem solar cells, known as multi-junction cells, are cells with stacked layers of different sub-cells, which are able to absorb different wavelengths of the light spectra. There are two terminal tandem cells, which have two sub-layers, and four terminal cells, which have four sub-layers. The sub-cells can be made of any type of cell but some combinations are more efficient than others. Tandem cells are desirable because they can preserve a large FF (Blanker et al., 2018). A higher FF for solar cells often equates to higher efficiency, depending on the materials used in the cell. The multiple layers in tandem solar cells reduce the blue-loss energy referenced earlier, allowing for higher efficiencies, although not always cheaper cells because of the increased amount of material. Nevertheless, tandem solar cells can result in higher efficiencies and may be more efficient than certain types of silicon cells, though there is no current research on this.

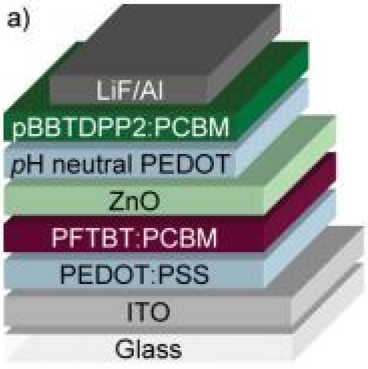

Figure 3. Image of a tandem solar cell (Gilot et al., 2010). The layers are built on a substrate of glass and a thin layer of indium tin oxide (ITO). The diagram also includes the subcells of the tandem with the pBBTDPP2:PCBM and PFTFBT:PCBM sections.

Thin film solar cells are cells that are created by fusing thin layers of material together. They are thinner than silicon solar cells, allowing them to be manipulated into durable cells. Thin film solar cells are becoming more prevalent in the solar cell market due to higher efficiencies and less material used (Lee et al., 2016). Some researchers hope to offset the increase in material use in tandem cells by using thin film cells. Others argue they are not beneficial enough to be used in solar cells. Nevertheless, thin film cells are a new area of research in photovoltaics that are used commonly in tandem structures (Todorov et al., 2018).

Perovskite, CIGS, a-Si:H, and CdTe

Perovskite is a thin film metal halide made of calcium titanate that is desirable in tandem cells because of its tunable bandgap (1.55 eV- 2.3 eV) (Li et al., 2017). The ability to adjust the bandgap to the needs of the specific type of cell makes it popular in developing cells, as this is a common issue. Perovskite also has a high absorption coefficient, allowing it to take in most of the photons in the specific wavelength interval being emitted by the sun rather than reflecting them away (Anwer et al., 2016). The absorption coefficient is related to the internal quantum efficiency (IQE), which is the ratio of electrons or holes to the number of photons that strike the cell. Because it is able to create more excitons from the photons that strike the cell and therefore increase the internal concentration of the cell, it becomes more efficient. Furthermore, perovskite has a large diffusion length, allowing it to last longer than other materials used in solar cells (Anwer et al., 2016). Although, perovskite has negative factors too. When being manufactured, lead is a major element of perovskite materials (Haider et al., 2018). Lead is toxic and raises concerns about whether perovskite is safe in nature during its lifetime. Another problem is that perovskite degrades when exposed to excessive amounts of ultraviolet radiation or humid conditions (Green et al., 2014; Li et al., 2017). These aspects can be concerning because toxicity is a health issue and in extreme conditions, perovskite would not last long. Moreover, perovskites are prone to defect formation during crystallization, which can hinder the effectiveness of the material (Guo et al., 2018). Precision is required when manufacturing, impairing the implementation of large scale manufacturing. Nevertheless, perovskite has proven to be a resourceful material for solar cells as its efficiencies have reached over 23.2% in 2018 from 3.8% in 2009 (Zhang et al., 2018).

The low cost of perovskite compared to other materials is one of its key attributes. The higher the efficiency and life expectancy of the solar cell is, the more return on investment a consumer will receive because the kilowatts per hour (kWh) will be higher. Perovskite cells were estimated to cost between 3.5-4.9 cents per kWh based on a 15 year lifetime, depending on the efficiency of the cell. Other cells made of different materials that included perovskite were estimated to cost between 4.22-5.22 cents per kWh (Li et al., 2018). Perovskites were also estimated to cost 20 cents per W_p (Kim et al., 2016). The cost of perovskite per kWh and per W_p can be compared to the cost of silicon solar technology, the largest quantity of solar cells on the market at 8-10 cents per kWh and $0.3-0.4 per watt at peak production (Saga et al., 2010).

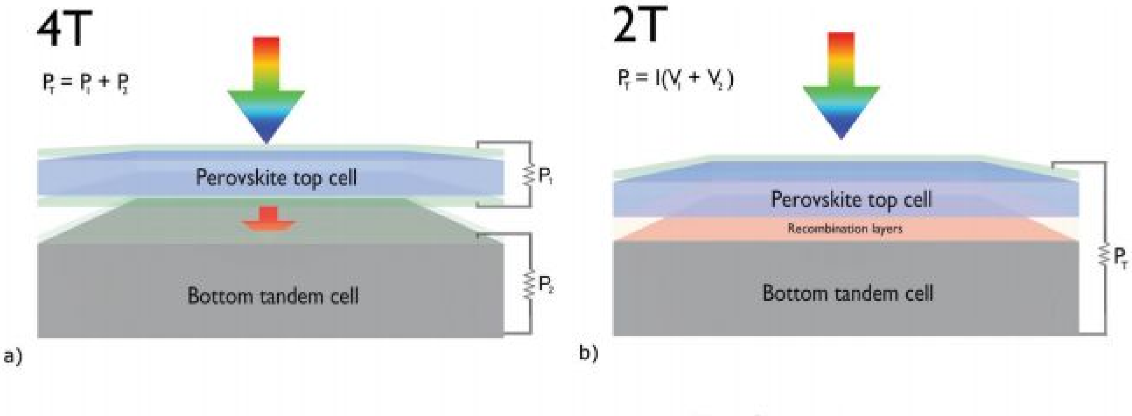

Figure 4. The image shows tandem solar cells with a perovskite top cell (Lal et al., 2017). The left cell shows a four terminal tandem cell and the right cell shows a two-terminal tandem solar cell. The two terminal cell displays the combination layers of the cell.

CIGS is a thin-film cell made from copper-indium-gallium-di-selenide, hence CIGS. Because CIGS is a thin film cell, higher efficiencies are achieved because higher voltages can be obtained with thinner layers of light absorption. CIGS has the highest efficiency of thin film solar cells at 22.9% (Torres-Jaramillo et al., 2018). Furthermore, CIGS has a direct bandgap around 1.2 eV that can be easily tuned and it even has a high absorption coefficient (Blanker et al., 2018). Because of these properties and the fact that it can be deposited by a variety of different techniques on different substrates, it allows CIGS to be efficient and favorable for building layers in tandem solar cells. CIGS has a high radiation resistance, preventing fast decomposition of the cell (Avancini et al., 2018). Despite this, CIGS pose some issues in that the abundance of indium is scarce, making it difficult to manufacture on a large-scale. The stability of CIGS, random defects due to quaternary composition are also issues. Finally, CIGS has a low V_{oc} because of its 1.2 eV bandgap, which can hinder efficiency yet it is not a major issue (Jean et al., 2015). As a result, CIGS is commercially manufactured because of their favorable attributes.

As for the price of CIGS, it was estimated that at 14% efficiency, the average price per kWh of the cell would be 67 cents per watt (Horowitz et al., 2016). Compared to conventional monocrystalline silicon, the cost per watt is significantly higher. Currently, CIGS cells have been improved to higher efficiencies than what was used to study the costs, and would therefore be less than the cost mentioned.

CdTe, or cadmium telluride, is another thin film cell that is commercially sold and holds a fair portion of the market share of thin film cells because of many advantageous features (Tsai et al., 2014). These features include high absorption across the light spectrum and a bandgap of 1.45 eV. Efficiencies for CdTe have reached 21.0%. Other features that make CdTe desirable are that they use high-throughput deposition processes, making it easier to manufacture. They also use roll-to-roll technique manufacturing and simple ways to process solutions, making CdTe easy to fabricate. Resultantly, they have low production costs. Issues with CdTe include that they require high processing temperatures, the element cadmium can be toxic if it decomposes extensively, and tellurium is scarce in nature. CdTe cells are still mostly environmentally friendly and are easy to use though (Jean et al., 2015; Li et al., 2017; Mei et al., 2018).

