Understanding the Solar Panel Properties and Manufacturing: An Insight to the Technology

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In order to combat climate change, the world has been making an effort to move away from polluting sources of energy, mainly fossil fuels. One of the most prominent alternatives is solar energy, which, in the US, contributes to about 3% of the energy grid. This article covers the many different types of solar panels, from those in industry use to those in lab development and testing. Split into four generations of four different time periods, this paper will cover the four generations of solar cell technologies. Although solar cell technologies widely vary, all the technologies have the same basic properties to be taken into consideration when used. The article describes common properties of solar panels, such as efficiency, which are then discussed for each type of solar panel along with each type of solar panel's manufacturing process. Finally, it identifies the most important properties of a solar panel to take into consideration when using or analyzing one.

Introduction

The universe, as we know it today, would not exist if not for energy. Energy is the measurement of matter's ability to do work, and work is the magnitude of force times the magnitude of displacement[1]. Or in other words, energy is what causes matter to move. Typically, the more movement in a system, the more energy in the system. Energy exists in two forms - potential energy ("stored energy") and kinetic energy ("moving energy"). These two forms of energy manifest in many ways. Common examples are thermal energy, light energy, electrical energy, and nuclear energy[1]. Humans use energy to generate electricity, allowing for lighting, heating, air-conditioning, transportation, electronics and more.

One of the most common ways humans harvest energy is through fossil fuels. They are created by plant remains which have been deposited into Earth's crust over millions of years under a buildup of sedimentation and are eventually fossilized. These fossils contain high amounts of carbon and hydrogen, which are then burned for energy. We burn fossil fuels to power buildings and transportation, and fossil fuels are also used in plastics and raw materials. However, since we burn such a high amount of fossil fuels, large amounts of carbon and hydrogen from the fossils have been released as CO2 in the atmosphere[2].

CO2 is a greenhouse gas, and it absorbs heat from the Earth's surface and re-releases it. The more CO2 in the atmosphere, the more thermal energy that is re-released towards Earth, contributing to our planet to heat up and climate change to occur[3]. And as humans, climate change has affected our infrastructure, health, agriculture, forestry, ecosystems, transportation networks, and air and water quality[4].

As of 2021, about 25% of the US's greenhouse gas emissions were created for the electric power industry. Of that, 24.3% directly came from fossil fuel combustions. That year, the US emitted the equivalent of 1540.9 million metric tons of CO2 from fossil fuel combustion for the electric power industry[5]. Thus, the need for an alternative to fossil fuels arises. One alternative is renewable energy, or energy that is harvested from natural sources that do not diminish in quantity or quality[6].

Some examples of renewable energy are - wind energy, hydropower, and solar energy which utilize wind, water and sunlight respectively. It is also critical for renewable energy to be implemented in a manner that meets the UN climate goals and targets regarding affordable, reliable, sustainable and modern energy for all[7]. Else, the purpose of renewable energy helping us sustain our planet is diminished.

This paper will narrow its focus to one form of renewable energy - solar energy. Solar radiation is harvested by specially designed panels that then convert the energy into electricity. In 2022, solar energy accounted for 4.5% of electricity production globally[8]. Solar energy is the fastest growing renewable source.

Solar panels do not use fossil fuel combustion to create electricity. Although there is undoubtedly pollution created from the manufacturing and disposal of solar panels, the fact remains that it creates much less pollution than the continuous burning of greenhouse gases for electricity. Today, solar panel research is mainly focused on producing greater amounts of electricity with cheaper, more environmentally friendly materials.

Physics of Photovoltaic Cells

Solar panels are built with specific materials called semiconductors so that they can utilize the photovoltaic effect, discovered in 1839 by Alexandre Edmond Becquerel, to harvest electricity[9]. All materials fall under the classification of a semiconductor, an insulator, or a conductor. Solar cell technology, and electronics in general, require semiconductors because they allow for better control over the flow of electrons. To better understand semiconductors, it's helpful to contrast them against insulators and conductors.

