Electronics I Final Project

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Fundamental Working Principle of a Solar Cell

General Physics of a Solar Cell (pn junction)

The general physics for a solar cell regards the photovoltaic effect. The photovoltaic effect is the creation of voltage and electric current in a material upon exposure to light, it is a physical and chemical phenomenon. The photovoltaic effect is closely related to the photoelectric effect. In either case, light is absorbed, causing excitation of an electron or other charge carrier to a higher-energy state. The main distinction is that the term photoelectric effect is now usually used when the electron is ejected out of the material (usually into a vacuum) and photovoltaic effect used when the excited charge carrier is still contained within the material.

General Steps of the Photovoltaic Effect in a Solar Cell

1. We have a doped pn junction that has an internal electric field. The makeup is as follows:
   - n-Layer: thin, highly doped
   - p-Layer: thick, lightly doped
   - This leads to a much larger depletion region, and thus a larger area for light to strike to free up more electrons so that they can flow, resulting in more current.
2. We have light from the sun shining on the pn junction which carries photons that hit electrons in the pn junction
   - The photons usually hit electrons on the p side because of the way the internal electric field is set up. The negative side of the electric field is on the p side so when we free electrons, they will flow to the n side, so if we free electrons on the n side they will remain on the n side so that doesn't provide anything useful.
3. The photons usually hit electrons on the p side because of the way the internal electric field is set up. The negative side of the electric field is on the p side so when we free electrons, they will flow to the n side, so if we free electrons on the n side they will remain on the n side so that doesn't provide anything useful.
4. Or the photon hits electrons in the neutral atoms on the p side and the separation of the electron from the atom could result in the electron to enter the internal electric field and then following the same procedure, flow to the n side due to the internal electric field
5. At the same time the electrons are moving, the holes are moving in the opposite direction
6. The more photons the pn junction receives, the more electrons accumulate on the n side of the junction and holes on the p side of the junction
7. Now assume we have enough electrons and holes accumulated on the ends of the pn junction so that a current (electrons) will flow from the p side to the n side through a wire connecting the two ends of the junction to a load

Consequences of pn Junction

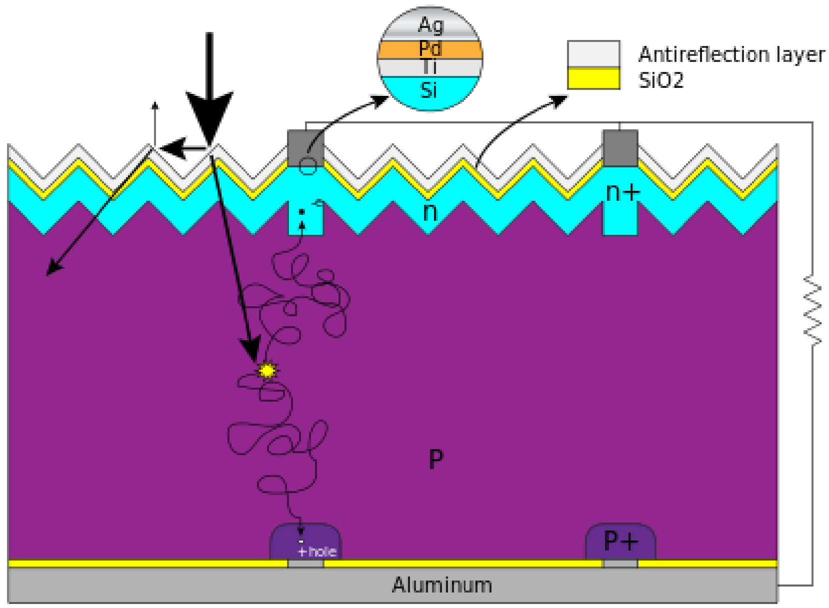


Figure 1: This figure depicts a multijunction solar cell where a photon has freed up an electron which then traveled the random looking path to get to the n side.

In simple terms, to free an electron, a photon has to hit it with enough energy. If the photon does not have enough energy then none of the photon's energy is absorbed. This results in losing the chance to absorb available energy. However, even when a photon has enough energy, if it has more than enough, the excess energy is also lost since the excess is not enough to free other electrons.

Another issue with this setup is risking electrons to recombine with holes. When an electron is freed by a photon, before it even manages go under the effect of the internal electric field, it may recombine with a hole. These issues have technical terms defined below:

- Resistive losses are are a portion of quantum efficiency, V_{OC} ratio, and fill factor.
- Reflectance losses are a portion of quantum efficiency under external quantum efficiency.
- Recombination losses are a portion of quantum efficiency, V_{OC} ratio, and fill factor.
  - Quantum efficiency refers to the percentage of photons that are converted to electric current when the cell is operated under short circuit conditions.
  - External quantum efficiency of a silicon solar cell includes the effect of optical losses such as transmission and reflection.
  - Fill factor is a measure of quality of a solar cell. This is the available power at the maximum power point (P_{m}) divided by the open circuit voltage (V_{OC}) and the short circuit current (I_{SC}).

