Solar cell and the challenges of future energy

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Abstract: In this paper solar cell and future challenges of energy is discussed. This paper has compiled the data from different sources and suggested the future perspectives. All non-renewable energy sources are going to be end by the time. Need of energy is increasing day by day. In this paper it is suggested how and by which technology we can reduce the coming Challenges.

Key words: Solar cell; Energy resources; Efficiency; photoelectric effect.

Introduction*: A brief history[12] :* Alexandre Edmond Becquerel invented the world's first photovoltaic cell[5] and thereby discovered the photovoltaic effect. He carried out an experiment in 1839, he placed two platinum electrodes in a container with silver chloride in an acidic solution. When illuminated voltage and current were produced over the electrodes and it was also noticed that the strength of the current changed with intensity. Hence photovoltaic effect is also known as the "Becquerel effect".

The photovoltaic development arose from the interest in the photoconductive effect in selenium after Willoughby Smith found that selenium shows photoconductivity in 1873. In 1877 William Grylls Adams and Richard Evans Day observed the photovoltaic effect in solidified selenium by illuminating a junction between selenium and platinum. It was the first demonstration of the photovoltaic effect in an all solid-state system, observing that electricity could be generated from light without moving parts. In 1884 the first rooftop solar array was installed in New York, having an efficiency of almost 1%. The solar array used selenium solar cells invented the year before by an American inventor Charles Fritts, showed that meaningful power might be extracted from the solar cells. It impressed Werner von Siemens who gave a statement that "The direct conversion of light into electricity has been shown for the first time". In initial stage of solar cell history optimism gripped the inventors. Fritts optimistically predicted that "we may ere long see the photoelectric plate competing with [coal-fired electrical-generating plants]". The first fossil-fueled power plants had been built three years before Fritts announced his intentions by Thomas Edison. At that time the technology seemed poised to gain importance in discovering the wonders of electricity. J. C. Maxwell praised the study of photo-electricity as "a very valuable contribution to science." But neither Maxwell nor Siemens had any idea as to how the phenomenon of photoelectricity will work. Maxwell wondered, "Is the radiation the immediate cause or does it act by producing some change in the chemical state?" Siemens urged "thorough investigation to determine upon what the electromotive light-action of selenium depends."

The physical understanding of the phenomenon was improved with contributions from the likes of Heinrich Hertz who investigated ultraviolet light photoconductivity and discovered the photoelectric effect. In 1905 Albert Einstein publishes a paper explaining the photoelectric effect[3] on a quantum basis later he got a Nobel Prize in Physics for this.

Bruno Lange, a German scientist whose 1931 solar panel resembled Fritts's design, predicted that, "in the not distant future, huge plants will employ thousands of these plates to transform sunlight into electric power that can compete with hydroelectric and steam-driven generators in running factories and lighting homes." But Lange's solar cell performance was not better than Fritts's. The progress towards practical solar was very slow.

Evolution of the modern solar cell :

The invention of the modern solar cell happened along with silicon transistor. Two famous scientists of Bell Laboratories, Calvin Fuller and Gerald Pearson, led the leading effort that made the silicon transistor from theory to working device. They made silicon containing a small concentration of gallium making the silicon p-doped. When a rod of the material was dipped into a hot lithium bath the portion of the silicon immersed in the lithium became n-doped. As the positively and negatively doped silicon met, a permanent electrical field developed. This is known as p-n junction, the basics of the transistor and solar cell, where all electronic activity occurs.

Working with several working models to improve the initial results Chapin optimized the silicon solar cells and got a solar cell with 6% efficiency. The resulting product, the Bell Solar Battery was announced to the press on April 25, 1954.

In the history of Bell Laboratories, few inventions excited the contemporary media and draw the attention of the unveiling of the silicon solar cell. In 1954 U.S. News speculated, "The silicon strips may provide more power than all the world's coal, oil, and uranium etc. The future is limitless." While this statement may be true in theoretically, commercially success of solar cells disappointed, despite technological breakthroughs. The high price tag limited solar cells. As the world was entering in the age of the space race, the application of the solar technology would reveal itself. The launch of Sputnik the world's first satellite occurred in 1957 and the launch of Vanguard 1 in 1958 observed the first use of solar cells on a satellite.

The Bell labs[13] invented the silicon solar cell in 1951. To improve the efficiency and fragility, alongwith Bell Labs, several other manufactures joined the development race. Leslie Hoffman got remarkable achievement in making the solar cell a practical and useful source of renewable energy. From 1957 to 1960, he improved its efficiency from 4.5 to 14 percent and lowered the production cost which made it a marketable item.