Semiconductors, insulators and conductors differ based on their electrical conductivity. Electrical conductivity refers to the ability of a material to conduct electricity[10] or the flow of electrons. It depends on the energy levels of the electrons within the atoms that make up the material. In an atom, electrons can only exist at discrete intervals around its nucleus, called energy levels. Between the energy bands are band gaps, where electrons cannot exist. The amount of energy it takes to cross from one band to another determines if a material is a semiconductor, an insulator or a conductor. When classifying materials, the two bands of interest are the valence band and the conduction band.

In conductors, the valence and conduction bands overlap such that electrons are free to move under an electric field, thus conducting electricity. In insulators, the valence band is filled, and the gap between the valence band and the conduction band is large. The energy needed for an electron to cross the band gap from the valence band to the conduction band is more than the amount of energy a photon can provide and more than the amount of energy an electric field can provide, thus electrons never enter the conduction band. Since the electrons are unable to access the conduction band and create net motion, insulators cannot conduct electricity. In semiconductors, the valence band is full at room temperature. The valence and conduction bands are closer together than they are in insulators and as such, external energy can excite an electron in the valence band to cross the band gap into the conduction band, leaving the electron free to move under an external electric field. The absence of an electron in the valence band of a semiconductor is called a hole and it acts as a positive charge carrier[11].

A photovoltaic cell [a solar cell] is typically made of two types of semiconductors. One layer is a n-type semiconductor, or a semiconductor specifically designed to have extra valence electrons and the other layer is a p-type semiconductor, or a semiconductor specifically designed to have fewer valence electrons. Where the n-type and p-type semiconductors meet, an electron field called a pn-junction forms. When a photon hits an electron in a semiconductor with the right amount of energy, the electron crosses the band gap between the valence band and the conduction band[12].

The pn-junction can bias the flow of electrons and holes so that electricity can be harvested[12]. The pn-junction itself has three layers, a neutral N-layer, a neutral P-layer, and sandwiched in-between is the depletion layer. The depletion layer is depleted of electrons and holes, and it prevents the diffusion of electrons and holes. Typically, the p-type material as a greater charge than the n-type material, causing an electric field. From this electrical field, electrons are accelerated to the n-layer and holes to the p-layer. The electric field also creates a built-in potential (electric potential) which is what moves the electrons and is about 0.9V for silicon pn-junctions[13].

Properties

Solar panels contain many properties which are often tailored towards their intended purpose, e.g., rigidity and transparency. However, ideal solar panels contain certain properties that allow for the most gain with the least amount of harm.

The efficiency, or conversion efficiency, of a solar cell is measured as the percentage of the solar energy shining on a solar cell that is converted into usable electricity. It is determined by measuring the current and voltage produced for different load resistances of a solar cell that's exposed to a standard level of light and maintained at a constant temperature. It is affected by the wavelength of light that's hitting the solar panel, whether the light is absorbed, reflected, passed through, or separates the electron-hole pair. Efficiency is also affected by the temperature of the solar panel, as high temperatures can cause semiconductor properties to shift and the physical panel to become damaged. Additionally, the rate of recombination of the electron-hole pair impacts the efficiency[15].

The photovoltaic effect involves an electron jumping from the valence band to the conduction band when exposed to the right amount of energy from a light photon[16]. The minimum amount of energy required from the photon to cause an electron to cover the distance from the valence band to the conduction band is called the band gap. The energy to excite the photon comes from light, the smaller the wavelength of a beam of light, the more energy that beam of light has. The band gap is measured in electron volts (eV). If the beam of light shining on a solar cell doesn't have enough energy to clear the bandgap, the light is often reflected. If the beam of light has a greater amount of energy than what is necessary to clear than the band gap, then the energy gets absorbed as thermal heat and the photon's energy is not converted to electricity. For solar cells, the bandgap should be between 1.1 and 1.7 eV[17].