IV Characteristics

IV and Power Graph for Si Solar Cell

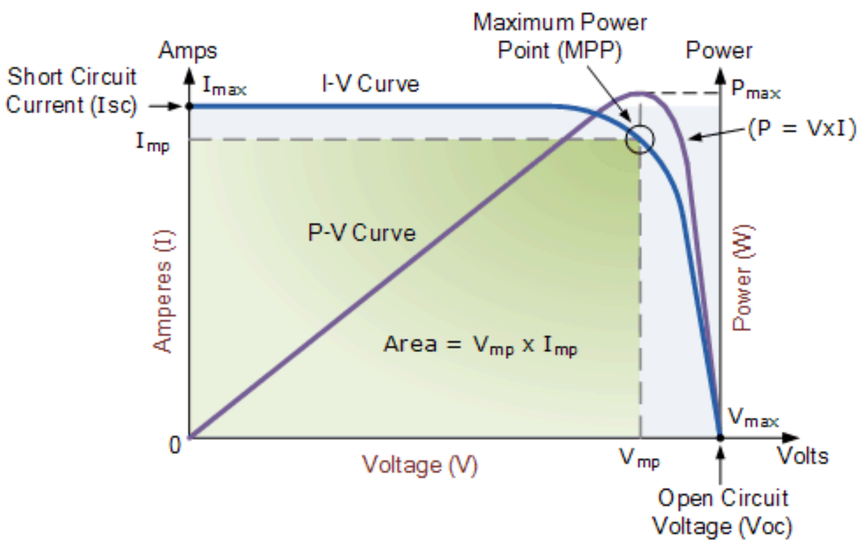


Figure 2: With more current, the temperature of a silicon pv increases which decreases voltage. Thus, current and voltage are inversely related.

IV and Power Graph for Si Array Solar Cell

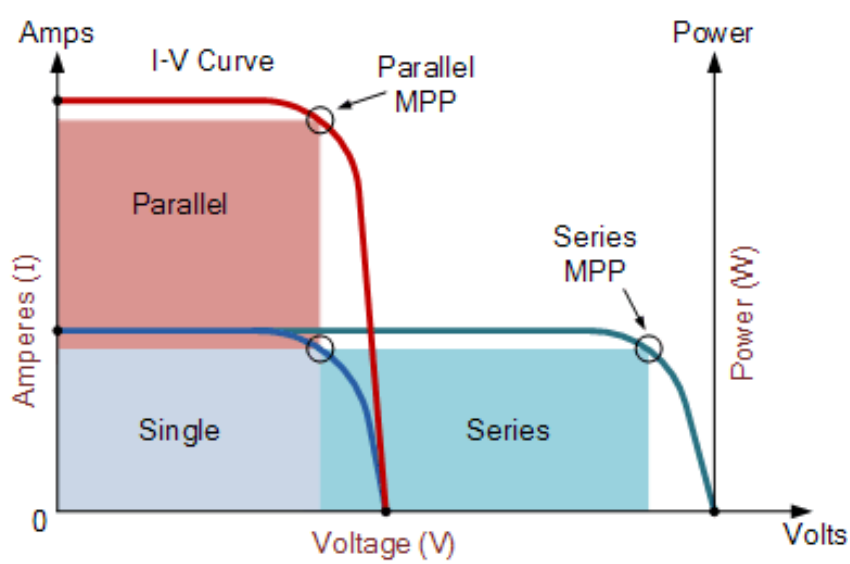


Figure 3: For different arrangements of silicon pv, we can achieve different maximum power outputs.

Materials and Efficiency

There are four main types of photovoltaics (pv) present in today's industry. We have the common silicon pv, thin film pv, organic pv, and concentration pv. When deciding on which pv to utilize, we look at price, material availability, lifespan, complexity, and most importantly, efficiency. Where efficiency is measured by the amount of electrical power coming out of a cell divided by the energy from sunlight coming in.