The costs of CdTe are 11 cents per kWh for the entire system at 14.7% efficiency (Sinha et al., 2013). With respect to cost per W_p, CdTe costs less than 50 cents at 20% efficiency rates (Major et al., 2014). Similarly to CIGS solar cells, the CdTe cost per W_p is higher when compared to monocrystalline solar cells and the cost per kWh is also higher. The costs at higher efficiencies would be cheaper though. The difference in cost between silicon and CdTe can be attributed to the cost of the material itself, the degradation rate, and the efficiency.

Hydrogenated amorphous silicon (a-Si:H) is the final type of thin film solar cell that is manufactured at the commercial level. This cell has a wide bandgap of around 1.66 eV and can be processed at temperatures under 20℃, making it preferable for manufacturing techniques (Blanker et al., 2018). The bandgap is high but nonetheless, a-Si:H has strong light absorption. a-Si:H also is able to absorb most of the photons in one layer of material, allowing for flexible and light cells, preferable for shipping purposes and production (Matsui et al., 2015). Silicon is non-toxic, cheap, and abundant, making it desirable to be used in solar cells. Some issues with a-Si:H include that they are vulnerable to degradation by light, preventing them from lasting long if exposed excessively. Their efficiency range of 14-15% is not as high as other thin film cells (Jean et al., 2015).

The cost per kWh for a-Si:H is estimated to be around 10 cents at a 13-17% efficiency level. The cost per W_p is estimated to be around 50 cents (Dobrotkova et al., 2012). These costs are more expensive than the previously mentioned monocrystalline solar cells per watt and the same per kWh.

Purpose

The purpose of the study is to investigate the effect of manipulating cells into tandem structures on the efficiency of a cell. Through investigating these cells, the cells with the most potential for cost-effectiveness by researching efficiency will be found. By finding which solar cells have better efficiencies when compared to each other, renewable energy of photovoltaics will have the potential of being cheaper and further improved. There is little to no research on whether thin film solar cells are more or less efficient than the widely used silicon cells, creating a gap in current research which this study aims to address. In finding the more efficient cells, one can discover which cells should be sold predominantly on the market. As a result, money can be saved on energy, decreasing the need for financial aid for families, companies, and other consumers of photovoltaic technology. More importantly, the dependence on fossil fuels is lessened because of better-found cells which are sold to more customers, decreasing the amount of greenhouse gas emissions and improving the quality of the environment, biosphere, and life for organisms on Earth.

Research Question

Can solar cells' structure be manipulated into a form of thin film tandem cell to produce more efficient solar cells compared to silicon solar cells?

Hypotheses

Alternative hypothesis: Thin-film tandem solar cells are more efficient as compared to silicon solar cells.

Null hypothesis: Thin film tandem solar cells are as or less efficient as silicon solar cells.

Types of Solar Cells Researched

Due to the information that was available through various databases, the following three types of tandem solar cells were researched: CIGS-Perovskite in a 4 Terminal stack, Perovskite-Perovskite, and CdTe/Si. Although there are more types of tandem solar cells, such as CIGS-a-Si:H, these three were selected because the information on them was most abundant. Furthermore, these cells tended to have higher efficiencies than other types of tandem cells that were able to be discovered, making them better than other types.

Silicon cells were also researched because they make up the majority of the solar market today. Their influence on photovoltaics is widespread and therefore, they were analyzed in this study. Using silicon cells as a control, the tandem solar cells were statistically compared to discover if there was greater efficiency in any of the tandem cells compared to the two major types of silicon cells.

Methods

Research databases such as ScienceDirect, EbscoHost, JSTOR, NREL, DOE, IEEE, PlosOne, EngineeringVillage, Knovel, Reaxys, NCBI, PubMed, Google Scholar, and ResearchGate were searched to obtain information on tandem solar cells. The tandem solar cells researched were CIGS-Perovskite 4T, Perovskite-Perovskite, and CdTe-Silicon. Silicon solar cells, both multicrystalline and monocrystalline, were researched to act as a control for comparison. Terms such as “tandem photovoltaics,” “CIGS-perovskite solar cells efficiency,” "multicrystalline silicon cell efficiency," "CdTe solar cells," "perovskite-perovskite efficiency," and "multicrystalline silicon cell efficiency" were used to obtain articles.

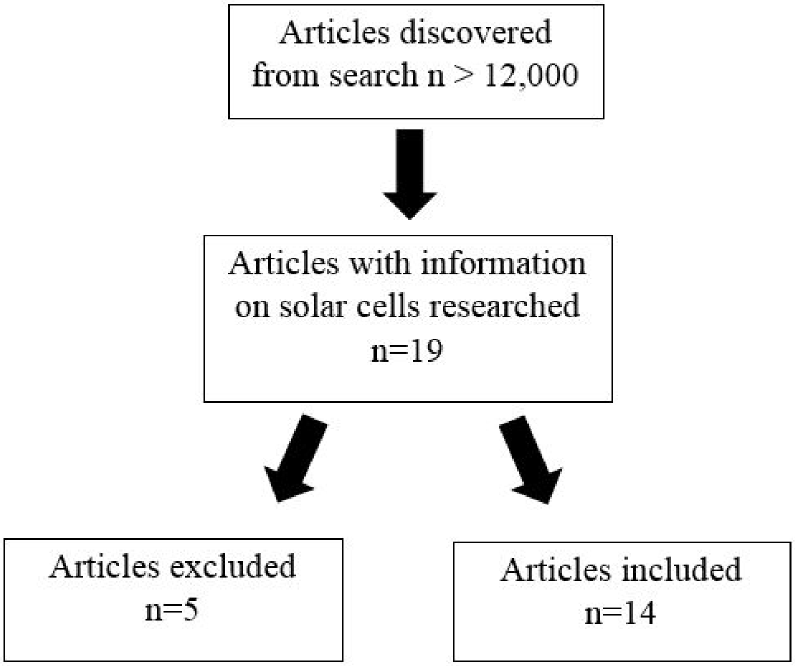

Figure 5. Diagram of article collection throughout the study.

Inclusion and Exclusion Criteria

Data were collected based on the variables in the papers. Bandgap did not have to be included as many papers excluded this information, but V_{oc}, J_{sc}, FF, and PCE were required in the analysis to ensure accuracy of data collection. Papers that used different methods, for example, differences in concentration of light or size of the cell for measuring efficiency, were excluded. Controlled variables were ensured to be the same throughout all academic papers used.

The criteria for selecting papers was to ensure that all the variables plotted were the same, including IQE and external quantum efficiency (EQE), which are the losses in energy due to the reflection of light, the voltage, and the current density. Variables that had to be the same throughout were the number of suns concentrated on the cell, or the amount of light used for each solar cell, the solar insolation degree of AM1.5, and any deviations for IQE plot. By confirming these variables are the same throughout, an accurate statistical test was able to be conducted.

Academic papers published before 2009 were not used in the study to keep the information recent, with the exception of one paper published in 2004 because it was deemed applicable by more recent sources. Academic papers that were based on meta-analysis, systematic literature review, or review articles were not included. Only papers that conducted experiments and measured variables were used to conduct a systematic literature review.

Statistical Analysis

The Analysis Toolpak in Excel was used to conduct statistical analysis. T-tests assuming unequal variance were conducted because of the standard deviations in the groups of data being different. The t-stat was then calculated, along with the p-values for both one-tail and two-tailed tests. Two-tailed tests were first analyzed to discover if there was a significant difference between the efficiencies of two different cells. If this was proven to be true, the one-tail tests were then examined to indicate if one cell's efficiency was higher than other, based on the average calculated. An alpha value of .05 was used. If the p-value was less than .05 in favor of the thin film tandem solar cells, then the null hypothesis would be rejected. If the p-value was higher than .05 in favor of the tandem cells or less than .05 in favor of the silicon cells, the null hypothesis would be accepted.