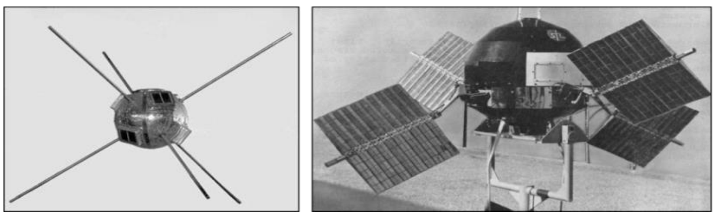

Figure . From the left Vanguard 1, Explorer 6, Telstar, and Skylab. Source: Wikipedia

In the early 1990s the technology used for space solar cells[9] began to diverge from the silicon technology to gallium arsenide based technology. Silicon Technology at that point had become prevalent for terrestrial applications. Introduction of gallium arsenide (GaAs) single-crystalline solar cells enable thin film solar cells and multi-junction solar cells, both were having lower weight and higher efficiency compared to silicon solar cells. The first GaAs heterostructure solar cells were invented by a team led by Zhores Alferov in the USSR in 1970. In the early 1980s, the efficiency of the best GaAs solar cells crossed over the efficiency of conventional crystalline silicon-based solar cells. GaAs-based devices achieved the highest-efficiency single-junction solar cell at 28.8%. Currently the most efficient solar cells in production are multi-junction photovoltaic cells. To capture more energy from the solar spectrum, these photovoltaic cells use a combination of several layers of gallium arsenide, indium gallium phosphide, and germanium. Leading edge multi-junction cells are capable of achieving efficiency nearly 38.8% under non-concentrated AM1.5G illumination and nearly 46% using concentrated AM1.5G illumination. The rovers Spirit and Opportunity, which are exploring the surface of Mars, are using these efficient triple junction solar cells.

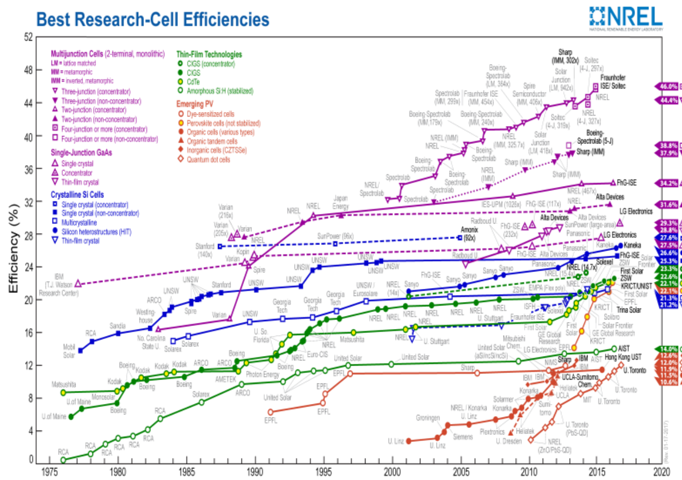

Figure: Reported timeline of solar cell energy conversion efficiencies since 1976 compiled by the National Renewable Energy Laboratory. Source: Wikipedia.

Available Energy sources:

Energy is a resource on which humanity dependent. Without energy, our society will stop functioning. In absence of energy, we will not able to find medicine to cure disease, prepare food, purify water, drive our cars, operate computers, study at night, room heaters, air-conditions, fans and so on. Our current energy need is roughly 15 TW (15x1012 W) and this number is going to increase in future. Historically fossil fuel (coal, petroleum, and natural gas) have enabled our energy consumption for the past century, and continues to dominate our energy production. Presently roughly 81% of our energy is supplied by fossil fuel, 2.7% is being supplied by nuclear energy, and the remaining share is renewable sources, with biomass has the largest source of energy at roughly 12%. The break-down of our energy consumption in figure shown below.

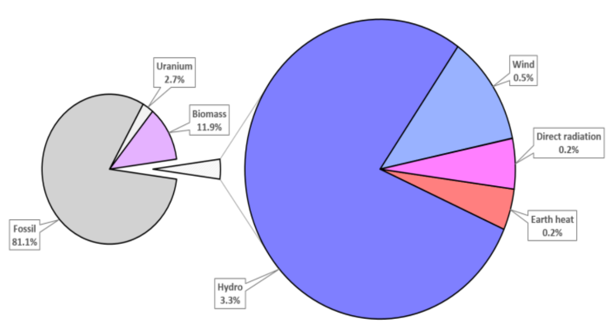

Figure: Current energy mix. The total energy consumption[14] is roughly 15 TW. Source: Wikipedia.

