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To what extent can solar panels effectively replace coal to generate electricity in China by 2060?

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Abstract. In recent years, due to technological progress, the cost of solar power generation has decreased, and the Chinese government has supported renewable energy technology, solar photovoltaic technology has developed rapidly. This paper discusses the development prospect of solar power generation in China. By analyzing and comparing the advantages and disadvantages of solar power generation and coal power generation in environment, manufacturing, cost and policy, we explore whether solar power generation can replace coal power generation. It focuses on the advantages of solar power generation in terms of environmental impact, the development of solar power generation promoted by the Chinese government's vigorous implementation of sustainable development strategies, and the many limitations of coal in these aspects, reflecting the advantages of solar energy in today's power generation methods. At the same time, it also analyzes the technological progress of solar power generation, the decline of costs, and the challenges of solar panel recycling. Efficiency has always been the most concerned aspect of solar power generation. Studies have found that the use of different materials, the efficiency of photovoltaic power generation is also different. Increased efficiency is also affected by external temperature, humidity, dust, and light. Solar energy also faces many limitations in this regard. Based on these studies, solar energy has great potential as a renewable energy source and has the potential to replace coal power generation on a large scale by 2060. This essay looks at these studies and concludes that there is potential.

Keywords: solar panels, green power, coal power generation

1. Introduction

Today, electricity is an indispensable driving force in people's lives, and it is needed in every situation, from industrial production and transportation to daily life. For the needs of today's economic and social development, energy consumption is rising sharply. Today, fossil fuels, including natural gas, oil, coal, etc. are still dominant in providing energy. However, the large-scale exploitation and use of fossil fuels have serious disadvantages, among which a large amount of greenhouse gases will be produced after the combustion of fossil fuels, resulting in air pollution, climate warming, acid rain and other drawbacks, seriously polluting the environment.

China is the largest developing country in the world. Since 2000, China has emitted more than 20 million tons of sulfur dioxide, ranking first in the world. Carbon dioxide emissions total more than 4.5 billion tons, ranking second in the world. [2] In order to improve the unreasonable energy structure and protect the environment, renewable energy has received much attention from the Chinese government. In order to encourage the development of renewable energy, in 2005, China promulgated the "Renewable Energy Development" to ensure the development of renewable energy. Recently, China pledged to decarbonize its energy system by shifting it to renewable sources, especially solar, wind, and hydropower. In 2014, president Xi Jingpin proposed that energy security is an overall and strategic issue related to national economic and social development. Promoting a revolution in energy production and consumption is a long-term strategy, and people must start from the present and accelerate the implementation of key tasks and major measures. [39]. And in 2020, he was speaking at the Climate Ambition Summit that “In September this year, I announced that China will increase its nationally determined Contributions, adopt more powerful policies and measures, and strive to reach a peak of carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060.” (2020, Xinhua net) By studying the physical potential of solar energy, solar photovoltaic is a huge decarbonizing resource in China. [15] As solar technology matures and costs fall, it is a promising alternative to coal power generation. [4]

In China, the total annual solar radiation is basically high in the west and low in the east, and high in the south and low in the north. Solar energy reserves are also relatively rich. In 2015, the wind and solar Energy Resource Center of the China Meteorological Administration estimated that the theoretical reserves of solar energy resources in 2015 in the country were 1.86 trillion kilowatts, and the annual solar radiation received by the land and ground was equivalent to 18,000 billion tons of standard coal, and the photovoltaic power generation efficiency was very good in 60% of the area of China's land.

Therefore, it is necessary to evaluate whether solar power can replace coal power generation. Compared with coal power generation, the advantage of solar power generation is that solar power generation has little environmental pollution. Although the pollution of solar panels in manufacturing and recycling is inevitable, the pollution of a large number of greenhouse gases generated by coal power generation is much smaller than that of coal power generation, and it is in line with China's strategic goal of sustainable development. The cost of solar power also continues to fall and is expected to become less expensive than coal power.