Results

Table 1. Summary of articles used in statistical analysis. Descriptions of each study and their application to the study are included.

Study	Design of Solar Cell	Method of Measurement (Light)	Application to Conducting Statistics	Usage (Yes or No)
Bush et al., 2017	Monolithic Perovskite/silicon Tandem Solar Cells	1 sun, AM 1.5G filter	None	No
Guchait et al., 2017	Cadmium Telluride/Silicon (CdTe/Si) Tandem Solar Cells	1 sun, AM 1.5G filter	CdTe/Si Cell V_{oc}, J_{sc}, FF, and PCE	Yes
Enam et al., 2017	Cadmium Telluride/Silicon (CdTe/Si) Tandem Solar Cells	1 sun, AM 1.5G filter	CdTe/Si Cell V_{oc}, J_{sc}, FF, PCE, and bandgap	Yes
Tamboli et al., 2017	CdTe/Silicon Tandem Solar Cells	1 sun, AM 1.5G filter	CdTe/Si Cell V_{oc}, J_{sc}, FF, and PCE	Yes
Kranz et al., 2015	High-Efficiency CIGS-Perovskite Thin Film Tandem Solar Cells	1 sun, AM 1.5G filter	CIGS-Perovskite V_{oc}, J_{sc}, FF, and PCE	Yes
Fu et al., 2015	Four-terminal Perovskite–CIGS tandem solar cells.	1 sun, AM 1.5G filter	CIGS-Perovskite V_{oc}, J_{sc}, FF, and PCE	Yes
Yang et al., 2015	Perovskite/Cu(In,Ga)(Se, S)2 Four Terminal Tandem Solar Cells	1 sun, AM 1.5G filter, light intensities differ from all other	CIGS-Perovskite V_{oc}, J_{sc}, FF, and PCE	No

		studies		
Guchhait et al., 2017	CIGS−Perovskite Tandem Solar Cells	1 sun, AM 1.5G filter	CIGS-Perovskite V_{oc}, J_{sc}, FF, and PCE	Yes
Rajagopal et al., 2017	Perovskite–Perovskite Tandem Solar Cells	1 sun, AM 1.5G filter	Perovskite-Perovskite V_{oc}, J_{sc}, FF, PCE, and bandgap	Yes
Anaya et al., 2017	ABX3 Perovskites for Tandem Solar Cells	1 sun, AM 1.5G filter	None	No
Forgács et al., 2017	Monolithic Perovskite/Perovskite Tandem Solar Cells	1 sun, AM 1.5G filter	Perovskite-perovskite V_{oc}, J_{sc}, FF, and PCE	Yes
Eperon et al., 2016	Perovskite-Perovskite tandem photovoltaics	1 sun, AM 1.5G filter	Perovskite-Perovskite V_{oc}, J_{sc}, FF, and PCE	Yes
Wali et al., 2017	Tandem perovskite solar cells	1 sun, AM 1.5G filter	Non Perovskite-Perovskite data	No
Zhao et al., 1998	‘‘Honeycomb’’ textured multicrystalline	Not included	No data that could be used	No
Schultz et al., 2004	Multicrystalline Silicon Solar Cells	1 sun, AM 1.5G filter	Multicrystalline V_{oc}, J_{sc}, FF, and PCE	Yes
Benick et al., 2017 (multiple articles)	N-type Si solar cells; High-efficiency n-type HP mc silicon solar cells	1 sun, AM 1.5G filter	Multicrystalline V_{oc}, J_{sc}, FF, and PCE	Yes
Zhang et al., 2015	Polycrystalline silicon solar cells	1 sun, AM 1.5G filter	Multicrystalline V_{oc}, J_{sc}, FF, and PCE	Yes
Yoshikawa et al., 2017	Silicon heterojunction solar cell	1 sun, AM 1.5G filter	Monocrystalline V_{oc}, J_{sc}, FF, and PCE	Yes
Richter et al., 2017 (multiple	N-type Si solar cells	1 sun, AM 1.5G filter	Monocrystalline V_{oc}, J_{sc}, FF, and PCE	Yes

information)				
Green et al., 2018	Solar cell efficiency tables	1 sun, AM 1.5G filter	Multicrystalline V_{oc}, J_{sc}, FF, and PCE	Yes

Table 2. Data collected for four terminal CIGS-Perovskite 4T cells.

	V_{oc} (V)	**J_{sc} mA/cm^{-2}**	**FF %**	**PCE %**	**Study**
Perovskite Top	0.98	20.1	78.1	16.0	Guchait et al., 2017
CIGS bottom	0.47	15.2	64.6	4.7	
4 Terminal Tandem				20.7	
Perovskite Top	1.1	17.4	73.6	14.2	Fu et al., 2015
CIGS bottom	0.67	12.7	74.9	6.3	
4 Terminal Tandem				20.5	
Perovskite Top	1.03	16.7	70.3	12.1	Kranz et al., 2015
CIGS bottom	0.66	14.4	77.4	7.4	
4 Terminal Tandem				19.5	

Only the information on the four terminal stack was included due to the efficiency being the focus of the study. The efficiencies were reported at 20.7%, 20.5%, and 19.5% for CIGS-Perovskite 4T.

Table 3. Data collected for CdTe/Si cells.

V_{oc} (V)	J_{sc} mA/cm^{-2}	FF %	PCE %	Study
0.69	39.40	83.9	22.8	Tamboli et al., 2017
1.15	27.61	89.4	28.5	Enam et al., 2017

CdTe/Si cells' efficiencies were found to be 22.8% and 28.457%.

Table 4. Data collected for Perovskite-Perovskite cells.

V_{oc} (V)	J_{sc} mA/cm^{-2}	FF%	PCE%	SPCE %	Study
1.66	14.50	0.7	16.9	17.0	Eperon et al., 2016
1.98	12.70	0.73	18.4	18.5	Rajagopal et al., 2017
2.29	9.83	80.3	N/A	18.1	Forgács et al., 2017

The efficiencies reported for Perovskite-Perovskite cells were 17.0%, 18.5%, and 18.1%.

Table 5. Data collected for multicrystalline silicon cells.

V_{oc} (V)	J_{sc} mA/cm^{-2}	FF%	PCE%	Study
0.67	40.76	79.7	21.9	Benick et al., 2017
0.67	39.80	80.0	21.3	Zhang et al., 2015
0.67	41.08	80.5	22.3	Benick et al., 2017
0.67	40.55	80.9	22.0	Green et al., 2018
0.66	38.00	80.9	20.4	Schultz et al., 2004

Data on polycrystalline cells were more abundant than the other cells. With five total articles used, efficiencies in the 20-22.1% range were reported.

Table 6. Data collected for monocrystalline silicon cells.

V_{oc} (V)	J_{sc} mA/cm^{-2}	FF%	PCE%	Study
0.74	42.65	84.9	26.7	Yoshikawa et al., 2017
0.72	42.54	83.3	25.7	Richter et al., 2017
0.72	42.87	83.1	25.8	Richter et al., 2017

Monocrystalline efficiencies were reported to be 26.7%, 25.7%, and 25.8% in the three peer-reviewed articles that were used in the study.

Table 7. t-Test results assuming unequal variance between multicrystalline and CIGS-Perovskite.

t-Test: Two-Sample Assuming Unequal Variances		
	Multicrystalline	***CIGS-Perovskite 4T***
Mean	**21.58**	**20.23**
Variance	**0.567**	**0.413**
Observations	**5**	**3**
df	**5**	
t Stat	**2.687**	
P(T<=t) one-tail	**0.02173**	
t Critical one-tail	**2.015**	
P(T<=t) two-tail	**0.04345**	

t Critical two-tail	**2.571**

The t-stat was calculated to be approximately 2.69 between multicrystalline and CIGS-Perovskite 4T with 5 degrees of freedom. P-values for both one-tailed and two-tailed t-tests were discovered to be less than .02 and .04 respectively.

