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Solar photovoltaics: Silicon cell principles, technology implementation, and future development

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Abstract. Solar energy is one of the most well-known renewable energies in the world, which can be directly used as heating source or can be converted to other sources of energy, like electricity. In this paper, the main technology of solar energy named solar photovoltaic will be discussed. Solar Photovoltaic utilizes the property of semiconductor, talking mainly about silicon in this project, to realize this technology. This is widely used as crystalline PV cells, thin film PV, and other PV technology (such as multi-junction PV cells and concentrating systems). The cost of power from PV plants has decreased globally around years but it still needs to reduce capital cost for countries lacking sunlight. In comparison to other renewable or non-renewable energy producing methods, PV has probably a smaller environmental effect. In normal operation, PV emits no gaseous or liquid contaminations and no radioactive substances, but people still need to strengthen the recycle of old silicon cells to avoid the leakage of toxic substances. The global photovoltaic market has increased rapidly in recent years, and it will also keep this increase in the future. The purpose of this project is giving a basic understanding of photovoltaics in these areas.

Keywords: renewable energy, solar photovoltaics, PV technology, PV systems

1. Introduction

Solar photovoltaic is a direct way to utilize solar energy by converting solar energy directly into electricity in a solid-state device called solar photovoltaic cell (PV cell). PV cell is made almost from silicon which is the second most affluent element in the Earth’s crust. It does not have moving parts and can theoretically operate in unlimited period without breaking down.

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People have tried to develop solar photovoltaics for a long time. In 1839, Edmond Becquerel found that the battery voltage increased while exposing silver plate under sunlight, which promoted the discovery of photovoltaic effect. In 1905, Albert Einstein laid the foundation for the general theory of the photo effect [1]. This theory stimulated the development of solar photovoltaic technology. In 1939, Russell Shoemaker Ohl found P-N junction and later developed the first silicon solar cell [2]. In 1954, scientists in Bell Laboratories showed the first practical silicon solar cell to the world [3]. After that, scientists made every endeavor to develop solar photovoltaic, and now, solar energy increases rapidly and has become one of the main sources of renewable energy in America. In 2020, it created 89198. 715 million kilowatt-hours electricity in USA [4].

After talking about the history, the physical principle of silicon solar photovoltaic and its implement should be introduced. Solar cells are a kind of electrical device to convert energy. A solar cell converts photon energy into direct current electricity in a direct way through a chemical/physical phenomenon named the photovoltaic effect which is that photons energy exceeds the band-gap of, being absorbed activating charge-carriers and thus caused electric current and voltage [5]. This theory is embodied in solar cells which utilize photovoltaic effect well. Solar cells are mainly made of silicon because of its universality and Single-junction c-Si is the main cell technology in PV cell market. This technology can be sorted by four categories: Mono-crystalline, Poly-crystalline, Heterojunction with Intrinsic Thin layer (HIT), and Microcrystalline [5]. Scientists makes silicon semiconductors with a tiny amount of impurity like boron and phosphorus to make p-type and n-type semiconductors. This combination creates electric field, like a junction, to generate electricity. Also, there are many other types of junctions, like multi-junction PV cells and concentrating systems, making this technology prosperous.

The economic impact of solar photovoltaic systems is also critical to mention. The c-Si cells have a dominant statue in recent market. Alltime layed out PV capacity of 139 gigawatts by the end of 2013 [6]. In terms of market share, c-Si cells are dominant in the market with 93% of the total produced capacity in 2015 [5]. The solar photovoltaics system has created a mountainous amount of electricity for people use. As of 2015, the fast-growing PV market is swiftly close to the 200 GW which is over 1% of total electricity generation worldwide [7]. In the future, the solar power is expected to be the largest source of electricity in the world. However, the capital cost of PV panels still needs to be decreased. People who want to utilize solar energy must pay a total of roughly $20,000 for the installation of solar panels and other essential components. This is in comparison to an average monthly power bill of $100. The calculations show that it will take more than fifteen years for the cost of solar panels to match the cost of conventional power. Thus, numerous people still do not want to use PV cells as a main source of getting energy. In this way, related organizations and authoritative should continuously make efforts to decreasing the cost of PV systems.