Solar power also has potential disadvantages. First of all, solar land will bring land pollution, and the efficiency of solar energy is extremely low, and now people are constantly exploring materials that can improve the efficiency of solar energy, some have an impact on the environment, and the price is high. And obviously most of the material efficiency is still too low to exceed the efficiency of coal-fired power generation.

I will discuss and analyze the advantages and disadvantages of solar power generation and coal power generation and the advanced nature of solar power generation to determine whether solar power has the potential to replace coal-fired power stations.

2. Research review

2.1. Production of energy

2.1.1. Coal to generate electricity

Components of coal are mainly carbon and hydrocarbons. When using coal to generate electricity, a series of chemical reactions will take place in the furnace. The powder coal is mixed with hot air and burned to produce steam, which turns the blades on the turbine that powers the generator, converting heat into mechanical energy. [1]

2.1.2. Solar-the distribution

Solar energy is renewable energy. Renewable energy refers to primary energy that is constantly replenished by nature on the human time scale through biological reproduction or other spontaneous processes to overcome energy depletion due to consumption. [22] Its biggest feature is renewable, environmentally friendly and widely distributed resources. It is widely distributed but uneven in China. (National Energy Administration, 2014) Due to the greater amount of solar radiation in the West, Ma Shenghong said in 2004 that the average annual daily radiation in most areas is more than 4 KWH per square meter, while the daily radiation in Tibet is as high as 7 KWH per square meter. (Xinhuanet, 2004) Compared with east zone, western China is more suitable for developing solar photovoltaic industry. [3] According to an investigation of Chinese Weather Bureau (CWB) the solar energy radiant quantity reaches the peak in the eastern part of Qinghai-Tibet Plateau and Tibet region. [2] However, distributed solar PV are mainly installed in southeast China, since there is a plenty of rooftop spaces [4].

2.2. The environmental impact of coal and solar

Using coal to generate electricity will cause amounts of environmental problems. Coal emits a lot of toxic chemical components and greenhouse gases when it burns. The acid gas released from it leads to a series of environmental problems such as global warming and air pollution. [5] Many prevalent respiratory and metabolic diseases among mammals are caused by the coal tar chemicals. Also, this is a test of the absorptive capacities of the soils, since there is a increasing amount of solid wastes to deal with. [5]

Solar power generation is a potential choice to solve these problems. Even though there are drawbacks such as consuming a mass of volumes of water to clean the solar panels and lead and cadmium released from the manufacturing process, its advantages far outweigh its disadvantages. Using solar panels can reduce carbon footprint, lead less water pollution and protect the natural resources. [6] A study showed that when solar panel replace coal to generate electricity in U.S., nearly 51,999 American lives from diseases caused by environmental problems caused by coal power generation will be saved every year. [7]

2.3. Technology of solar panel and coal

Up to now, using coal to generate electricity still dominate the power generation. The efficiency of coal power plants is generally 33% in the word, higher efficiency can be achieved 45%. [8] Compared with the coal, the efficiency of solar panels remains between 15% and 20%, and the most efficient solar panel reaches around 40% efficiency. [9] Photovoltaic cells usually divided into 3 types: (1) use crystalline silicon (c-Si) in simple crystal-line form (sc-Si) and in the multicrystalline form (mc-Si) in

photovoltaic system which is widely used in commerce. For example, Silicon nanowire cells (SiNWs) is an applicable photovoltaic cell with high efficiency and low cost. [10] But in the meantime, George Dodd also noted that nowadays, the silicon solar cells only have a conversion rate of 28%, and has reached its limits. Hence, solar panel technology has to be developed. A perovskite solar cell which is cheaper and easier to produce can be taken into consideration. [11] (2) use film photovoltaic technologies such as cadmium telluride which has the ideal gap in photovoltaic systems and (3) use organic photovoltaic technologies like graphene which are immature nowadays in photovoltaic systems. The materials used to fabricate solar panel should be non-poisonous, easy to manufacture, suitable conversion efficiency, and the bandgap should be small. [10]

Making the solar panels have a more efficient conversion rate not only require the innovation of materials but also improvement in installing solar panel. The environmental condition, the materials used in Solar Power Plant (SPP) and the design of SPP will lead the losses in SPP production.