Table 8. t-Test results assuming unequal variance between multicrystalline and CdTe/Si.

t-Test: Two-Sample Assuming Unequal Variances		
	Multicrystalline	***CdTe/Si***
Mean	**21.58**	**25.63**
Variance	**0.567**	**16.0**
Observations	**5**	**2**
df	**1**	
t Stat	**-1.421**	
P(T<=t) one-tail	**0.1952**	
t Critical one-tail	**6.314**	
P(T<=t) two-tail	**0.3903**	
t Critical two-tail	**12.706**	

P-values of .19 and .39 were calculated when comparing multicrystalline and CdTe/Si. The t-stat number was -1.42 with 1 degree of freedom.

Table 9. t-Test results assuming unequal variance between multicrystalline and Perovskite-Perovskite.

t-Test: Two-Sample Assuming Unequal Variances

	Multicrystalline	***Perovskite-Perovskite***
Mean	**21.58**	**17.87**
Variance	**0.567**	**0.603**
Observations	**5**	**3**
df	**4**	
t Stat	**6.621**	
P(T<=t) one-tail	**0.001349**	
t Critical one-tail	**2.132**	
P(T<=t) two-tail	**0.002698**	
t Critical two-tail	**2.776**	

When statistically reviewing monocrystalline and perovskite-perovskite, p-values of .0013 and .0027 were calculated for the one-tailed and two-tailed tests at 4 degrees of freedom. The t-stat was 6.62.

Table 10. t-Test results assuming unequal variance between monocrystalline and CIGS-Perovskite.

t-Test: Two-Sample Assuming Unequal Variances		
	Monocrystalline	***CIGS-Perovskite 41***
Mean	**26.07**	**20.23**
Variance	**0.303**	**0.413**
Observations	**3**	**3**

df	**4**
t Stat	**11.935**
P(T<=t) one-tail	**0.0001412**
t Critical one-tail	**2.132**
P(T<=t) two-tail	**0.0002824**
t Critical two-tail	**2.776**

One and two-tailed tests resulted in .00014 and .00028 p-values between monocrystalline and CIGS-Perovskite 4T. The t-stat was 11.94 with 4 degrees of freedom.

Table 11. t-Test results assuming unequal variance between monocrystalline and CdTe/Si.

t-Test: Two-Sample Assuming Unequal Variances		
	Monocrystalline	***CdTe/Si***
Mean	**26.07**	**25.63**
Variance	**0.303**	**16.0**
Observations	**3**	**2**
df	**1**	
t Stat	**0.1539**	
P(T<=t) one-tail	**0.4514**	
t Critical one-tail	**6.314**	
P(T<=t) two-tail	**0.9028**	
t Critical two-tail	**12.706**	

With a t-stat of .15, high p-values of .45 and .90 were found with one-tailed and two-tailed tests in the comparison between monocrystalline and CdTe/Si at 1 degree of freedom.

Table 12. t-Test results assuming unequal variance between monocrystalline and Perovskite-Perovskite.

t-Test: Two-Sample Assuming Unequal Variances		
	Monocrystalline	***Perovskite-Perovskite***
Mean	**26.07**	**17.87**
Variance	**0.303**	**0.603**
Observations	**3**	**3**
df	**4**	
t Stat	**14.916**	
P(T<=t) one-tail	**5.883E-05**	
t Critical one-tail	**2.132**	
P(T<=t) two-tail	**0.0001177**	
t Critical two-tail	**2.776**	

A t-stat of 14.92 was calculated, resulting in p-values of 5.9E-05 and .00012 in one and two-tailed tests between monocrystalline and perovskite-perovskite. There were 4 degrees of freedom.

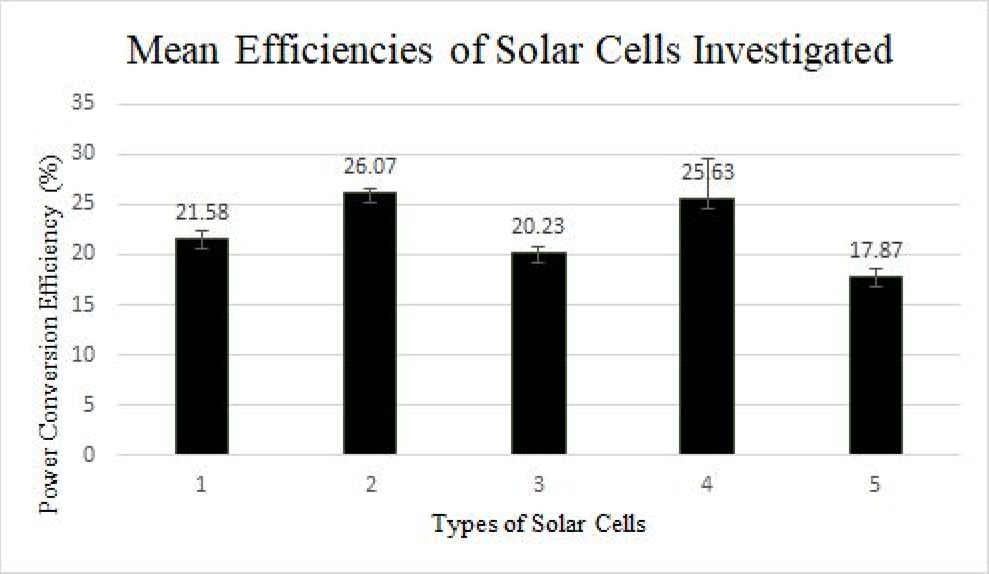

Figure 6. Efficiencies of solar cells collected from 14 peer-reviewed articles. 1) Polycrystalline 2) Monocrystalline 3) CIGS/Perovskite 4T 4) CdTe/Silicon 5) Perovskite/Perovskite.

Discussion

When comparing silicon cells to the tandem cells researched, it is evident that tandem solar cells do not have higher efficiencies on average. The reported p-values in Tables 7, 9, 10, and 12, all of which are lower than the selected alpha value of .05 in favor of the silicon cells, indicate that both types of silicon cells are statistically proven to be more efficient than Perovskite-Perovskite and CIGS-Perovskite 4T. As for the CdTe/Si cells compared to the silicon solar cells, the p-values, as calculated in Tables 8 and 11, are greater than .05, showing no statistical difference between the efficiency of the cells. This could be due to the large standard deviation of the data collected for CdTe/Si, as the more spread out the data is, the less conclusive t-test results may be. Figure 5 depicts the mean differences inefficiencies between the cells and hints that silicon is more efficient than tandem cells. The p-values calculated support these results except in the case of CdTe/Si where no statistical difference was found.

With these results in mind, it is shown that none of the three tandem solar cells investigated have higher efficiencies than silicon solar cells. As a result, silicon solar cells generate more electricity and could therefore be more economically viable than tandem cells. Although not explored deeply in this study, the cost of the materials and the fabrication method of the cell also have significant influence on the cost of electricity generated by the cells. Because silicon is abundant in nature, it is cheaper to obtain than materials used in thin film cells that are used in the tandem combination. These factors lead silicon cells to control the large majority of the market. Despite this being true, the potential of silicon to further grow as a material in the solar industry is minimal because of extensive research already done in the electronics industry. Consequently, other materials, especially perovskite, CdTe, and CIGS, have much more potential to be more efficient because they are new technology in the photovoltaic industry, and therefore could be economically feasible for middle-class families in the future. Silicon cells currently dominate the solar market, but if research is done to improve less popular types of cells, costs of thin film cells can be lessened to become more accessible than silicon for everyday use. Ultimately, this would provide greater benefits to the environment because of lessened dependence on more harmful methods of electricity generation. Finally, costs for electricity could decrease as a result of higher efficiency cells as when utility bills decrease in cost, consumers will have more disposable income. This allows for a greater flow of money, benefiting the economy. It can also help some to pay off other loans and debts, making economic stress for these people decrease.

Sources of Error

Sources of error in the investigation consist of small amounts of data and differing researchers conducting tests on the same type of cell. The low number of articles that were available for each type of cell affects the robustness of the data set and therefore the validity of the outcome. Generally, more papers should be included in the study to make the results more concrete, although access to more papers was inhibited partially because of private companies withholding data and because of lack of access to certain databases. With respect to the papers themselves, if there were significant differences between articles, then one was excluded. Nonetheless, small types of errors not mentioned in each study could result in differing data that could cause an error in the study, for example, temperature, humidity, and other conditions that could possibly affect the efficiency of the cells.