Beside the influence brought to economy, the environmental impact of solar photovoltaics is also positive. In general, the solar photovoltaics have lowest environmental impact compared to other sources of energy. Normally, solar photovoltaics do not create liquid or gaseous contaminations and radioactive particles [8]. However, people still need to be aware of the potential impact. Except amorphous silicon, most PV technologies in business use toxic heavy metals, like CIGS containing cadmium sulfide and crystalline silicon modules containing lead [9]. Thus, people should recycle the old solar cells in time to avoid these potential dangers threatening to the environment.

2. History of Solar Photovoltaics

2.1. History of efficiency improvements in silicon solar cells

Silicon solar cells based on photovoltaic technology, which was observed by Alexandre Edmond Becquerel in 1839. After this, scientists made many solar cells based on different materials, such as selenium. But it was not until 1941 when Russell S Ohl from Bell Telephone Experiment Center applied for patent

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US2402662A, a photosensitive device, that the modern silicon photovoltaic cell was not really born, although its efficiency was less than 1% at the time.

Beginning in 1950, Bell Labs continued to invest in solar cell research, and by 1954, they had a silicon solar cell with an efficiency of over 6%, the first commercially available silicon cell. Since then, Bell Labs, General Electric, and Hoffman Electronics have all contributed to silicon battery research. Among them, Hoffman Electronics achieved 10% in 1959 by using grid contacts to reduce resistance. In the same year, polycrystalline silicon cells came out with an efficiency of 5%.

Just a year later, Hoffman Electronics produced solar cells with 14% efficiency. But after that, people will focus more on polysilicon, amorphous silicon, or other composite cells. The development of monocrystalline silicon cells is slow. As of 1980, the efficiency of monocrystalline silicon cells reached 20%, which was slightly inferior to that of gallium arsenide cells. At the same time, the efficiency of polycrystalline silicon cells is also close to 15%. On the eve of the millennium, the efficiency of monocrystalline silicon solar cells exceeded 25%, using a technology called passivated emitter, rear locally diffused (PERL) cell.

In the 21st century, silicon-containing composite solar cells have become a new development direction. In 2016, UNSW engineers set a new world record by converting unfocused sunlight into electricity with an efficiency of 34.5%. This is the highest efficiency ever achieved by a silicon-based solar cell known to date.

2.2. History of Applications of Silicon Solar Cells

It is generally believed that the Bell Telephone Company was the first to realize usable silicon solar cells. Bell has been producing solar cells for space activities since 1950. Subsequently, Western Electric, Hoffman Electronics and AT&T have all been involved in the commercialization of solar energy. Among them, the n-on-p silicon solar cell created by T. Mandelkorn of US Signal Corps Laboratories in 1958 was the most representative. It was not damaged by radiation so was suitable for using in space. In the same year, Vanguard 1, the first artificial satellite powered mainly by solar cells, was successfully launched.

In the following years, silicon solar cells have been widely used and developed in the aerospace field. In 1967, Soyuz 1 became the first manned spacecraft to be equipped with solar cells. In addition, Salyut 1, the world's first space station, and Skylab, the world's first orbiting space laboratory, were powered by silicon solar cells.

At the same time, silicon solar cells have gradually entered people's lives. Solar watches, solar computers, and things like that had come out. The most energy-consuming batteries are still used for building energy. A sufficiently prominent example, George Bush and Barack Obama installed additional solar cells in the White House in 2003 and 2010, respectively.

Since it was put into use in 1950, the total amount of solar cells has exceeded 500 kilowatts after 27 years. Moreover, the total amount of solar cells reached 1000 MW in 1999. The vast majority of this is contributed by silicon solar cells. And this number continues to grow.