Silicon PV

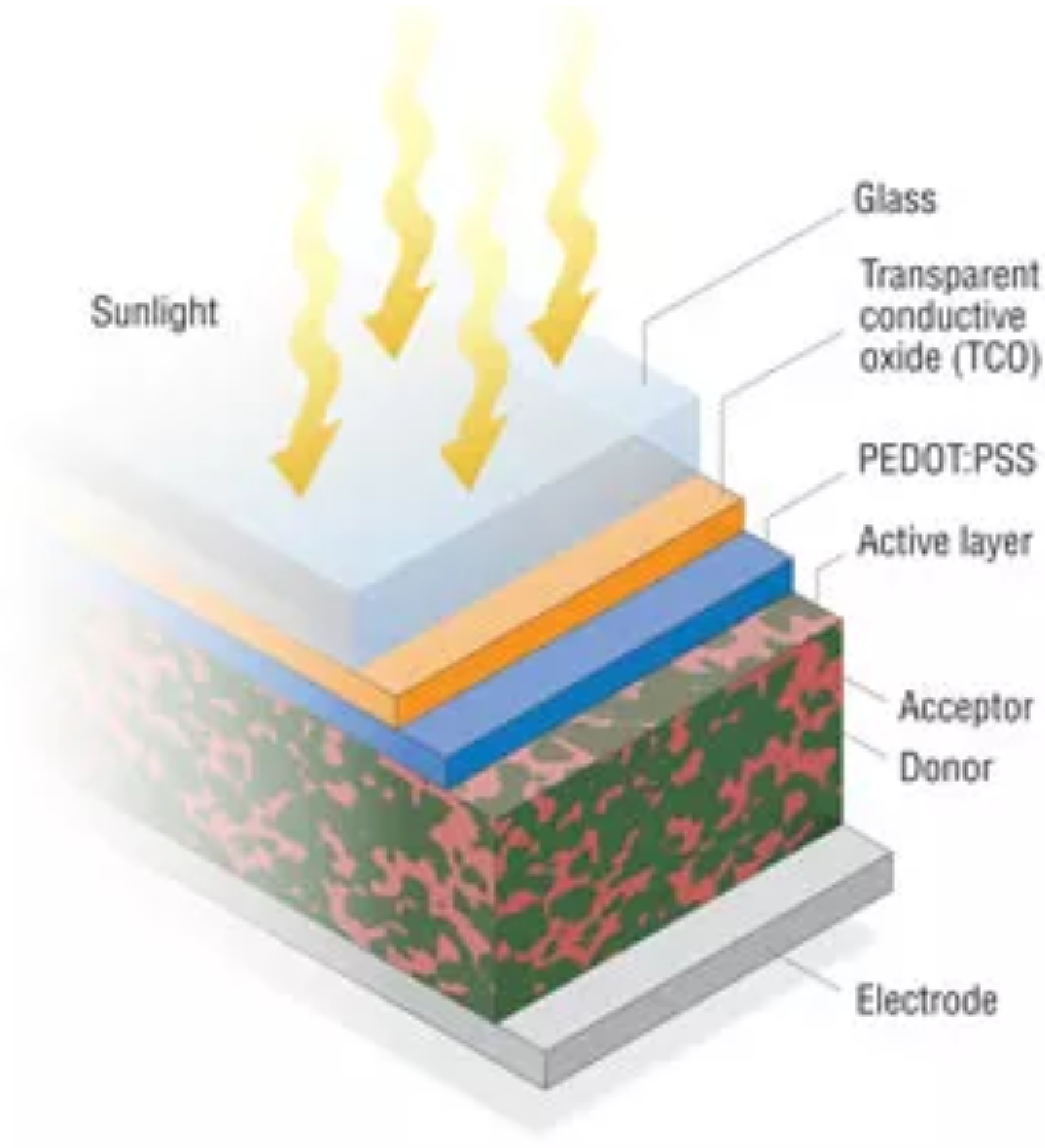
As the second most abundant element on Earth, silicon is the most commonly used material for pv, with over 90% of modules sold today using silicon. Silicon is low cost, and has a typical operating lifetime of 25 years before there are noticeable efficiency decreases. Even after 25 years, silicon pv are generally still able to produce 80% of its initial power. Silicon pv are usually able to achieve 20% efficiency.

Thin Film PV

Thin film pv is when pv material is deposited on supporting material such as glass, plastic, or metal. The top 2 pv material currently being used are cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS). CdTe requires low manufacture cost but not is not as efficient as silicon pv. CIGS can achieve additional electronic and optical properties but it is not as easy to combine four elements for the pv. Moreover, thin film requires more protection than Si to operate outside which increases the overall cost. Generally, thin film can achieve 18% efficiency.