Conclusion

The systematic literature review provides strong evidence that thin film tandem cells are not more efficient than silicon cells. Peer-reviewed papers in this study support the null hypothesis, indicating silicon solar cells are better cells to use for solar energy purposes due to them generating electricity at higher efficiencies. Ultimately, the findings suggest tandem solar cells are not more efficient than silicon solar cells and therefore they are better for energy generated when considering the amount produced, aiding both the environment and the economy.

Further Work

To further contribute to the study, research on different types of thin film solar cells could have been conducted. Given the amount of time to conduct this investigation, only three types of solar cells were able to be researched. Different types of tandem solar cells could have been investigated to truly find the different behaviors. Different types of tandem solar cells, such as different types of two and four terminal solar cells, would have been a possible research pathway to discover efficiencies and compare them to silicon. Comparing only three types of solar cells tightens the entire field of possible materials and types, limiting the scope of the project. If more time allowed, more types could have been researched and compared.

Different variables with each of the solar cells also could be investigated, such as stability (longevity), size, doping concentration in the fabrication process, and the method of cell manufacturing. These are all factors that play into the cost of solar cells at purchase. Research of these variables on the cells studied could give better context to the exact cost of electricity generated by solar technology.

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References

Abdolmaleky, M., & Shama, F. (2018). Design of an efficient double-junction CGS/CIGS solar cell. *Optik, 172,* 271-277. Retrieved from https://doi.org/10.1016/j.ijleo.2018.07.038

Ali, F., & Hossain, F. (2017). Influence of front and back contacts on photovoltaic performances of p-n homojunction Si solar cell: Considering an electron-blocking layer. *International Journal of Photoenergy, 2017,* 1-6. Retrieved from https://doi.org/10.1155/2017/7415851

Anaya, M., Lozano, G., Calvo, M. E., & Míguez, H. (2017). ABX 3 Perovskites for Tandem Solar Cells. *Joule, 1*(4), 769–793. Doi: 10.1016/j.joule.2017.09.017

Askari, S. S. A., Kumar, M., & Das, M.K. (2016). Performance analysis of perovskite on Si tandem solar cell. *Materials Today, 4,* 12647-12650. Retrieved from https://doi.org/10.1016/j.matpr.2017.10.076

Bach, W. (1981). Fossil fuel resources and their impacts on environment and climate. *International Journal of Hydrogen Energy, 6*(2), 185-201. Retrieved from https://doi.org/10.1016/0360-3199(81)90007-0

Bailie, C. D., Christoforo, M. G., Mailoa, J. P., Bowring, A. R., Unger, E. L., Nguyen, W. H., … McGehee, M. D. (2015). Semi-transparent perovskite solar cells for tandems with silicon and CIGS. *Energy and Environmental Science, 8,* 956-963. Retrieved from https://pubs.rsc.org/en/content/

Ball, J. M., Stranks, S. D., Hoerantner, M., Hüttner, S., Zhang, W., Crossland, E., … Snaith, H. J. (2015). Optical properties and limiting photocurrent of thin-film perovskite solar cells. *Energy & Environmental Science, 8*(2), 1-9. Doi: 10.1039/C4EE03224A

Balo, F., & Şağbanşua, L. (2016). The selection of the best solar panel for the photovoltaic system design by using AHP. *Energy Procedia, 100,* 50-53. Retrieved from https://doi.org/10.1016/j.egypro.2016.10.151

Barnett, A., Kirkpatrick, D., Honsberg, C., Moore, D., Wanlass, M., Emery, K., … Schmidt, G. (2009). Very high efficiency solar cell modules. *Progress in Photovoltaics: Research and Applications, 17,* 75-83. Doi: 10.1002/pip.852

Beckman, W. A., & Duffie, J. A. (1991). *Solar engineering of thermal processes* (2nd ed.). John Wiley and Sons, Inc.

Benick, J., Richter, A., Muller, R., Hauser, H., Feldmann, F., Krenckel, P., … Glunz, S. W. (2017). High-efficiency n-Type HP mc silicon solar cells. *IEEE Journal of Photovoltaics, 7*(5), 1171–1175. Doi: 10.1109/jphotov.2017.2714139

Blanker, A.J., Berendsen, P., Phung, N., Vroon, Z.E.A.P., Zeman, M., & Smets, A.H.M. (2018). Advanced light management techniques for two-terminal hybrid tandem solar cells. *Solar Energy Materials and Solar Cells, 181,* 77-82. Retrieved from https://doi.org/10.1016/j.solmat.2018.02.017

Buonomano, A., Calise, F., & Vicidomini, M. (2016). Design, simulation and experimental investigation of a solar system based on PV panels and PVT collectors. *Energies, 9*(497), 1-17. Retrieved from http://web.a.ebscohost.com/ehost/detail/

Bush, K. A., Palmstrom, A. F., Yu, Z. J., Boccard, M., Cheacharoen, R., Mailoa, J. P., … McGehee, M. D. (2017). 23.6%-efficient monolithic perovskite/silicon tandem solar cells with improved stability. *Nature Energy, 2,* 1-17. Retrieved from https://doi.org/10.1038/nenergy.2017.9

Candelise, C., Winskel1, M., & Gross, R. (2012). Implications for CdTe and CIGS technologies production costs of indium and tellurium scarcity. *Progress in Photovoltaics: Research and Applications,* n.p. Retrieved from https://doi.org/10.1002/pip.2216

Chang, N. L., Ho-Baillie, A. W. Y., Vak, D., Gao, M., Green, M. A., & Egan, R. J. (2018). Manufacturing cost and market potential analysis of demonstrated roll-to-roll perovskite photovoltaic cell processes. *Solar Energy Materials and Solar Cells, 174,* 314-324. Retrieved from https://doi.org/10.1016/j.solmat.2017.08.038

Chen, A., Yossef, M., & Zhang, C. (2018). Strain effect on the performance of amorphous silicon and perovskite solar cells. *Solar Energy, 163,* 243-250. Retrieved from https://doi.org/10.1016/j.solener.2018.01.057

Chu, S., & Majumdar, A. (2012). Opportunities and challenges for a sustainable energy future. *Nature, 488,* 294-303. Doi: 10.1038/nature11475

Currie, M. J., Mapel, J. K., Heidel, T. D., Goffri, S. & Baldo, M. A. (2008). High-efficiency organic solar concentrators for photovoltaics. *Science, 321*(5886), 226-228. Doi: 10.1126/science.1158342

damp conditions: Comparison with the same interfacial layers. *Solar Energy Materials & Solar Cells, 128,* 41-47. Retrieved from https://doi.org/10.1016/j.solmat.2014.04.036

Dastrup, S., Zivin, J. G., Costa, D. L., & Kahn, M. E. (2012). Understanding the solar home price premium: Electricity generation and "green" social status. *European Economic Review, 56*(5), 961-973. Retrieved from https://doi.org/10.1016/j.euroecorev.2012.02.006

Davis, S. J., Caldeira, K., & Matthews, H. D. (2010). Future CO2 emissions and climate change from existing energy infrastructure. *Science, 329*, 1330-1333. Retrieved from cloudfront.escholarship.org/dist/prd/

Dobrotkova, Z., Surana, K., & Audinet, P. (2018). The price of solar energy: Comparing competitive auctions for utility-scale solar PV in developing countries. *Energy Policy, 118*, 133–148. Doi: 10.1016/j.enpol.2018.03.036

Duan, J., Zhao, Y., He, B., & Tang, Q. (2018). Efficiency enhancement of bifacial dye-sensitized solar cells through bi-tandem carbon quantum dots tailored transparent counter electrodes. *Electrochimica Acta, 278,* 204-209. Retrieved from https://doi.org/10.1016/j.electacta.2018.05.057

Elumalai, N. K., & Uddin, A. (2015). Open circuit voltage of organic solar cells: An in-depth review. *Energy & Environmental Science, 9*(2), n.p. Doi: 10.1039/c5ee02871j