3. Physical Principles

3.1. Photovoltaic Effect

To understand the principles of silicon solar cells, you must first understand photovoltaics. When a substance is exposed to light, the photovoltaic effect causes voltage and current to be generated. It is a natural chemical and physical occurrence. Solid-state electronics, particularly photodiodes, are used in the most popular variation of the photovoltaic effect. The photodiode is exposed to sunshine or other suitably intense light, which excites the electrons in the valence band to jump to the conduction band and become free. Some of these excited electrons disperse and eventually arrive at the rectifying junction (often a diode p-n junction), where the inherent potential accelerates them into the n-type semiconductor material (Galvani

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potential). Some of the light energy is transformed into electric energy as a result of the generation of an electromotive force and an electric current. When two photons are absorbed simultaneously, a phenomenon known as the two-photon photovoltaic effect can also take place. In silicon solar cells, P-N junction-related photovoltaics are mainly used.

3.2. Silicon and P-N Junctions

Inside of a single semiconductor crystal, a p-n junction is the border or interface between two different types of semiconductor materials: p-type and n-type. In the outer shells of the electrically neutral atoms there, the "p" (positive) side has an excess of holes, whereas the "n" (negative) side has an excess of electrons. This permits just one path of electrical current to flow across the junction. Doping is used to construct P-N junctions. Doping is the intentional introduction of impurities into an intrinsic semiconductor.

When we dope silicon with nitrogen elements, arsenic or antimony introduce an extra electron to each dopant, which can then be thermally or photolytically excited into the conduction band, forming an n-type semiconductor. Similarly, when we dope with the counterpart in boron group elements, acceptor levels are introduced that trap electrons that may be excited from the filled valence band, forming a p-type semiconductor. If two kinds of silicon are connected, a P-N junction can be formed.

4. Technology Implementation of Crystalline Silicon

Currently, the leading cell technology in the global PV industry is single-junction c-Si. According to their crystalline structure, the wafer-based conventional cells may be divided into four basic categories: mono-crystalline, poly-crystalline (i.e., multi-crystalline), heterojunction with intrinsic thin layer (HIT), and microcrystalline.

4.1. The Manufacturing of silicon modules

The carbothermic reduction of silicates in an electric arc furnace is the first step in the creation of a conventional silicon solar cell. Through an endothermic reaction with carbon, the silicon-oxygen bond in SiO_2 is broken in this process using significant electrical energy. While CO_2 and tiny SiO_2 particles escape with the flu-gas, molten Si-metal with entrained impurities is taken out of the furnace's bottom. The main procedure of manufacturing a solar module is shown in Figure 1.

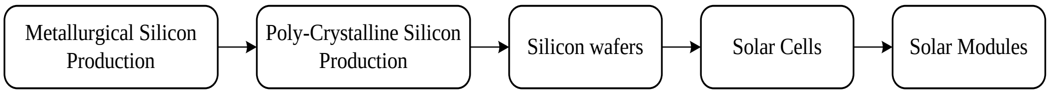

Figure 1. The main procedure of solar modules manufacturing.

Regardless of the ultimate crystalline structure, the first step in the fabrication of c-Si cells attempts to produce high-grade, purified silicon. To create metallurgical-grade silicon, quartz sand (SiO_2) and coal (C) are treated as raw materials within an electric arc furnace.

In numerous reactors, MG-Si is put through further high-tech processes to create solar-grade polysilicon. These reactors include the fluidized bed reactor and the Siemens reactor, two types of common purification technology created and first patented by the German corporation Siemens between 1954 and 1961 [10].

Typically, two procedures are required to make very pure poly-silicon appropriate for solar cells and microelectronics. In the first stage, tri-chlorosilane is created when MG-Si interacts with HCl to produce a variety of chlorosilanes (TCS). TCS may be purified by distillation because to its typical boiling point of 31.8 °C.

As in a chemical vapor deposition method, silicon accumulates on the silicon rods. High-quality solar cells may be created using silicon that is 6 N or greater, which is referred to as solar grade silicon. As a

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result, the entire process starts with silicon that is low in purity and ends with poly-silicon that is high in purity.