Solar cells degrade over time and have a life cycle. Solar panels in industry typically have a life cycle of 25 years. Once solar panels reach the end of their life cycle, they become hazardous waste. By 2030, the US is estimated to have up to one million tons of solar panel waste. Ideally solar panels should have the longest possible life span, after which they should be disposed of properly[18]. When not handled accordingly, hazardous waste may cause negative health effects on the surrounding environ-

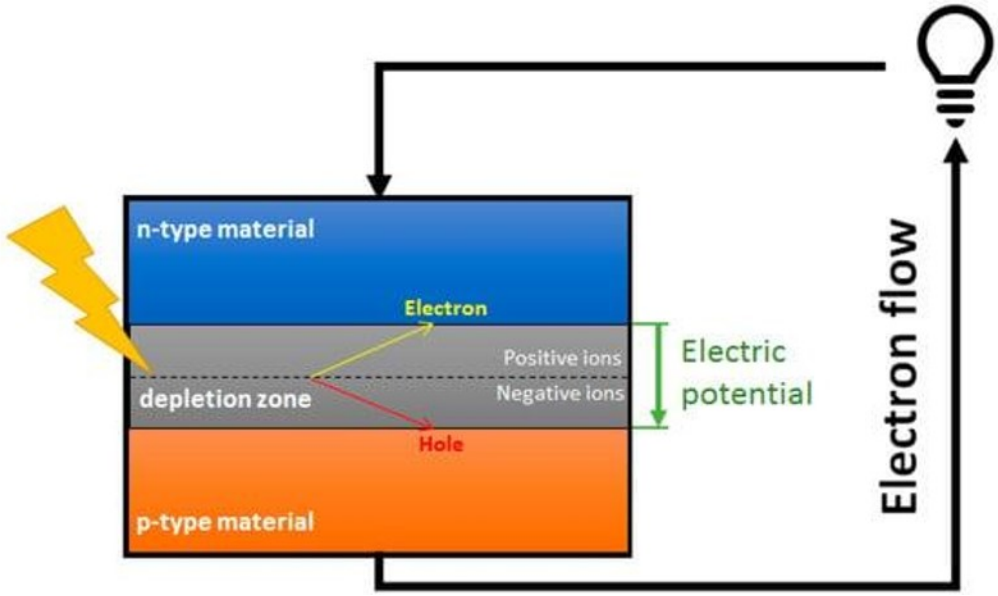

Fig. 1 Schematic representation of a photovoltaic cell, showing the n-type and p-type layers[14].

ment and population. Relationships have been drawn between hazardous waste and certain types of cancers, asthma, and adverse birth outcomes due to pollutants such as heavy metals and dioxins contaminating the surrounding area. To properly dispose of hazardous waste, it should be brought to proper disposal facilities[19].

Often, solar cells work best at lower temperatures because higher temperatures cause semiconductor properties to shift. High temperatures can lead to a slight increase of current and a huge decrease in voltage, negatively affecting the efficiency of a solar cell12. Different solar cells have different abilities to resist temperature influence. For example, OPVC's have a high thermal stability whereas PVSCs have a low thermal stability and are affected heavily by temperature[14].

The amount of tolerance to radiation that a solar panel has affects its life cycle and efficiency over time. "Radiation tolerance is determined as an ability of crystalline materials to withstand the accumulation of the radiation induced disorder"[20] or in other words, the amount of resistance a material has to radiation. Irradiation is the measure of radiation received on the surface of a material. In crystalline semiconductors, irradiation causes lattice defects or a displacement of atoms in the material, often resulting in changes of the bandgap. It also affects the minority carrier lifetime (how fast the electron-hole pairs recombine)[21]. In amorphous materials (non-crystalline structures), irradiation causes empty regions of atoms and over/under coordinated atoms[22].