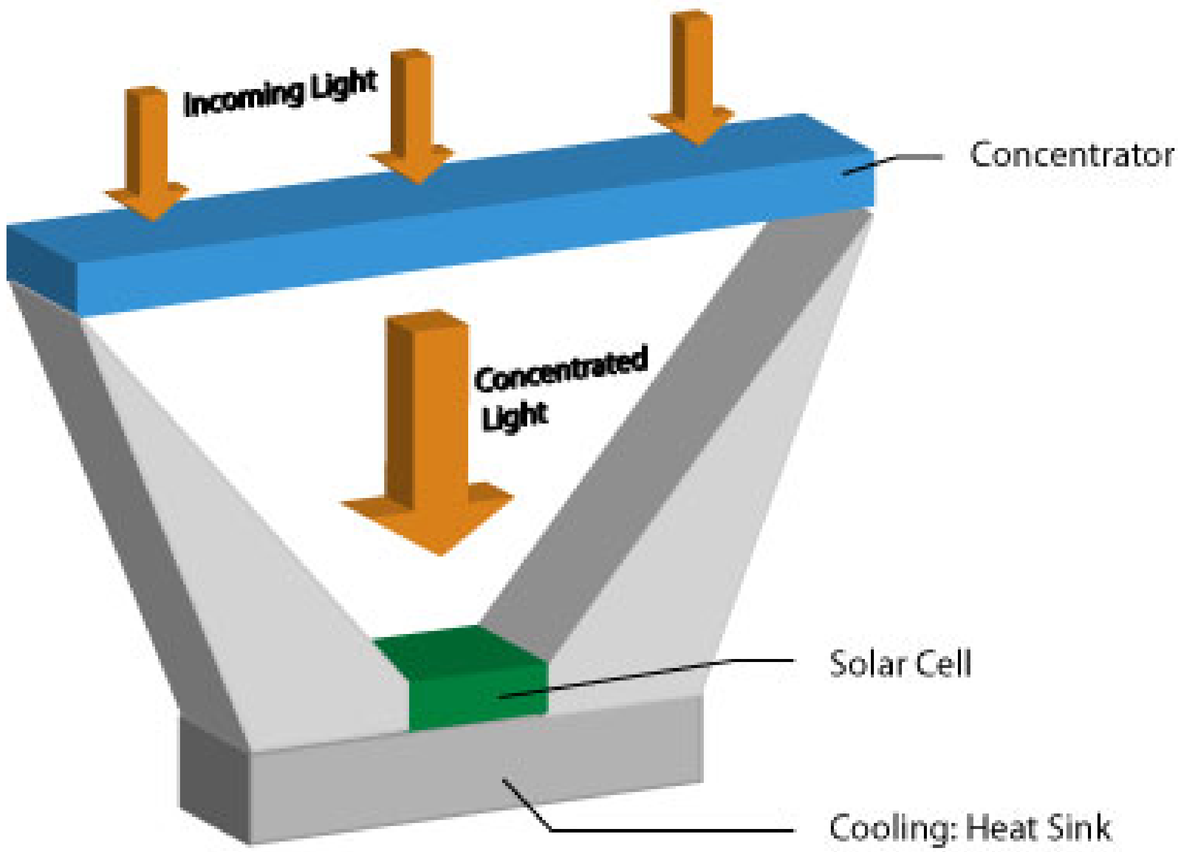
Organic PV

Organic pv aims to provide an Earth-abundant and low-energy-production pv solution. Currently, organic pv usually requires a bulk heterojunction blending of soluble n- and p-type semiconductors, such as PCBM and P3HT. Advantages to organic pv include customizability where specific properties of the solar cell can be controlled such as sensitivity. Also, organic pv cost less than silicon pv. However, they are hardly as efficient and have shorter lifespans than silicon pv. The maximum efficiency achieved for organic pv is only at 11%.

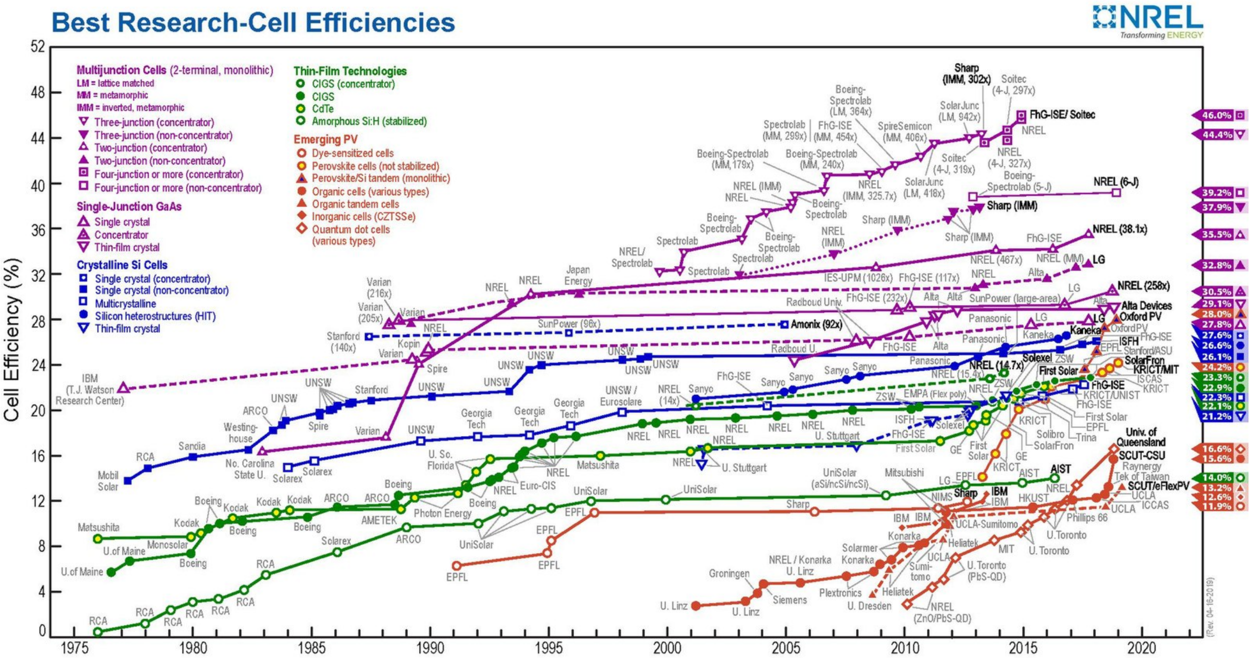


Concentration PV

Concentration pv focuses sunlight using mirrors and lenses. This results in higher efficiency due to the concentration of light into the solar cell. However, this requires more materials other than the solar cell itself and it requires tracking to line up the pv to be perpendicular to sunlight. The excess material and complex set up drastically increases the price for concentration pv. However, there has been a maximum efficiency of 46% that has been achieved with concentration pv.