Enam, F. M. T., Rahman, K. S., Kamaruzzaman, M. I., Sobayel, K., Bais, B., Akhtaruzzaman, M., Alamoud, A. R. M., & Amin, N. (2017). Design prospects of cadmium telluride/silicon (CdTe/Si) tandem solar cells from numerical simulation. *Optik, 137,* 397-406. Retrieved from https://doi.org/10.1016/j.ijleo.2017.03.106

Eperon, G. E., Leijtens, T., Bush, K. A., Prasanna, R., Green, T., Wang, J. T. W., … Snaith, H. J. (2016). Perovskite-perovskite tandem photovoltaics with optimized bandgaps. *Science, 354*(6314), 861-865. Doi: 10.1126/science.aaf9717

Forgács, D., Gil-Escrig, L., Pérez-Del-Rey, D., Momblona, C., Werner, J., Niesen, B., … Bolink, H. J. (2016). Efficient Monolithic Perovskite/Perovskite Tandem Solar Cells. *Advanced Energy Materials, 7*(8), 1602121. Doi: 10.1002/aenm.201602121

Fu, F., Feurer, T., Jager, T., Avancini, E., Bissig, B., Yoon, S., … Tiwari, A. N. (2015). Low-temperature-processed efficient semi-transparent planar perovskite solar cells for bifacial and tandem applications. *Nature Communications, 6*(8932), 1-9. Doi:

10.1038/ncomms9932

Gilot J., Wienk, M. M., & Janssen, R. A. J. (2010). Optimizing polymer tandem solar cells. *Advanced Energy Materials, 22*(8), 67-71. Doi: 10.1002/adma.200902398

Goebel, C., Cheng, V., & Jacobsen, H. A. (2017). Profitability of residential battery energy storage combined with solar photovoltaics. *Energies, 10*(976), 1-17. Retrieved from http://web.a.ebscohost.com/ehost/detail/

Green, M. A., Emery, K., Hishikawa, Y., & Warta, W. (2010). Solar cell efficiency tables (version 36). *Progress in Photovoltaics: Research and Applications, 18*(5), 346–352. Doi: 10.1002/pip.1021

Green, M. A., Emery, K., Hishikawa, Y., Warta, W., & Dunlop, E. D. (2013). Solar cell efficiency tables (version 42). *Progress in Photovoltaics: Research and Applications, 21*(5), 827–837. Doi: 10.1002/pip.2404

Green, M. A., Hishikawa, Y., Dunlop, E. D., Levi, D. H., Hohl-Ebinger, J., & Ho-Baillie, A. W. Y. (2017). Solar cell efficiency tables (version 51). *Progress in Photovoltaics: Research and Applications, 26*(1), 3–12. Doi: 10.1002/pip.2978

Green, M. A., Hishikawa, Y., Warta, W., Dunlop, E. D., Levi, D. H., Hohl-Ebinger, J., & Ho-Baillie, A. W. H. (2017). Solar cell efficiency tables (version 50). *Progress in Photovoltaics: Research and Applications, 25*(7), 668–676. Doi: 10.1002/pip.2909

Green, M. A., Ho-Baillie, A., & Snaith, H. J. (2014). The emergence of perovskite solar cells. *Nature Photonics, 8,* 506-514. Doi: 10.1038/nphoton.2014.134

Guchhait, A., Dewi, H. A., Leow, S. W., Wang, H., Han, G., Suhaimi, F. B., … Mathews, N. (2017). Over 20% efficient CIGS–perovskite tandem solar cells. *ACS Energy Letters,* *2*(4), 807–812. Doi: 10.1021/acsenergylett.7b00187

Haider, M., Zhen, C., Wu, T., Liu, G., & Cheng, H. M. (2018). Boosting efficiency and stability of perovskite solar cells with nickel phthalocyanine as a low-cost hole transporting layer material. *Journal of Materials Science & Technology, 34,* 1474-1480. Retrieved from https://doi.org/10.1016/j.jmst.2018.03.005

Han, D., & Yoo, S. (2014). The stability of normal vs. inverted organic solar cells under highly

Helander, M. G. (2012). Solution-processible electrodes. *Science, 336*(6079), 302-303. Retrieved from https://www.jstor.org/stable/41584691

Hoekstra, A. Y., & Wiedmann, T. O. (2014). Humanity's unsustainable environmental footprint. *Science, 344*(6188), 1114-1117. Doi: 10.1126/science.1248365

Horowitz, K. A. W., Fu, R., & Woodhouse, M. (2016). An analysis of glass–glass CIGS manufacturing costs. *Solar Energy Materials & Solar Cells, 154,* 1-10. Retrieved from https://doi.org/10.1016/j.solmat.2016.04.029

Inganäs, O., Zhang, F., & Andersson, M. R. (2012). Alternating copolymers and alternative device geometries for organic photovoltaics. *Ambio, 41 (Supplement 2)*, 138-142. Doi: 10.1007/s 13280-0 12-0276-3

Ito, M., Kato, K., Komoto, K., Kichimi, T., & Kurokawa, K. (2008). A comparative study on cost and life-cycle analysis for 100 MW very large-scale PV (VLS-PV) systems in deserts using m-Si, a-Si, CdTe, and Cis modules. *Progress In Photovoltaics: Research And Applications, 16,* 17-30. Doi: 10.1002/pip.770

Jean, J., Brown, P. R., Jaffe, R. L., Buonassisi, T., & Bulovic, V. (2015). Pathways for photovoltaics. *Energy Environ, 8,* 1200-1219. Retrieved from https://pubs.rsc.org/en/content/

Kabir, E., Kumar, P., Kumar, S., Adelodun, A. A., & Kim, K. H. (2018). Solar energy: Potential and future prospects. *Renewable and Sustainable Energy Reviews, 82*(1), 894-900. Retrieved from https://doi.org/10.1016/j.rser.2017.09.094

Kaelin, M., Rudmann, D., & Tiwari, A. N. (2005. Low cost processing of CIGS thin film solar cells. *Solar Energy, 77*(6), 749-756. Retrieved from https://doi.org/10.1016/j.solener.2004.08.015

Kim, B. J., Kim, D. H., Kwon, S. L., Park, S. Y., Li, Z., Zhu, K., & Jung, H. S. (2016). Selective dissolution of halide perovskites as a step towards recycling solar cells. *Nature Communications, 7,* n.p. Doi: 10.1038/ncomms11735

Kim, J. Y., Lee, K., Coates, N. E., Moses, D., Nguyen, T., Dante, M. & Heeger, A. J. (2007). Efficient tandem polymer solar cells fabricated by all-solution processing. *Science, 317*(5835), 222-225. Doi: 10.1126/science.1141711

Kim, K., Yoo, J.S., Ahn, S. K., Eo, Y. J., Cho, J.S., Gwak, J., & Yun, J. H. (2017). Performance prediction of chalcopyrite-based dual-junction tandem solar cells. *Solar Energy, 155,* 167-177. Retrieved from https://doi.org/10.1016/j.solener.2017.05.080

Kranz, F., Abate, A., Feurer, T., Fu, F., Avancini, E., Lockinger, J., … Tiwari, A. N. (2015). High-efficiency polycrystalline thin film tandem solar cells. *Journal of Physical Chemistry Letters, 6*(14), 2676–2681. Doi: 10.1021/acs.jpclett.5b01108

Kroll, U., Shah, A., Keppner, H., Meier, J., Torres, P., & Fischer, D. (1997). Potential of

VHF-plasmas for low-cost production of a-Si:H solar cells. *Solar Energy Materials and Solar Cells, 48*(1-4), 343-350. Retrieved from https://doi.org/10.1016/S0927-0248(98)80000-7

Lal, N. N., Dkhissi, Y., Li, W., Hou, Q., Cheng, Y. B., & Bach, U. (2017). Perovskite tandem solar cells. *Advanced Energy Materials, 7,* 1-18. Retrieved from https://doi.org/10.1002/aenm.201602761

Lee, M. M., Teuscher, J., Miyasaka, T., Murakami, T. N., & Snaith, H.J. (2012). Efficient hybrid solar cells based on meso-superstructured organometal halide perovskites. *Science, 338*(6107), 643-647. Doi: 10.1126/science.1228604

Lee, S., Kim, C. W., Lee, Y. J., Park, J., Kim, Y., Jeong, C., & Yi, J. (2019). Electron beam irradiated Al doped ZnO thin films as efficient tunnel recombination junction for hydrogenated amorphous Silicon/Cu(In,Ga)Se2 tandem solar cells. *Journal of Nanoscience and Nanotechnology, 19*(3), 1480-1484. Doi: 10.1166/jnn.2019.16259.