Fossil fuels are continuously being formed via natural processes like anaerobic decomposition of buried dead organisms fueled by photosynthesis. These fuels are generally considered non-renewable resources because fossil fuels take millions of years to form and the known viable reserves are being depleted faster than new ones are being made. Due pollution and high CO_2 level we have to find alternative energy source even if fossil fuels can cover the energy consumption for many years to come. there are many other reasons to look for alternatives. Main drawback of fossil fuels is generation of CO2. At the same time the combustion of fossil fuels also produces other air pollutants, such as nitrogen oxides, sulfur dioxide, volatile organic compounds, and heavy metals. Before we proceed for alternative of fossil fuel we have to look availability of other energy sources. Below we can see the approximate estimates of the available power from each energy process.

- Tide: 0.3 TW
- Earth heat: 2 TW
- Hydro power: 4 TW
- Wind: 75 TW
- Biomass: 6 TW
- Direct radiation: 26,000 TW
- Coal: 900 TWy
- Petroleum: 240 TWy
- Natural gas: 215 TWy
- Uranium: 300 TWy

Here the numbers written against fossil fuel and uranium are in total energy, the remaining numbers are written as resources available per year. These numbers may vary from source to source but the magnitudes of the numbers are reasonably accurate.

Available energy: Let us calculate the direct radiation from the sun reaching to ourselves.The luminosity[11] of the sun to be 3.828·1026 W, and the distance from the sun is one astronomical unit or 1.496·1011 m. Considering the amount of energy lost to due atmospheric scattering and absorption we can assume that 51% will be transmitted through the atmosphere. Here we are considering only count of the landmass, so we consider the water to landmass ratio on Earth is nearly 29%. The total technical potential of direct radiation therefore becomes 26,000 TW, which is a very big number. The available energy is plotted for all renewable energy sources plus fossil and uranium.

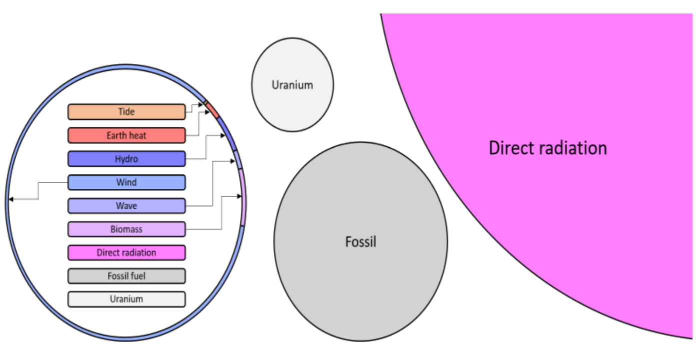

Figure: Diagram of energy sources by available resources. Notice that while all renewable sources are given per year, the fossil and uranium sources are complete available resources. The direct radiation is only partially shown. Source: Wikipedia

Looking at figure we can infer that direct radiation contribution dwarfs all other resources including the total available reserve of fossil fuel. This should, however, not come as a surprise, as direct radiation is the primary energy source behind almost all the energy sources listed. Let us look back and look at the processes and primary energy sources behind the energy sources on which we rely. If we consider the primary energy source behind all the energy technologies we use, they fall under four categories: movement of the planets, earth heat, solar radiation, and supernova. In figure below the flowchart links the primary energy to its concrete uses.

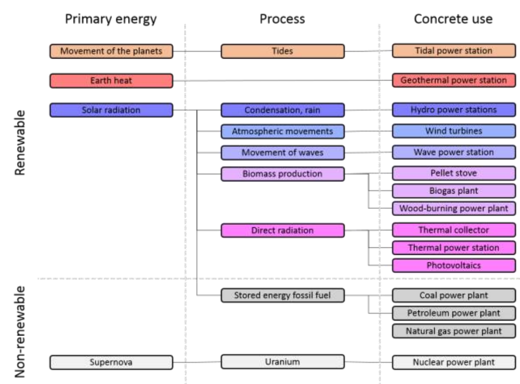

Figure: All energy sources categorized by their primary energy, process, and concrete use.