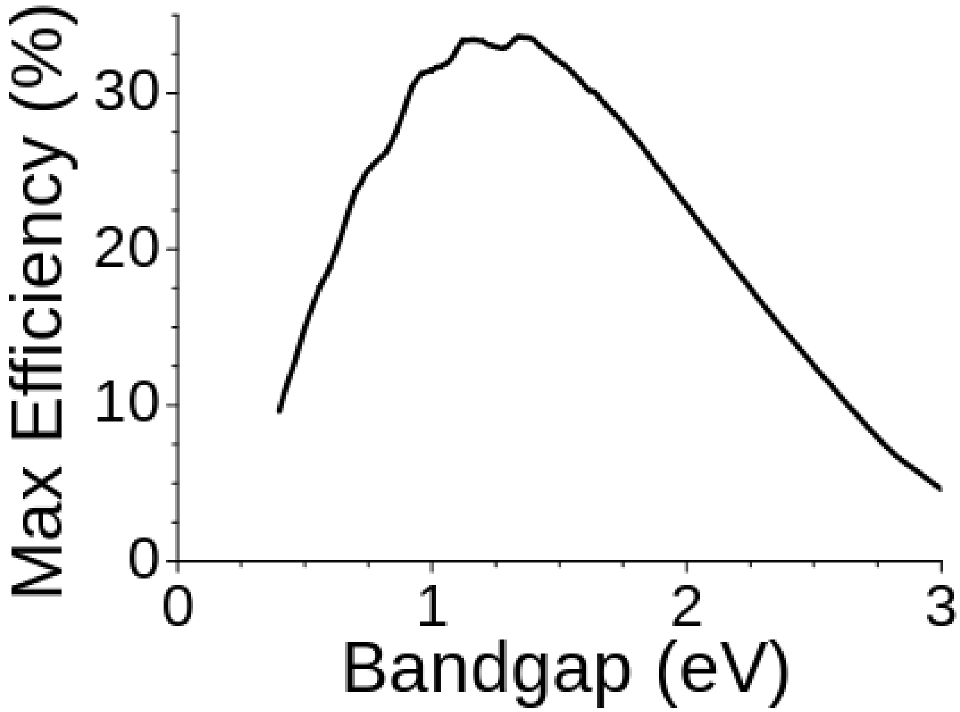


General Facts Regarding Efficiency



This graph summarizes the efficiencies of different types of pv. The purple indicates multijunction cells which proves to be the most efficient. Along with the single junction pv made with GaAs which proves to have high efficiency but is poisonous which makes it not ideal for use in public areas. Next we have the blue section which is for the crystalline silicon pv. Its efficiency is not as high, but as discussed previously, other factors make it ideal for industry and home use. Closely following silicon pv, we have thin film technologies which can achieve efficiencies close to those of silicon pv as mentioned before. Lastly, we have emerging pv which includes organic pv. These alternative solutions are still far from efficient to be of practical use.

Shockley–Queisser Limit



The Shockley–Queisser limit is the limit of efficiency of a solar cell, without the concentration of solar radiation. The curve is wiggly because of IR absorption bands in the atmosphere. This graph shows that the best efficiency that can be reached for single junction pv is around 33.7%. Therefore, silicon pv being able to achieve 20% efficiency on average is a positive factor. We are already close to maximizing utilization of silicon pv.

PV Cell Chemistries and Differences

Silicon

Silicon is the most commonly used material for solar cells in the present day. The technical term used for silicon solar cells is crystalline silicon pv due to the crystal structure of silicon pv. There are different types of silicon solar cells such as monocrystalline solar cells, polycrystalline solar cells, and amorphous solar cells, all with different kinds of crystal structures.

Overall, crystalline single silicon technology is used to produce photovoltaic cells representing about 90% of today's market. Crystalline photovoltaic cells starts with melting silicon, and then crystallised it into ingots or casting's of pure silicon. Thin slices of silicon called wafers, are cut from a single crystal of silicon (Mono-crystalline) or from a block of silicon crystals (Polycrystalline) to make individual cells. Due to the rigid structure of the silicon wafers, these pv have to be transported as is, making it difficult to deliver. The conversion efficiency for these types of photovoltaic cell ranges between 10% to 20%.

Thin Film

Thin Film Solar Cells are another type of photovoltaic cell which were originally developed for space applications with a better power-to-size and weight ratio compared to the previous crystalline silicon devices. Instead of working with tangible pv material such as silicon, thin film photovoltaics are produced by printing or spraying a thin semiconductor layer of pv material onto a glass, metal or plastic support. By applying these materials using such methods, we can obtain thin layers. The overall thickness of each photovoltaic cell is substantially smaller than an equivalent cut crystalline cell, hence the name “thin film”.

Since the pv materials used in these types of photovoltaic cells are sprayed directly onto a glass or a metal substrate, the manufacturing process becomes faster and it also makes it cheaper. As a result, thin film pv technology became more viable for use in a home solar system due to a shorter payback time. Also, due to the materials used, thin film pv have higher light absorption than crystalline materials such as silicon.

However, thin film pv cells suffer from poor cell conversion efficiency due to their non-single crystal structure. Thus, to achieve as much efficiency as crystalline materials, larger sized cells have to be used which requires increased cost for space.

Semiconductor materials used for the thin film types of photovoltaic cell include: Cadmium Telluride, Amorphous Silicon and Copper Indium diSelenide or CIS.

Single Junction

Single junction solar cells are comprised of only one solar cell which means there is only on pn junction in it. This also means that the pv is make up of one material. As a result, the pv can only absorb a narrow range of wavelengths. This is an issue since solar cells want to convert as much of the energy that is received to electrical energy since efficiency itself is already limited, we want to be able to absorb as much energy as possible.