Making thin silicon wafers is required as the following stage. New wafer saws can produce wafers with a thickness of 180 μm, in line with the recent industry trend toward thinner wafers. Although thin wafers are useful since they require less material, they shouldn't be too thin because they are fragile and challenging to produce. Melting and re-solidifying pure silicon constitutes the most common wafering procedure. Then, like in the microelectronics sector, these silicon ingots are sliced into wafers. In the Czochralski method, a revolving seed crystal is progressively drawn out of a molten solution to provide massive single-crystalline silicon rods/ingots.

From silicon wafers, solar cells are made in a series of stages. To improve the optical and electrical characteristics, the wafers are first given a chemical treatment. To create the p-n junction, which has excess and insufficient electrons in the conduction bands, silicon, a group element, is doped with nearby group and elements, generally boron and phosphorous. By capturing incident light within the cell, anti-reflection coating layers decrease reflection losses at the front surface. To finish the solar cell, front and rear electrical connectors are added. Finally, individual cells are assembled into panels and adorned with inverters and other devices to generate power according to the needs of the end user.

Ethylene vinyl acetate is used as an encapsulant while the solar cells are soldered and laminated to a front glass panel to form modules. The energy conversion efficiency of conventional solar cell modules is between 12 and 15%, or about 2% less efficient than the efficiency of individual cells.

From the theoretical part, it is known that solar modules can generate electricity by absorbing sunlight, but the electricity they generated is DC, and we need to convert it into AC.

4.2. Power Inverter for silicon PV modules

As the global need for electricity rises, PV power provided to the utility grid is becoming more and more visible. The inverter is needed for two reasons. First, the output of a solar PV array is converted from DC to 50 or 60 Hz AC electricity via an inverter. Inverters can use high frequency switching or be transformer-based. Inverters can be standalone, linked to the utility, or a mix of the two. Second, the inverter should include a feature for tracking the Maximum Power Point since the power provided by the module(s) is particularly sensitive to the point of operation (MPP).

For PV systems to operate reliably and safely during grid connectivity, inverter technology is essential. It is also necessary to produce high-quality electricity for AC utility systems at an affordable price.

5. Typical System Description

It is possible to categorize PV-based power producing systems into two groups—grid-connected PV systems and standalone PV systems [11].

5.1. Stand-alone PV systems

A PV generator, energy storage, charge controllers, and power conditioners make up these systems.

In the case of a stand-alone system, as seen in Figure 2, there is no contact between the system and a utility grid. When demand exceeds power generation, the battery bank is needed to store extra energy that is released. A standalone PV system may be subject to both DC and AC loads. All components of the PV system are protected by power conditioning systems.

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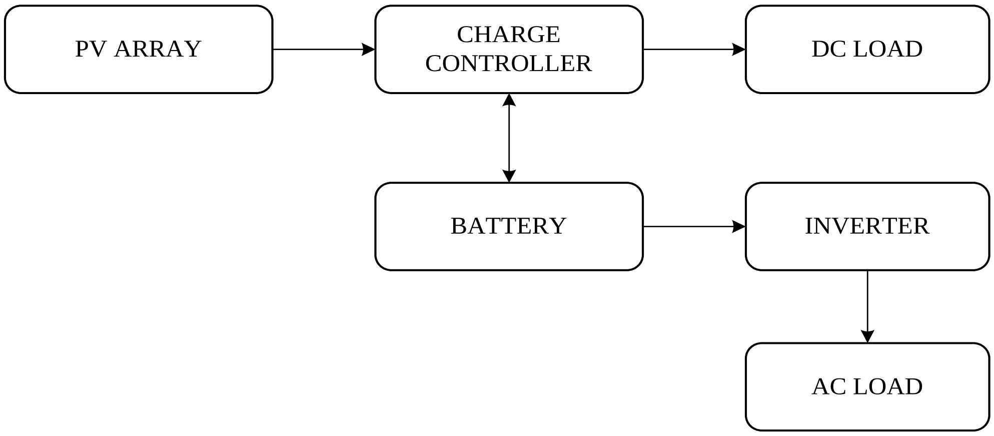

Figure 1. Stand-alone PV systems illustration.