We know that the original process behind fossil fuel is photosynthesis, a process fueled by the direct radiation from our sun. The same is true for biomass. Condensation and rain, the process behind hydropower is also fueled by sunlight, as is atmospheric movements (wind) and waves. The only primary energy source aside from solar radiation which contributes significantly to our energy mix is uranium. Together with other heavy elements, uranium was formed in the supernova signifying the last stellar evolutionary stages of massive stars. The supply of uranium on Earth is therefore fixed, and uranium must be considered a depletable resource on Earth.

Looking back at the energy mix, it is remarkable that only about 16% of the world consumption is based on renewable energy sources. Wikipedia hosts an interesting list of countries by electricity production from renewable sources. Some countries have an energy mix dominated by renewable sources even going up to 100% of the electricity production. In all cases these high numbers arise because of fortunate geographical conditions making hydropower a dominant solution. The country scoring highest when disregarding hydropower is Denmark with 56.58 percent of its electricity being generated from renewable sources mainly wind, biomass, and solar. These numbers demonstrate that renewable energy sources can generate a much larger share of our energy, however, we must also remember that renewable electricity production, from sources such as wind power and solar power can be criticized for being variable or intermittent, as weather and day/night cycles dictate. In countries, such as Denmark, this problem is solved by importing energy from neighboring countries when production is low. A complete switch to renewable energy will not be easy, and many solutions need to be implemented. The takeaway point from this text is that renewable sources are fully capable of delivering all the energy we can ever need. We need to deploy and develop renewable technology to optimally use the resources available to us and at the same time evolve our electrical grid and energy storage options.

Sunlight at Earth Surface

As we are discussing the solar cells, let us now turn our attention to solar energy. The Sun itself is a massive fusion reactor in which hydrogen atoms is fused into helium. The energy from this fusion reaction is released into Space in the form of radiation. We have already encountered the value for the radiation power of the sun (3.828·1026 W)[10], which we used to calculate the solar constant (1,367 W/m2). The number we calculated is the value as measured outside Earth's atmosphere. In figure one can see the spectrum[6] both inside and outside the atmosphere. We designate the light as measured outside the atmosphere Air Mass 0 (AM0) since this light has not passed through the atmosphere. The irradiance of this light is the already mentioned 1,367 W/m2, the solar constant.

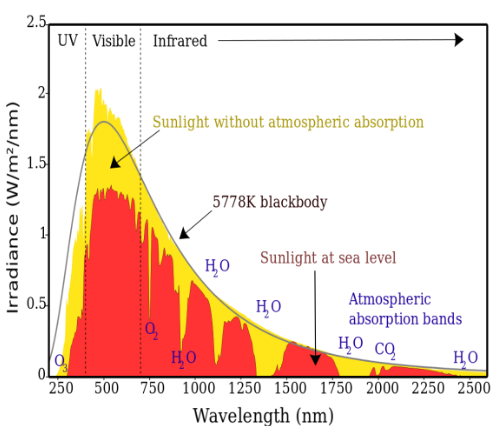

Figure Solar radiation spectrum for direct light at both the top of Earth's atmosphere (yellow area) and at sea level (red area). As light passes through the atmosphere, some is absorbed by gases with specific absorption bands. Source Wikimedia.

The spectrum changes when the sunlight passes through the atmosphere. There are various reasons for this change

- **Reflection of light**: Sunlight is reflected in the atmosphere reducing the radiation reaching the Earth
- **Absorption of light**: Gases (O_2, O_3, H_2O, CO_2……) with specific absorption bands absorb a part of the radiation causing gaps in the spectrum.
- **Rayleigh scattering**: When light falls on particles smaller than the wavelength Rayleigh scattering occurs. As the effect is strongly wavelength dependent, shorter wavelengths are scattered strongly causing the blue color of the sky.
- **Scattering of aerosols and dust particles**: This effect is a Mie scattering event and concerns particles larger than the wavelength. The number of aerosols and dust particles depends greatly on location, being greatest in industrial and densely populated areas.

As the effect of the atmosphere is dependent on the length of the path through the atmosphere it is necessary to designate different spectra according to the path through the atmosphere. Therefore, the use the term Air Mass (AM) followed by a number indicating the distance through the atmosphere. AM0 is the spectrum outside the atmosphere. AM1 is the spectrum after it has traveled the vertical height of the atmosphere. if the sun is at an angle to the Earth's surface the effective thickness will be greater. AM1.5 atmosphere thickness, corresponds to a solar zenith angle of z=48.2° and indicates that the light has travelled 1.5 times the vertical path through the atmosphere. The specific value of 1.5 has been selected in the 1970s for standardization purposes, based on an analysis of solar irradiance data in the United States. Since then, the solar industry has been using AM1.5 for all standardized testing or rating of terrestrial solar cells or modules.