Lee, S., Kim, S., Kim, Y., Park, J., & Yi, J. (2018). Computational design of high efficiency a-Si:H/CIGS monolithic tandem solar cell. *Optik, 173,* 132-138. Retrieved from https://doi.org/10.1016/j.ijleo.2018.08.004

Lee, T. D., & Ebong, A. U. (2016). A review of thin film solar cell technologies and challenges. *Renewable and Sustainable Energy Reviews, 70,* 1286-1297. Retrieved from http://dx.doi.org/10.1016/j.rser.2016.12.028

Li, M., Liu, X., Wen, S., Liu, S., Heng, J., Qin, D., … Huang, W. (2017). CdTe nanocrystal hetero-junction solar cells with high open circuit voltage based on Sb-doped TiO_2 electron acceptor materials. *Nanomaterials, 7*(101), 1-8. Doi: 10.3390/nano7050101

Li, Y., Hu, H., Chen, B., Salim, T., Lam, Y.M., Yuan, N., & Ding, J. (2017). Solution-processed perovskite-kesterite reflective tandem solar cells. *Solar Energy, 155,* 35-38. Retrieved from https://doi.org/10.1016/j.solener.2017.06.026

Li, Y., Hu, H., Chen, B., Salim, T., Zhang, J., Yuan, N.Y., … Lam, Y. (2016). Reflective perovskite solar cells for efficient tandem application. *Journal of Materials Chemistry C,* 1-15. Retrieved from https://pubs.rsc.org/en/content/

Li, Z., Zhao, Y., Wang, X., Sun, Y., Zhao, Z., Li, Y., Zhou, H. & Chen, Q. (2018). Cost analysis of perovskite tandem photovoltaics. *Joule, 2*(8), 1559-1572. Retrieved from https://doi.org/10.1016/j.joule.2018.05.001

Louwen, A., van Sark, W., Schropp, R., & Faaij, A. (2016). A cost roadmap for silicon heterojunction solar cells. *Solar Energy Materials & Solar Cells, 147*, 295-314. Retrieved from https://doi.org/10.1016/j.solmat.2015.12.026

Luke, N., Zabin, C., Velasco, D., & Collier, R. (2017). Diversity in California's clean energy workforce: access to jobs for disadvantaged workers in renewable energy construction. *Green Economy Program*, 1-18. Retrieved from http://laborcenter.berkeley.edu/pdf/2017/

Ma, W., Jackson, A., Wang, C., Moghadam, F., & Sinha, A. K. (2018). 24% efficiency hybrid cell technology integrating a low-cost, precision-pattern Cu metallization used for advanced PCB. *IEEE 7th World Conference on Photovoltaic Energy Conversion*, 3732-3737. Doi: 10.1109/pvsc.2018.8548258

Major, J. D., Treharne, R. E., Phillips, L. J., Durose, K. (2014). A low-cost non-toxic post-growth activation step for CdTe solar cells. *Nature, 000,* 0-8. Doi: 10.1038/nature13435

Manuel, J. (2005). Innovative technologies: Organic solar cells. *Environmental Health Perspectives, 113*(5), 301. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/

Masuko, K., Shigematsu, M., Hashiguchi, T., Fujishima, D., Kai, M., Yoshimura, N., … Okamoto, S. (2014). Achievement of more than 25% conversion efficiency with crystalline silicon heterojunction solar cell. *IEEE Journal of Photovoltaics, 4*(6), 1433–1435. Doi: 10.1109/jphotov.2014.2352151

Matsui, T., Bidiville, A., Maejima, K., Sai, H., Koida, T., Suezaki, T., … Kondo, M. (2015). High-efficiency amorphous silicon solar cells: Impact of deposition rate on metastability. *Applied Physics Letters, 053901*, 1-5. Retrieved from https://doi.org/10.1063/1.4907001

Mei, X., Wu, B., Guo, X., Liu, X., Rong, Z., Liu, S., … Chen, B. (2018). Efficient CdTe nanocrystal/TiO2 hetero-junction solar cells with open circuit voltage breaking 0.8 V by incorporating a thin layer of CdS nanocrystal. *Nanomaterials, 8*(8), 614-625. Doi: 10.3390/nano8080614

Mejia, F. A., & Kleissl, J. (2013). Soiling losses for solar photovoltaic systems in California. *Solar Energy, 95,* 357-363. Retrieved from https://doi.org/10.1016/j.solener.2013.06.028

Mekhilef, S., Saidur, R., & Safari, A. (2011). A review on solar energy use in industries. *Renewable and Sustainable Energy Reviews, 15,* 1777-1790. Doi: 10.1016/j.rser.2010.12.018

Meral, M. E., & Dincer, F. (2011). A review of the factors affecting operation and efficiency of photovoltaic based electricity generation systems. *Renewable and Sustainable Energy Reviews, 15,* 2176-2184. Retrieved from https://www.elsevier.com/locate/rser

Miller, L., & Carriveau, R. (2018). A review of energy storage financing-Learning from and partnering with the renewable energy industry. *Journal of Energy Storage*, *19,* 311-319. Retrieved from https://doi.org/10.1016/j.est.2018.08.007

Mrinalini, M., Islavath, N., Prasanthkumar, S., & Giribabu, L. (2018). Stipulating low production cost solar cells all set to retail…!. *The Chemical Record, 18,* 1-15. Doi: 10.1002/tcr.201800106

Mukashev, B. N., Betekbaev, A.A., Kalygulov, D. A., Pavlov, A. A., & Skakov, D. M. (2015). Study of silicon production processes and development of solar cell fabrication technologies. *Semiconductors, 49*(10), 1375-1382. Retrieved from http://web.a.ebscohost.com/ehost/detail/

Nfaoui, M., & El-Hami, K. (2018). Extracting the maximum energy from solar panels. *Energy Reports, 4,* 536-546. Retrieved from https://www.sciencedirect.com/science/article/

Oon, C. H., & Ng, K. W. (2017). CIGS photovoltaics for the urban tropics. *Energy Procedia, 143,* 733-738. Retrieved from https://doi.org/10.1016/j.egypro.2017.12.754

Park, J., Liang, W., Choi, J., El-Keib, A. A., Shahidehpour, M., & Billinton, R. (2009). A probabilistic reliability evaluation of a power system including solar/photovoltaic cell generator. *IEEE Spectrum,* 464-468. Doi: 10.1109/pes.2009.5275722

Polman, A., Knight, M., Garnett, E. C., Ehrler, B., & Sinke, W. C. (2016). Photovoltaic materials: Present efficiencies and future challenges. *Science, 352*(6283), 307-318. Doi: 10.1126/science.aad4424

Prakash, J., Singh, A., Sathiyan, G., Ranjan, R., Singh, A., Garg, A., Gupta, R. K. (2018). Progress in tailoring perovskite based solar cells through compositional engineering:

Materials properties, photovoltaic performance and critical issues. *Materials Today Energy, 9,* 440-486. Retrieved from https://doi.org/10.1016/j.mtener.2018.07.003

Pujari, N. S., Cellere, G., Falcon, T., Hage, F., Zwegers, M., Bernreuter, J., … Yu, G. (2018). *International technology roadmap for photovoltaic: 2017 results including maturity report 2018* (7th ed.). Retrieved from https://pv.vdma.org/documents/105945/

Qi, B., & Wang, J. (2013). Fill factor in organic solar cells. *Physical Chemistry Chemical Physics, 15*(23), 8972-8982. Doi: 10.1039/c3cp51383a