5.2. Grid connected PV systems

As seen in Figure 3, these systems are interconnected with the regional electrical grid. The power generated by the grid-connected system throughout the day can be used directly or sold to any electricity supply company. When the PV system cannot produce electricity in the evening owing to the lack of sunshine, power can be purchased and stored from the local network. Since the systems supply energy directly to the load or grid as needed, no battery storage is used in them.

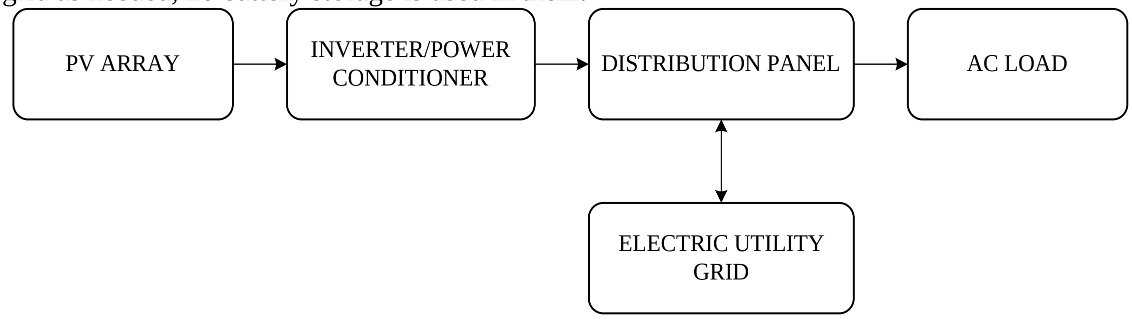

Figure 2. Grid-connected PV systems illustration.

6. Environmental Impact

First of all, when considering the way how photovoltaic generation produces electricity, solar photovoltaic is quite environmentally-friendly. Compared to other technology, such as thermal power generation and nuclear electricity generation, solar photovoltaic generation do not burn any fuel or materials, which means it does not produce any pollution, such as CO_2 and other harmful gasses, during the process. "Global carbon dioxide emissions from energy combustion and industrial processes reached 36.3 billion tons in 2021, of which nearly 14.6 billion tons were emitted by the electricity and heating sectors" [12]. As a result, if the world uses solar power on a large scale instead of thermal power, carbon dioxide emissions will surely be greatly reduced, and global warming will be solved easily. Also, photovoltaic generation is safe and reliable, no noise, low failure rate. That's why most of power stations are built in rural areas, but the solar panels are build on the top of buildings. Moreover, as the structure of solar panels is not complicated, it can be simply installed and easily combined with the buildings, so it can enable us to prevent harm to the environment and plants when putting cables far away.

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However, upon further reflection, solar photovoltaic still has many negative influences to the environment. As we know, the solar cell module is the most fundamental component of photovoltaic power generation. Currently, crystalline silicon photovoltaic cells have a conversion efficiency of 13% to 17% whereas amorphous silicon photovoltaic cells only have a conversion efficiency of 5% to 8%. The power density of photovoltaic power generation is limited due to the poor photoelectric conversion efficiency, making it challenging to create a high-power generating system. As a result, solar photovoltaic generation needs to take up plenty of land resource to achieve more amount of electricity produced. Then, it may be a waste of land resources, for example, deforestation may be needed to gain more space for solar photovoltaic generation. In addition, crystalline silicon cell production uses a lot of energy and produces a lot of pollutants. Pure silicon serves as the primary raw material in crystalline silicon cells. It must through several chemical and physical processes from silica sand to crystalline silicon with purity above 99.9%, which not only costs a lot of energy but also contributes to environmental damage. “A Chinese polysilicon maker, Luoyang Zhongsi High-tech Co., has been dumping toxic waste silicon tetrachloride on the fields around its factories for the past nine months, making it impossible for crops to grow. Silicon tetrachloride is a by-product produced in the manufacture of polysilicon. It is a highly toxic substance and will cause serious pollution to the environment. Because of the high cost of recycling the material, most Chinese solar plants are not equipped or fully installed with recycling equipment. When encountering moist air, silicon tetrachloride is decomposed into silicic acid and hydrogen chloride, a highly toxic gas. It has strong irritation to human eyes, skin and respiratory tract, and will explode in case of fire.” [13]