When we sum the energy according to the AM1.5 spectrum form above figure, we find that only 835 W/m^2 is received. Thus only 61% of the originally available 1367 W/m^2 is received at Earth as direct radiation. However, it is important to note that we are now forgetting a large portion of radiation, namely the diffuse radiation caused by the scattering of the light in the atmosphere. To account for this, we use the AM1.5G spectrum, where G stands for global radiation and is a summation of the direct and diffuse radiation. This is the reason we use 1000 W/m^2 as the total irradiance when we determine the peak power of a solar module.

Area need: Let us see how well solar cells would be able to cover our energy needs. Let us therefore calculate the area needed to cover the Earths energy consumption (15 TW) with solar cells at 10% efficiency. Since we know the solar constant to be: 1000 W/m2 . This calculation η is the efficiency, while σ is the solar constant. To calculate a realistic area on Earth needed to cover our energy consumption we need to add some assumptions to consider the day/night cycle, as well as atmospheric conditions. If we assume eight hours of average daylight and that 70% of all days have sunshine, we can calculate a realistic area needed to supply the world with solar power.640,000 km^2 .This is a big area, in fact it is roughly size of France. We assumed 10% efficiency which is well within reach of current technology. If we place all the solar panels in the Sahara desert in Africa with its area of 9,200,000 square kilometers, we can find space for our world energy producing solar park 14 times. Realistically we would need to distribute the solar panels all over the world to produce power matching demand. We will also need to find solutions to store energy when the sun is not shining.

Working[2]: In order to understand how solar cells work it is important to understand the structure and properties of semiconductors. When sunlight shines on the solar cell, photons (light particles) bombard the upper surface[7].

1. The photons carry their energy down through the cell.
2. Upon absorption the photon gives its energy to an electron creating an electron / hole pair.
3. The electron moves across the barrier into the upper n-type layer and escapes out into the circuit.
4. Flowing around the circuit, the electron charges the battery.

Spectral efficiency: A fundamental limit to the efficiency of a solar cell has to do with the bandgap of the semiconductor[8] used. Photons with energy less than the bandgap, does not get absorbed and photons with energy exceeding the bandgap, lose their excess energy through thermalization[4].

This wavelength corresponds to the wavelength of light that is just absorbed. The portion of the solar spectrum above λ_G cannot be used for electrical energy, because the photons have less energy than the bandgap. The portion of the light is thus lost as transmission, see figure 1.

For photons with energy exceeding the bandgap ($\lambda < \lambda G$), the energy is sufficient for absorption. The surplus energy of the photons is, however, given up as the electron relaxes down to the bottom of the conduction band. We call this process thermalization loss. This means that any surplus energy cannot be used for electrical energy. In figure below the visualization of the spectral usage for a silicon solar cell with a bandgap of 1.11 eV is shown.

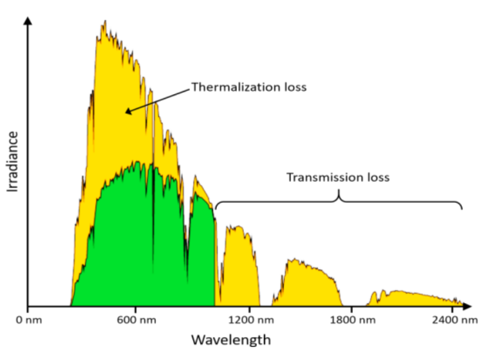

Figure: Spectral losses in a silicon solar cell device with a bandgap of 1.11 eV. All photons with energy lower than the bandgap are lost to transmission, while higher energy photons lose their excess energy to thermalization.

Theoretical efficiency: When we talk about determining the efficiency limit of a solar cell there are two things we have excluded when we calculated the spectral efficiency. Firstly, in a real solar cell it is not possible to use the full voltage,

V_{Max} = EG/q. Secondly, the fill factor cannot be 100% and therefore the maximum power point current and voltage will be lower than ISC and VOC. Both these limitations come from the fact that a real solar cell has a p-n junction. When we include these two limitations it is possible to calculate a theoretical efficiency limit for any given bandgap energy, see figure below. It is important to note that we assume all photons are absorbed and contribute to the photo current. For any real solar cell there will be some reflection losses, recombination losses, etc. However, it is remarkable that the record laboratory efficiency for silicon solar cells today is 26.6%, when we know the theoretical limit is 29.4%.