Currently, many solar panels contain toxic materials in either the actual semiconductor in the solar panel or an additional coating added to the solar panel. Hard metals like lead and cadmium may be present at concentrations high enough to leach into the environment, classifying solar panels as hazardous waste[18]. In addition, toxic semiconductors such as gallium arsenide are often used in solar panels. When exposed to humans, gallium arsenide causes toxicity to various organs such as the lungs, kidney, and brain[23].

Types of solar panels

There are many types of solar panels, different solar panels have been in development for different amounts of time. The different stages of solar panel technologies are classified into generations.

Generations

- **The First Generation (1GEN)** includes solar cells made from thick crystalline films of monocrystalline (m-si), polycrystalline (p-si) and gallium arsenide (GaAs) technologies. These are the oldest and most common solar panels[14], and tend to be more expensive.

- **The Second Generation (2GEN)** includes technologies made from thin films of Amorphous silicon (a-Si), Microcrystalline silicon (μc-Si), Copper indium gallium selenide (CIGS) and Cadmium Telluride (CdTe). They were developed with an aim of reducing the high cost that 1GEN solar panels required[14], but are still fairly expensive.

- **The Third Generation (3GEN)** includes organic photovoltaic solar cells (OPVC), dyed-sensitized solar cells

(DSSC), active quantum dots (QD), Perovskite solar cells (PVSC), and Multi-Junction solar cells. These are newer technologies based on different compounds. Multi-Junction (MJ) solar cells involve stacking layers of inorganics[14].

- **Fourth Generation (4GEN)** technologies are in the various stages of research and haven't reached the mass production stage[17]. They utilize nano-technologies such as combining thin films with nanomaterials like carbon nanotubes, graphene, and metal oxides[14].

First Generation:

- **Monocrystalline Solar Cells (1GEN)** (m-Si) have efficiencies from 15-24.4%, a bandgap of 1.1 eV, and a lifespan of 25 years[17]. m-Si solar cells are manufactured using the Czochralski process[14], where a seed crystal is attached to a vertical arm. The vertical arm is then dipped, held and rotated over the material's melt to form the crystal around the seed[24]. The temperature must be precisely controlled during the long production times of crystal growth, and there is great energy consumption through heat loss. Once the crystal is grown, it is cut to produce m-Si wafers. However, m-Si wafers use extremely high purity silicon[14] which must be refined. m-Si solar cells have a high manufacturing cost, partially caused by the silicon waste from cutting the crystals. Beyond that, they are sensitive to temperature[17]. Because m-Si solar cells are made of silicon, they are non-toxic and made of a stable material[17]. Being 1GEN solar cells, m-Si cells have been in the industry for decades.

- Polycrystalline solar cells (1GEN) (p-Si) have efficiencies from 10-18%, a bandgap of 1.7 eV and a life span of 14 years[17]. The p-Si wafers are manufactured using the Siemens process[14], in which silicon is deposited from a mix of either silane or trichlorosilane (TCS) gas with excess hydrogen gas on high purity silicon fragments in a reaction chamber. The silicon fragments are heated up, and a reaction between the TCS and hydrogen gas deposits elemental silicon onto the filaments, making the polycrystalline silicon. During the deposition process, the temperature of the gases and filaments, as well as the deposition rate, must be carefully controlled[25]. However, the material is made of randomly oriented silicon crystals, creating impurities. In comparison to m-Si solar cells, p-Si solar cells have a much simpler manufacturing process, but the low material quality causes a lower voltage and current[14]. Beyond that, p-Si cells also have a higher temperature sensitivity. The cells are made of silicon, and so they are non-toxic and stable.