Multi Junction

Multi-junction solar cells are comprised of multiple individual solar cells grown on top of each other. The use of multiple semiconducting materials allows the absorbance of a broader range of wavelengths, improving the cell's sunlight to electrical energy conversion efficiency.Each sub-cell is composed of a unique material that absorbs a specific portion of the solar spectrum. By adding additional sub-cells designed to absorb increasingly narrow segments of the solar spectrum, we can drive solar cell efficiencies to 50% and beyond. Traditional single-junction cells have a maximum theoretical efficiency of 33.16%. Theoretically, an infinite number of junctions would have a limiting efficiency of 86.8% under highly concentrated sunlight. However, this efficiency is gained at the cost of increased complexity and manufacturing price and thus their use is limited to special roles, like ones that take advantage of their high power to weight ratio.

The majority of multi-junction cells that have been produced to date use three layers (although many tandem a-Si:H/mc-Si modules have been produced and are widely available). However, the triple junction cells require the use of semiconductors that can be tuned to specific frequencies, which has led to most of them being made of gallium arsenide (GaAs) compounds, often germanium for the bottom-, GaAs for the middle-, and $GaInP_2$ for the top-cell.

Crystalline Silicon vs Thin Film PV

With crystalline pv, we usually work with silicon which is abundant and cheap. The efficiency that can be achieved from crystalline pv is close to its theoretical limit. However, the structure is rigid making it difficult to transport. Thin film pv directly tackles this problem of crystalline pv through the application of spraying pv material onto a supporting material. Due to this application process, the pv is very thin, making it tangible for transportation. However, at the same time, the materials that can be used for thin film pv are not as abundant as silicon and result in pv that are not as efficient as silicon pv although they come close.

Single Junction vs Multi Junction

The main advantage that single junction pv have over multi junction pv is the requirement for less materials. Single junction pv are only made up of one type of material making the initial part of the manufacturing process simpler. However, efficiency is the more important factor that defines how good a pv is. Due to multi junction pv using different materials, more wavelengths of light can be absorbed, increasing efficiency. The difference in theoretical efficiency is quite large where single junction pv has a limit of 33.8% and multi junction pv has a limit of 86.8%. There is more room for research and thus improvement for multi junction pv. However, along with these advantages comes with the disadvantage of price. Multi-junction will cost at least 2-2.5 times as much as single-junction solar cells.

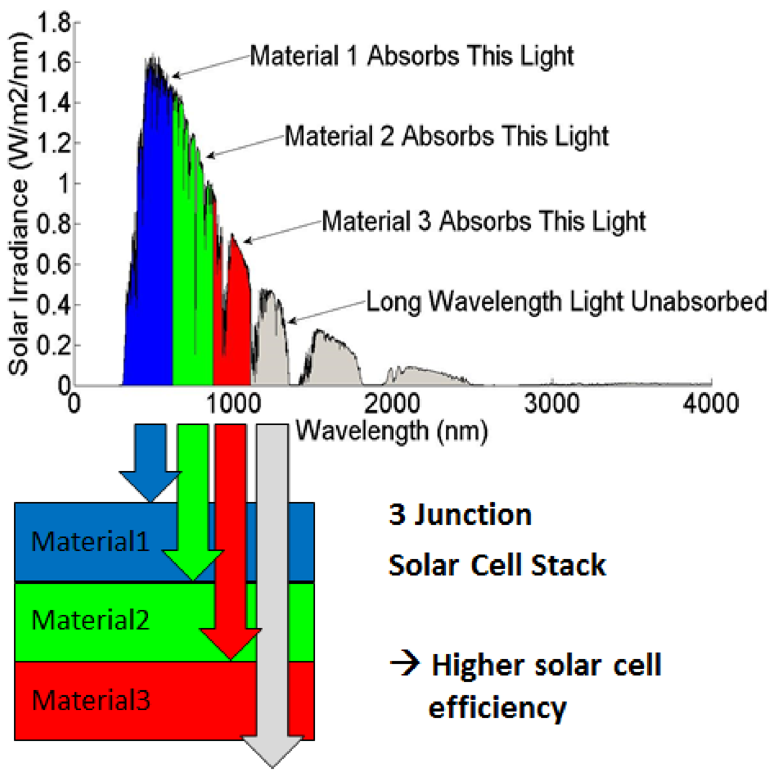


Figure 4: Multi junction materials absorbing different wavelengths.