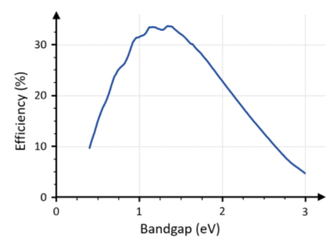

Figure Theoretical efficiency and its dependence on the bandgap energy. The wiggles in the curve are a result of the IR absorption bands in the atmosphere.

Solar modules: Single solar cells are fragile and may not produce enough power for a given application; therefore, solar cells typically are integrated in solar modules. In figure below, a typical example of a solar module is seen. The individual cells are connected electrically in series into a cell string by means of galvanized copper strips. The strings are placed between two sheets of ethyl-vinyl-acetate (ETA). On the front side a glass window is placed and a rear-side foil is placed on the back. This sandwich is heated in a laminator and the EVA material softens and flows around the cells, encapsulating them. The structure is then mounted in an aluminum frame, creating the finished solar module.

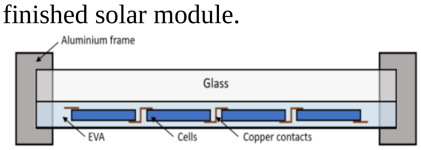

Figure: Structure of a glass-foil module in an aluminum frame.

Thin film solar cells : Thin film solar cells are made by depositing one or more thin layer or thin films of photovoltaic material on a substrate, such as glass, plastic or metal. In contrast to silicon solar cells, thin film solar cells use direct bandgap materials, allowing for thinner absorbing layers. Film thickness varies from a few nanometers to tens of micrometers, much thinner than crystalline silicon solar cells which use wafers with thicknesses of 200 µm. This thinness allows thin film solar cells to be flexible, and lower in weight.

Copper indium gallium selenide (CIGS) is one of three mainstream thin-film PV technologies, the other two being cadmium telluride (CdTe) and amorphous silicon. With all three materials, the absorbing layers are thin enough to be flexible, allowing them to be deposited on flexible substrates. However, all three technologies normally use high-temperature deposition techniques and therefore the best performances come from cells deposited on glass.

The efficiency of thin film solar cells is generally less than conventional solar cells, especially for commercial solutions. The world records for amorphous silicon, cadmium telluride, and CIGS are 14%, 22.1%, and 22.6% respectively. This places both cadmium telluride and CIGS above the experimental efficiencies of multi-crystalline silicon solar cells. The market share of thin film technologies market-share has never reached more than 20% in the last two decades and has been declining in recent years to about 9% of worldwide photovoltaic installations in 2013. Despite the competition from conventional silicon solar cells, the thin film technologies hold many unique promises, allowing solar cells to be produced with much lower energy payback times, and with much lower material consumption.

Solar cell technologies[1] : Throughout this course we have looked into various solar cell technologies. The chart in figure shows the various solar cell technologies with their most important advantages and disadvantages. Peak laboratory efficiency as well as module efficiency is reported table shown below.

	Cell technology	$\eta_{Cell\ Lab}$ (%)	η_{Module} (%)	Important advantages and disadvantages
First generation	Mono crystalline silicon	25.3	20	Very high efficiency Unlimited availability Very high stability Very high energy payback time
	Poly crystalline silicon	21.2	17	High efficiency Unlimited availability Very high stability Reasonable energy payback time
Second generation	Amorphous silicon	14	7	Low energy payback time Low efficiency Poor stability
	Cadmium telluride	22.1	11	Low energy payback time Medium efficiency Scarcity problem
	Copper indium gallium selenide	22.6	15	Low energy payback time High efficiency Scarcity problem
Third generation	Dye sensitized	11.9	-	Low energy payback time Unlimited availability Low efficiency Temperature stability
	III/V semiconductor	37.7	-	Extremely high efficiency Scarcity problem Only sensible in concentrator systems
	Polymer	11.5	6	Extremely fast manufacture time Extremely low energy payback time Unlimited availability Low efficiency Poor stability
	Perovskite	22.1	-	High potential efficiency Unproven stability Uses toxic elements

Figure . Comparison of various solar cell technologies

Conclusion: As discussed above today roughly 81% of our energy is supplied by fossil fuel, 2.7% is being supplied by nuclear energy, and the remaining share is renewable sources, with biomass being the largest source of energy at roughly 12%. The contribution of solar energy is only 0.2%. Maximum commercially used solar cell is mono-crystalline silicon though the lab efficiency of third generation solar cell III/IV semiconductor is highest. To overcome with challenges of energy only solar cell is the solution.

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