In conclusion, sun light resource is nearly unlimited, which means it is an excellent renewable energy. Also, the way of producing electricity is quite clean and cheap. However, before producing the electricity, manufacturing the solar panel by silicon with high purity is extremely harmful to the environment.

7. Economics of Domestic Solar Heating

The new energy industry has become a strategic emerging industry in China. At the same time, the goal of "accelerating the promotion and application of solar thermal utilization technology and opening up a diversified solar photovoltaic power generation market" is put forward by the “plan” [14] of Chinese government, so as to better develop and utilize solar energy. First, as the developing of solar heating, it created thousands of hundreds of job opportunities. By the end of 2016, China's installed capacity for solar power generation was 34.54 million kW, and the total installed capacity was 77.42 million kW, according to data from the Energy Bureau of China in 2017, including 30.3GW of ground power stations and 4.24GW of distributed power stations. In the annual report of the PV industry disclosure in 2016, 29 of the 31 A-share listed companies achieved growth and 2 suffered losses. In 2016, the annual installation volume increased by more than 120%” [15], which shows that photovoltaic power generation is greatly favored and recognized. As the result, the industry needed to hire more workers in order to achieve more production. Then, it can not only make the industry have more profit to do innovation, but also let more people have higher wage to do consumption in order to promote the domestic real GDP. Moreover, Chinese government introduced a “plan” [14] to give the solar heating industry subsidy. Because of this subsidy, the industry could reduce the cost of production and had more money to do innovation, so the firms would reduce the price of the electricity created by photovoltaic power generation. Then, people can enjoy using the electricity with much lower price. According to the British magazine [16], “Industrial and commercial solar power systems in Chinese cities are already cheaper than grid power, which only needs ￥0.25/kW·h”. In addition, according to this plan, the government encouraged the competitions between different firms in this industry in order to increase producers’ motivation. Overall, it improved the international competitiveness of Chinese photovoltaic generation industry.

However, the Chinese market is still not ready to use this technology widely. Because our country realized the environmental protection problem relatively late, the development time of photovoltaic industry is not long, which leads to our country is still using the underlying technology and is not strong of innovation, many key equipment and materials are imported. What's more. As China is still a developing country and has a low GDP per capita, people's average living standard is still low and most people can not realize the importance of using renewable energy, so producers are not willing to develop solar power technology. As a result, if Chinese government still wants to promote photovoltaic industry, it needs to spend a lot of money to encourage producers which may cause the government becomes budget deficit and does not have enough money to do other things, such as education and infrastructure. According to Chinese solar power policies [17], "the government will give subsidy of average ￥0.42 per kilowatt hour for solar power ", so it will be a great amount of money spent to develop photovoltaic industry. Also, giving subsidy shows a strong planning economy, which is extremely disadvantageous to the formation of a single market. In conclusion, although solar heating industry contributes a lot of positive impact to the Chinese economy, the economy system partly impedes the development of photovoltaic industry.

8. Conclusions

In conclusion, this project aims to introduce the solar photovoltaics in order to let people get basic knowledge for this technology. This project does introduction mainly in six areas: Definition, history, physical ideas, implementations, economic impact, and environmental influences. The purpose of this project is to review recent status of solar photovoltaics and current progress. By comparing basic physical principles and developing routes, we find the energy conversion efficiency improvement. Also, we do research on weighing interests between efficiency improvement and production cost.

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