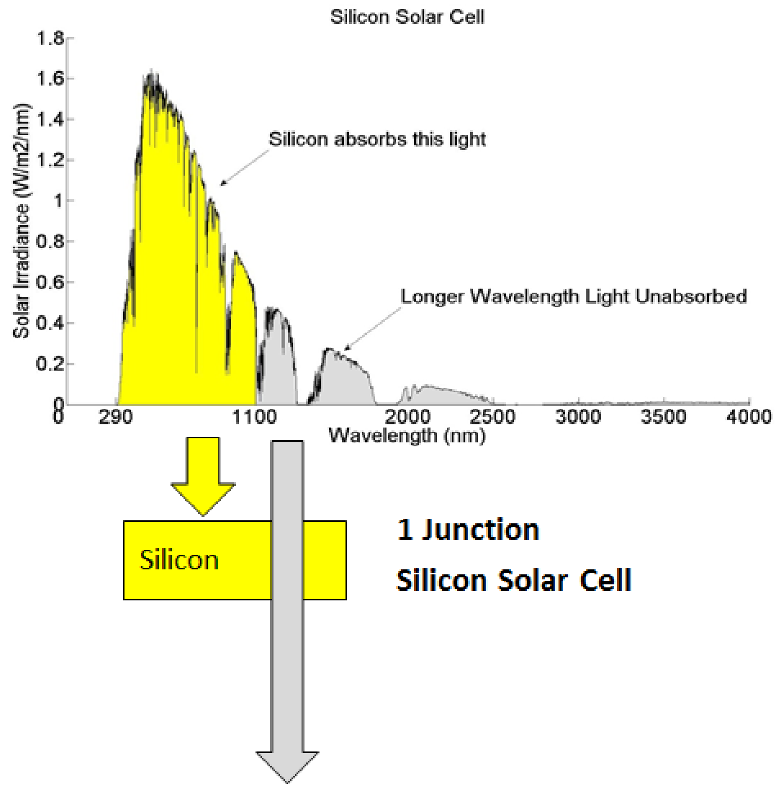


Figure 5: A single silicon junction absorbing wavelengths within its range.

Design

We need to design a power system for a cruiser participating in the World Solar Challenge. The main factors to be considered are power, cost, total surface area, efficiency, and energy storage.

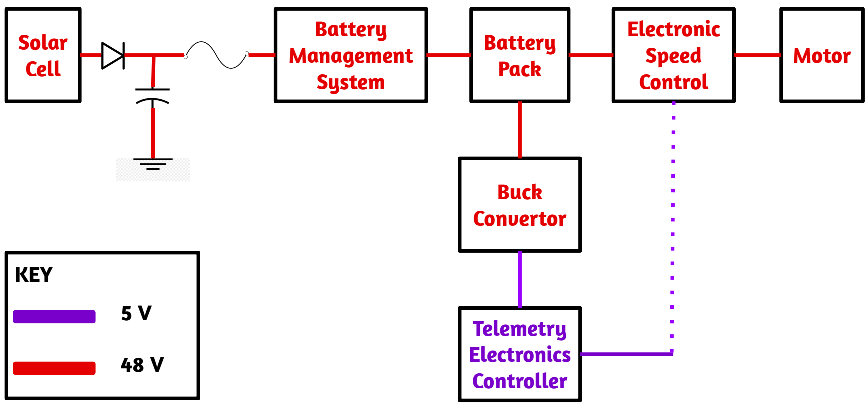


Figure 6: A Block Diagram of the Solar Collector and Energy Storage mechanism that would go in a characteristic car.

Limiting Factors

According to the 2019 Rules and Regulations, a Cruiser Vehicle is allowed a maximum of $5.000m^2$ of Silicon Solar Panels.

In terms of energy storage, there are no restrictions to the total mass of the rechargeable electrochemical cells for the Cruiser Car. However, the *amount* of energy stored in the cells does factor into the score. By that token, 18650 cells are chosen for the battery pack, as they offer a high capacity, are widely used in consumer electronics, and have well-documented and supported charging methods.

Finally, the motor used is also a factor; we choose a motor that is common to solar car designs, that is 1-2 horsepower, which translates to approximately 800 to 1500 Watts. For the purposes of this design, we assume a 48V, 800W Brushless DC motor.

Components

Solar Cells

We choose Grade A Monocrystalline Solar Cells for their efficiency, and cost effectiveness. One example of a viable option is the MISOL Mono Solar Cell, which are 125mm x 125mm cells with a Voltage Maximum Power Point of 0.523V per cell, and a Current Maximum Power point of 5.215A. By connecting the cells in series and parallel, we can achieve a nominal voltage of 48V.

Based on the $5m^2$ limit, we can use 310 total solar panels, where 3 sets of 103 series solar cells are connected together in parallel.

Based on the efficiency detailed in the Misol Solar Cell spec, we achieve:

$$\frac{2.8W}{125^2 mm^2} * \frac{1000^2 mm^2}{1m^2} = 179.2W/m^2 \tag{1}$$

For our total power across $5m^2$, we obtain:

$$\frac{172.9W}{1m^2} * 5m^2 = 896W \tag{2}$$

This dictates the power rating of the motor we can use, so we choose an 800 W motor.

Filtering

Because the voltage from the solar cell is not necessarily stable, we need to put the necessary filtering and protection circuits between the solar panel and the remaining electronics.