Rajagopal, A., Yang, Z., Jo, S. B., Braly, I. L., Liang, P.-W., Hillhouse, H. W., & Jen, A. K.-Y. (2017). Highly Efficient Perovskite-Perovskite Tandem Solar Cells Reaching 80% of the Theoretical Limit in Photovoltage. *Advanced Materials, 29(34),* 1-10. Doi: 10.1002/adma.201702140

Richter, A., Benick, J., Feldmann, F., Fell, A., Hermle, M., & Glunz, S. W. (2017). n-Type Si solar cells with passivating electron contact: Identifying sources for efficiency limitations by wafer thickness and resistivity variation. *Solar Energy Materials and Solar Cells, 173*, 96–105. Doi: 10.1016/j.solmat.2017.05.042

Rohatgi, A., & Meier, D. (2010). Developing novel low-cost, high-throughput processing techniques for 20%-efficient monocrystalline silicon solar cells. *Photovoltaics International, 10*, 87-93. Retrieved from http://suniva.com/documents/

Saga, T. (2010). Advances in crystalline silicon solar cell technology for industrial mass production. *NPG Asia Mater, 2*(3), 96–102. Doi: 10.1038/asiamat.2010.82

Schultz, O., Glunz, S. W., & Willeke, G. P. (2004). Short communication: accelerated publication: Multicrystalline silicon solar cells exceeding 20% efficiency. *Progress in*

Photovoltaics: Research and Applications, 12(7), 553–558. Doi: 10.1002/pip.583

Sethia, T., Bharti, S., Shukla, S., & Sharma, P. (2017). Intelligent solar panel installation. *International Journal of Recent Research Aspects, 4*(3), 59-62. Retrieved from http://web.a.ebscohost.com/ehost/detail/

Shi, Z., Liu, H., Li, J., Wang, F., Bai, Y., Bian, X., … Tan, Z. (2018). Engineering the interconnecting layer for efficient inverted tandem polymer solar cells with absorption complementary fullerene and nonfullerene acceptors. *Solar Energy Materials and Solar Cells, 180,* 1-9. Retrieved from https://doi.org/10.1016/j.solmat.2018.02.010

Sinha, P., de Wild-Scholten, M., Wade, A., & Breyer, C. (2013). Total cost electricity pricing of photovoltaics. *28th European Photovoltaic Solar Energy Conference and Exhibition*, n.p. Doi: 10.4229/28theupvsec2013-6do.10.4

Steinkemper, H., Michl, B., Hermle, M., & Glunz, S. W. (2016). Choosing the best silicon material parameters for different solar cell architectures. *Energy Procedia, 92,* 225-231. Retrieved from https://doi.org/10.1016/j.egypro.2016.07.063

Streets, D. G. (2005). Black smoke in China and its climate effects. *Asian Economic Papers, 4*(2), 1–23. Doi: 10.1162/asep.2005.4.2.1

Streets, D. G. (2006). Black smoke in China and its climate effects. *Asian Economic Papers, 4*(2), 1-23. Doi: 10.1162/asep.2005.4.2.1

Tamboli, A. C., Bobela, D. C., Kanevce, A., Remo, T., Alberi, K., & Woodhouse, M. (2017). Low-cost CdTe/Silicon tandem solar cells. *IEEE Journal of Photovoltaics, 7*(6), 1-6. Doi: 10.1109/JPHOTOV.2017.2737361

Taşçıoğlu, A., Taşkın, O., & Vardar, A. (2016). A Power Case Study for Monocrystalline and

Polycrystalline Solar Panels in Bursa City, Turkey. *International Journal of Photoenergy, 2016,* 1–7. Doi: 10.1155/2016/7324138

Todorov, T., Gershon, T., Gunawan, O., Lee, Y. S., Sturdevant, C., Chang, L. Y., & Guha, S. (2015). Monolithic perovskite-CIGS tandem solar cells via in situ band gap engineering. *Advanced Energy Materials, 5*(23), 1-6. Doi: 10.1002/aenm.201500799

Todorov, T. K., Bishop, D. M., & Lee, Y. S. (2018). Materials perspectives for next-generation low-cost tandem solar cells. *Solar Energy Materials and Solar Cells, 180,* 350-357. Retrieved from https://doi.org/10.1016/j.solmat.2017.07.033

Torres-Jaramillo, S., Morale-Acevedo, A., Bernal-Correa, R., & Pulzara-Mora, A. (2018). Optimizing two and four-terminal CuGaSe2/CuInGaSe2 tandem solar cells for achieving high efficiencies. *Optik,* n.d. Retrieved from https://doi.org/10.1016/j.ijleo.2018.08.124

Tsai, C. Y., & Tsai, C. Y. (2014). Development of tandem amorphous/microcrystalline silicon thin-film large-area see-through color solar panels with reflective layer and 4-step laser scribing for building-integrated photovoltaic applications. *Journal of Nanomaterials, 2014,* 1-9. Retrieved from http://dx.doi.org/10.1155/2014/809261

Twidell J, & Weir, T. (2015). *Renewable energy sources.* London, UK: Routledge.

Uz, D. (2017). Energy efficiency investments in small and medium sized manufacturing firms: The case of California energy crisis. *Energy Economics,* 1-30. Doi: 10.1016/j.eneco.2017.12.206

Wali, Q., Elumalai, N. K., Iqbal, Y., Uddin, A., & Jose, R. (2018). Tandem perovskite solar cells. *Renewable and Sustainable Energy Reviews, 84*, 89–110. Doi: 10.1016/j.rser.2018.01.005

Yang, F., Kang, D. W., & Kim, Y. S. (2017). An efficient and thermally stable interconnecting layer for tandem organic solar cells. *Solar Energy, 155,* 552-560. Retrieved from https://doi.org/10.1016/j.solener.2017.06.054

Yang, Y., Chen, Q., Hsieh, Y.-T., Song, T.-B., Marco, N. D., Zhou, H., & Yang, Y. (2015). Multilayer transparent top electrode for solution processed perovskite/Cu(In,Ga)(Se,S)2 four terminal tandem solar cells. *ACS Nano, 9*(7), 7714–7721. Doi: 10.1021/acsnano.5b03189

Yoshikawa, K., Kawasaki, H., Yoshida, W., Irie, T., Konishi, K., Nakano, K., … Yamamoto, K. (2017). Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%. *Nature Energy, 2*(5), 1-8. Doi: 10.1038/nenergy.2017.32

You, J., Dou, L., Yoshimura, K., Kato, T., Ohya, K., Moriarty, T., … Yang, Y. (2012). A polymer tandem solar cell with 10.6% power conversion efficiency. *Nature Communications*, *4*(1446), 1-10. Retrieved from https://www.nature.com/articles/ncomms2411

Zhang, J., Cao, D., Cui, Y., Putson, C., Song, C., & Huang, P. (2018). Investigation of the influence of electron avalanche on the crystallinity of backsheet in solar photovoltaic system for sustainable energy. *Journal of Cleaner Production,* 1-19. Doi: 10.1016/j.jclepro.2018.03.302

Zhang, S., Pan, X., Jiao, H., Deng, W., Xu, J., Chen, Y., … Verlinden, P. J. (2016). 335-W World-record p-type monocrystalline module with 20.6% efficient PERC solar cells. *IEEE Journal of Photovoltaics, 6*(1), 145–152. Doi: 10.1109/jphotov.2015.2498039

Zhang, X., Li, M., Dall'Agnese, C., Chen, G, Wang, X.F., & Miyasaka, T. (2018). Thermo-evaporated pentacene and perylene as hole transport materials for perovskite solar cells. *Dyes and Pigments, 160,* 285-291. Retrieved from https://doi.org/10.1016/j.dyepig.2018.07.053

Zhao, J., Wang, A., Green, M. A., & Ferrazza, F. (1998). 19.8% efficient "honeycomb" textured multicrystalline and 24.4% monocrystalline silicon solar cells. *Applied Physics Letters, 73*(14), 1991–1993. Doi: 10.1063/1.122345

Zweibel, K. (1990). *Harnessing solar power: The photovoltaics challenge*. New York, NY: Plenum Press.

Zweibel, K. (2010). The impact of tellurium supply on cadmium telluride photovoltaics. *Science, 328*(5979), 699-701. Doi: 10.1126/science.1189690