- Gallium Arsenide solar cells (1GEN) (GaAs) have efficiencies from 18.4-28.8%[14], a band gap of 1.43 eV and a life span of 18 years[17]. GaAs cells are manufactured in four steps. Growth of the material, wafer processing, epitaxy and manufacturing of device. A mixture of Ga, As and the dopant material reacts under a high temperature, forming the material. Then the block is cut into wafers, which are then cleaned and polished. Through a process called epitaxy, additional crystalline growth of the same or different compound occurs on the GaAs wafers. After that comes the assembly of the device[17]. GaAs solar cells are extremely expensive, more so than m-Si solar cells. The material is stable and has a low temperature sensitivity[17]. However, as a material, gallium arsenide is toxic to the human body and environment[26].

Second Generation:

- **Amorphous Silicon solar cells (2GEN)** (a-Si) have efficiencies from 5-12%, a band gap of 1.7 eV and a lifespan of 15 years[17]. a-Si solar cells are manufactured using plasma-enhanced vapor deposition (PECVD) to form silicon thin films. The substrate upon which the material is deposited can be flexible and inexpensive, like stainless steel or plastics. The process is the roll-to-roll method, but the evaporation process is slow, and the conductive glass layer required is costly so overall the manufacturing price is only slightly less than a crystalline solar cell[27]. Because amorphous silicon contains no crystals, it can only be doped with specific materials (usually hydrogen)[14]. Overall, a-Si cells are less expensive and more available in large quantities. Since it's made of silicon, it's also non-toxic and stable[17] a-Si solar cells have a low temperature sensitivity[28].

- **Copper Indium Gallium Selenide solar cells (2GEN)** (CIGS) have an efficiency of 20%, a band gap ranging from 1.1-1.7 eV and a lifespan of 12 years[14,17]. CIGS cells are manufactured with a substrate (a metal, ceramic or polymer sheet) that's covered by a back contact, typically pulverized molybdenum. The CIGS layer (p-type) is grown onto the substrate using co-evaporation where the CIGS is evaporated and then condensed onto the substrate. A buffer layer (n-type) is then deposited. Finally, an anti-reflective coating is applied to the cell. The co-evaporation process requires a great deal of energy[14] and although it's a thin film and less material is required; CIGS solar cells are expensive. Beyond that, CIGS solar cells aren't stable, are temperature sensitive and unreliable[17]. CIGS solar cells are toxic as the metals leaching from damaged cells pose environmental threats[29].

- **Cadmium Telluride solar cells (2GEN)** (CdTe) have efficiencies from 15-16%, a band gap of 1.45 eV and a lifespan of 20 years[17]. CdTe solar cells are manufactured through a multiple deposition process where CdS vapor is deposited onto a transparent conductive oxide film supported on a heat-treated glass. Then, a CdTe layer is deposited onto the CdS layer. Then the insulation and rear contact is added, the cell is encapsulated, wires are attached, and the tempered rear glass is placed. The deposition process takes less than 2.5 hours. CdTe solar cells are less temperature sensitive than crystalline silicon cells[14] but still are highly sensitive to temperature. CdTe cells are less expensive, but highly toxic due to cadmium being a toxic metal. In addition, Te is a limited material[17].

Third Generation:

- **Dye-Sensitized solar cells (3GEN)** (DSSC) have efficiencies from 5-20%[17], and they work differently than traditional solar cells. The sensitizing dye is excited when exposed to sunlight, and an electron moves to the conduction band of the film. The dye helps direct the electrons to the anode and is then reused in the external charge before once again becoming part of the cathode. DSSC are produced with the roll-to-roll method and have five different layers. A transparent anode treated with a transparent TCO layer upon which a layer of mesoporous oxide is deposited. After, a monolayer of dye is bonded to the surface of the mesoporous oxide. Then, there's a layer of electrolyte containing a redox mediator and a cathode layer made with a crystal coated catalyst. DSSC aren't expensive and work well in low light, however they are highly temperature sensitive and most contain highly toxic materials[14].