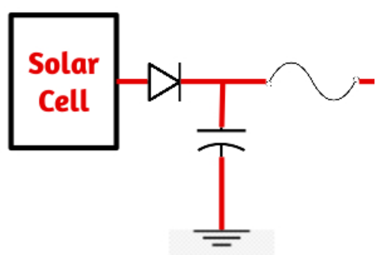


Figure 7: Blocking Diode and Filtering Capacitor

We connect a blocking diode (Figure 7) to the output of the solar cell. We use a diode with a maximum voltage of at least 48V and 15A, such as the FFSH5065A from On Semiconductor. This is followed by a fuse rated for the maximum current of the battery charging circuit (15A). A filtering capacitor is used to smooth the output of the solar panel into the charging circuit. The value of this capacitor is dependent on the amount of ripple in the solar panel output, though a large capacitor roughly 1000 μF should suffice

Charging Circuit and Battery

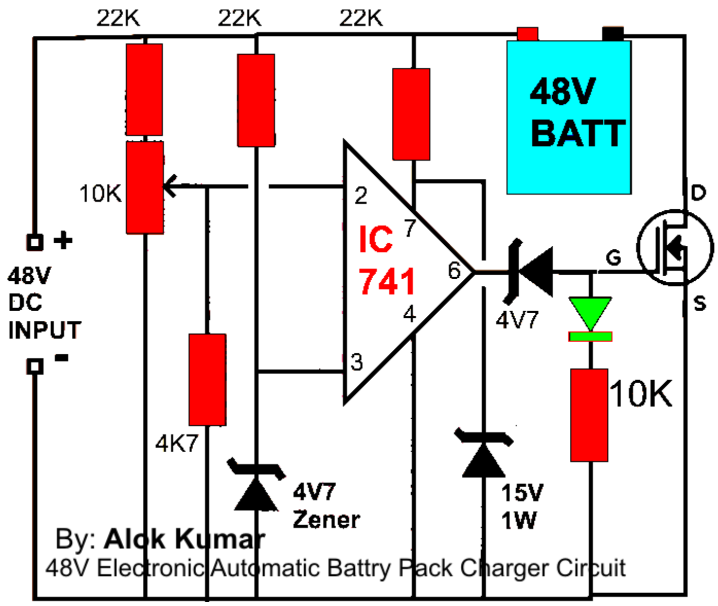


Figure 8: A sample solar charging battery circuit.

Next is the charging circuit and battery pack. There are many charging circuits available in public domain; for example, the one presented in Figure 8. This circuit uses an operational amplifier as a comparator, and when the battery voltage exceeds 48 V then the op amp switches off. The specific turn off voltage can be controlled for different power cells. This circuit should operate without problem, but due to the unstable nature of solar power, additional filtering would be needed.

In addition, due to manufacturing variations in 18650 cells, not every cell contains the same energy (while the cells are rated for 3200 mAh, they often contain a variation of that amount). To counter this inaccuracy, we use a Battery Management System, which controls the charge to different cells differently.

To achieve the necessary 48 volts, we use a 14S (14 Series pack) configuration, with 7 cells per pack. With roughly 3.7 volts per cell, 14 in series would return roughly 51.8 V, which when not fully charged will provide the necessary 48 volts for the motor. The slight excess is generally within the tolerable range of motors, is likely also dissipated over the wiring of the vehicle.

Electronic Speed Control and Motor

As stated previously, the Brushless DC (BLDC) Motor is rated for 48V and 800W, which roughly equates to 1 horsepower, and is characteristic of solar cars, scooters, trikes and other vehicles of this class.

An Electronic speed control (ESC) is necessary to generate 3-phase AC to drive the BLDC motor. The ESC allows for precise speed manipulation through any on-vehicle electronics.

Electronics and Telemetry

While not immediately part of the power delivery and energy storage part of the vehicle, electronics are necessary to operate the ESC for precise speed control. In addition, the electronics can be connected to varying sensors that can provide feedback regarding the vehicle's performance, that can be transmitted to radios on the vehicle.

The aforementioned radios make up the telemetry portion of the vehicle, as they provide the team with metrics like battery health (from the BMS) or motor temperature.

To power these electronics, the 48V line must be stepped down to 5V, the operating voltage of most microcontrollers. While we could do this using a linear regulator, that would be a waste of electricity, a commodity that should be conserved on a solar vehicle. We instead do this using a buck converter, which may have a schematic similar to the one in Figure 9. This type of circuit much more efficiently steps down the DC 48V to DC 5V.

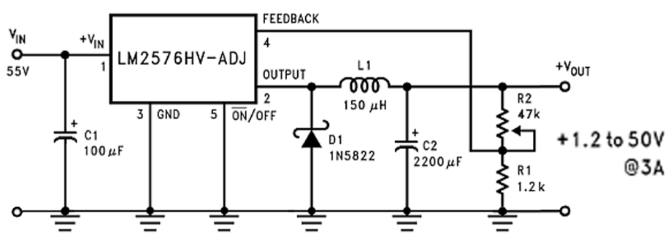


Figure 9: A sample Buck Converter.

Cost

The following cost estimates are rough calculations based on available market prices. Cheaper options likely exist if we purchase directly through supplier.

Component	**Cost**
Solar Cells	\$600
Filtering Electronics	∼\$50
Battery Management System	\$35
100x 3200 mAh 18650 Battery	\$225
48 V 800 W BLDC Motor	\$100
Electronics, Sensors, Telemetry	∼\$300

Price Links

https://vruzend.com/product/52v-14s-battery-management-system-bms/

https://www.amazon.com/MISOL-Solar-GRADE-monocrystalline-module/dp/B00MCKJ8LI?th=1

https://www.electricscooterparts.com/motors48volt.html

https://www.ebay.com/itm/100x-Panasonic-NCR18650BD-10A-3200mAh-LITHIUM-ION-Rechargeable-Battery-Cell
333135785516?epid=22031089654&hash=item4d9070ae2c:g:2IEAAOSws7Fcu~st#viTabs_0

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