- **Organic photovoltaic solar cells (3GEN)** (OPVCs) have efficiencies of 9-11%[17]. They generate electricity with an electron donor material and an electron acceptor material. The donor material absorbs photons and creates and confines excited electron/hole pairs which are then separated using electric fields. The acceptor material acquires the electrons. The bandgap of an OPVC is defined as the distance between the highest occupied energy level of the donor material and the highest energy level that is empty of the acceptor material. OPVCs are classified into two groups: polymer solar cells (PVCs) and small molecule solar cells. PVCs are manufactured of an indium tin oxide conductive glass covered by a polymeric hole transporting layer, an active layer, an electron transport layer and a low work function metal electrode[14]. OPVCs are low cost, have low temperature sensitivity[17] and can be toxic.

- **Quantum Dot Solar cells (3GEN)** (QD) have efficiencies of 11-17%[17] and contain nano-scale semiconductor materials. The bandgap of QDs is so small that they are considered as continuous bands[14]. QD cells are fabricated by epitaxial growth on a substrate crystal[17] however there is little experience in the overall development and manufacturing of QDs[14]. Although QDs have a low production cost and low energy consumption, they are highly toxic[17]. Quantum dots also require a stable polymer shell, but the shells affect optical properties and degrade[14].

- **Perovskite Solar cells (3GEN)** (PVSC) have efficiencies of 21.1-21.6% and their bandgaps are tunable by altering the material of the film. They are manufactured through printing and sputtering techniques that are cheap and simple. However, PVCS have high instability issues due to the solubility of the absorber material and tend to be temperature sensitive[14].

- **Multi-Junction Solar cells (3GEN)** (MJ) have efficiencies of 35.8% and higher[17] and are made of multiple different p-n junctions of multiple types of semiconductors stacked to catch different wavelengths of light. Therefore, there is no one bandgap. MJ cells typically include a transparent electrode, a recombination layer, a cell with a lower bandgap than the previous one and a back contact. The more junctions there are, the higher the efficiency[14]. However, MJ solar cells are complex and extremely expensive.

Fourth Generation

- **Graphene-Based Solar Cells (4GEN)** integrate graphene with other existing solar cell technologies, such as perovskite solar cells, quantum dot solar cells, and organic photovoltaic solar cells. Therefore, they don't have fixed band gaps. Graphene has a high sensitivity to light and is both highly transparent and a fantastic conductor (however those properties change with the thickness of the graphene film). It also has a high mechanical strength and flexibility. Thin films of graphene are deposited onto the solar cell either by electrochemical exfoliation, chemical vapor deposition, or epitaxial growth. Issues with graphene arise in the lack of a simple, reliable method of deposition and the adhesion of the graphene thin film. Beyond that, graphene-based solar cells cannot be handled in solutions due to graphene's poor hydrophilicity[17].

Important Properties

The properties of solar panels are often intertwined. The five properties listed are properties that should be taken into heavy consideration when looking at solar panels.

- **Efficiency:** The higher the efficiency, the more electricity that solar panel can produce at a particular size. The band

Table 1 Comparison of Different Types of Solar Cells

Solar Cell	Abbr.	Efficiency	Band gap (eV)	Toxicity	Price of manufacturing	Life Cycle (yrs)	Temperature Stability
Monocrystalline Solar Cells (1GEN)	m-Si	15-24.4%	1.1 eV	Non-toxic	High	25 years	Low
Polycrystalline Solar Cells (1GEN)	p-Si	10-18%	1.7 eV	Non-toxic	High	14 years	Low
Gallium Arsenide Solar Cells (1GEN)	GaAs	18.4-28.8%	1.43 eV	Toxic	High	18 years	High
Amorphous Silicon Solar Cells (2GEN)	a-Si	5-12%	1.7 eV	Non-toxic	Low	15 years	High
Copper Indium Gallium Selenide Solar Cells (2GEN)	CIGS	20%	1.1-1.7 eV	Toxic	High	12 years	Low
Cadmium Telluride Solar Cells (2GEN)	CdTe	15-16%	1.45 eV	Toxic	Low	20 years	Low
Dye-Sensitized Solar Cells (3GEN)	DSSC	5-20%	N/A	Varies	Low	N/A	High
Organic Photovoltaic Solar Cells (3GEN)	OPVC	9-11%	Varies	Varies	Low	N/A	Low
Perovskite Solar Cells (3GEN)	PVSC	21.1-21.6%	Varies	Toxic	Low	N/A	High
Multi-Junction Solar Cells (3GEN)	MJ	>35.8%	N/A	Toxic	High	N/A	N/A
Quantum Dot Solar Cells (3GEN)	QD	11-17%	N/A	Toxic	Low	N/A	High

gap, temperature stability, and radiation tolerance are all properties that affect the efficiency of a solar cell. Since the purpose of a solar panel is to produce electricity from solar energy, and efficiency is a measure of the amount of usable electricity produced, efficiency is one of the most important properties to consider in solar panels [13,21].

- **Toxicity:** Solar panels are a form of green energy and help harvest electricity without further polluting the environment. However, solar panels also have a lifespan, and at the end of that lifespan the solar panels must be disposed of [18]. It is contradictory for solar panels to contain toxic materials that could leach into the environment when the panel is in use, gets damaged or at disposal when they are supposed to be an alternative, clean form of energy.

- **Price of Manufacturing:** Typically, the higher the cost of manufacturing, the more complicated the process of manufacturing the solar panel is. The process of manufacturing solar panels can involve toxic chemicals, massive amounts of water and lots of energy [17]. Once again, solar panels are meant to help the environment, not hurt it. Furthermore, a more expensive solar panel results in customers having to pay more money.

- **Material availability:** The materials that solar panels use, semiconductors, glass and metals, must be mined or made. The less abundant the material, the more energy is put into obtaining the material. This causes the material price to increase, and therefore the overall price of the solar panel also increases [17]. If it's a synthetic material, manufacturers must figure out a way to make that line as efficient as possible. There may also be some ethical issues with mining certain materials used in solar panels.

- **Life cycle:** The life cycle of a solar panel is more of an overarching property, where many other properties affect it. Temperature instability can cause a solar panel to suffer not only efficiency issues, but actual physical damage that then causes the solar panel to be fixed or replaced. Physical damage can also expose the surrounding environment to the toxic materials used in the solar panel. Irradiation damage can lower the efficiency of a solar panel. If the efficiency of a solar panel drops, and the amount of electricity it is producing is insufficient, then the solar panel will get replaced and the ruined solar panel will be disposed of. It's important to create a long-lasting solar panel because then there will be less solar panel waste to dispose of [13,19].

However, these properties are secondary to fulfilling the original requirements necessary to complete the task of the solar panels. For example, take solar panels in building windows. It doesn't make sense to choose the solar panel of the highest efficiency in industry, because those solar panels aren't transparent. However, it is important to consider the efficiency as much as possible when deciding between different types of transparent solar panels for the windows.

Conclusion

Solar panels are not one size fits all. Depending on the purpose of the solar panel (e.g., solar farm, building windows, mobile home roof), they are designed for specific properties such as transparency or high efficacy. Today, innovation in this area is focused mainly upon 3GEN and 4GEN solar cell technologies. Apart from multi-junction solar panels, 3GEN technologies haven't broken into the industry well. 4GEN solar cell technologies are in various stages of research, and likely won't enter the industry for years. In contrast, 1GEN and 2GEN solar cell technologies are well established and used in the current industry, whether that's on solar farms or tiny houses.

The performance of solar panels depends on more than just its design. External factors such as the time of day, the angle of the sun, the current weather patterns, and the location and altitude at which the solar panels are placed prevent solar panels from functioning at full efficiency. And yet, solar panels generate a huge portion of electricity on the electrical grids. Solar energy is currently the fastest growing form of renewable energy and solar cell technology has the potential to be everywhere. With time, solar energy will only become more accessible.

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