However, a single DC-DC converter layer for each sub-PV module string is provided by Distributed MPPT (Maximum Power Point Monitoring) techniques can decline the losses of SPP. [12]

2.4. Cost of solar panel and coal

US coal power demand has been declining since 2011, and has fell to 966,000 gigawatthours (GWh) by 2019. (2020) From an investigation, around 85.17% of current coal-fired power plants face a cost crisis in the subsidy-free context.[4] And simultaneously, the researchers found that China's solar PV has a 78.6 percent potential in 2020 to be equal to or lower than local coal- fired power prices, and continue to rise. [15] The cost of making solar cells has fallen dramatically in recent years. At every duplication of cumulative production module, the module price decreased nearly 19%. It has a large probability that the price of photovoltaic materials of thin film and organic materials will decrease 80%. [10] A study has shown that the cost of solar PV power generation fell from CNY5.6–15.1kWh−1 to CNY0.29-0.79 kWh-l between 2000 and 2018 the cost of manufacture dropped to around CNY2

Wp-1 [17] By 2060, solar could provide 43.2 percent of China's electricity needs for less than 2.5 cents per kilowatt-hour. [15]. Most experts agree that the cost of producing solar panels and therefore solar energy is falling.

2.5. Policy of sustainable energy

China is facing unique energy challenges due to its fast economic growth and high energy consumption. The key to achieve the national sustainable development Goals, is to reach the peak of carbon dioxide emissions by adjusting the energy structure, reducing energy intensity. [13] China's overall energy strategy is striving to shift from a coal-based energy system to a sustainable energy system. [14] As a clean energy, solar energy conforms to the sustainable energy policy. China has also issued a number of policies to develop the photovoltaic industry. From 2000, the Chinese government has proclaimed around 109 policies to support the solar PV industry. To guide the photovoltaic industry towards a more sustainable and efficient development path, the government has adopted the 531 Policy. Since National Development and Reform Commission issued an incentive policy “Notice to play the role of the leverage of electricity tariff to promote the healthy development of solar PV industry” on August 30th, distributed solar PV projects have been scaling up since 2013.Since then, for 15 years, distributed generation projects have received FIT, demonstration projects, and free grid-connection services policy support from the central government. [17]

Table 1. Sources on Energy Policy and Solar Technology: Validity and Usage Overview

Source	Validity	Usage
Yi Wang, 2014, The economic impact of emission peaking control policies and China’s sustainable development	The authors are in the institute of Policy and Management, Chinese Academy of Science, Beijing 100190, China. Therefore, this is reliable.	Understand China's current energy policy towards low carbon development.
Brian Church,2023, Solar panel efficiency	Brian Church specializes in writing about solar energy, sustainability, and outdoor recreation and tourism. He has covered these topics full time since 2019, production blogs, white papers, buyers guide a more to help people make the most of our planet’s natural resources. He has a bachelor’s degree in marketing from John Carroll University. Therefore, their opinions are valid.	This article shows the conversion efficiency of solar energy today, and the trends that may improve in the future
Xia Yang,et al, 2010, A comprehensive review on the development of sustainable energy strategy and implementation in China	One of the authors worked as a junior consultant in UTLnnovation LLC in the Netherlands from 2007 to 2008, currently, she is doing her Postdoctoral research in the Department of Electricity Engineering from Tsinghua University, Beijing, China.	It shows China's current energy policy and future goals.

Table 1. (continued).

	One of the authors has worked in 11 different departments with 18 years of experience in both Northeast China Grid Company Limited and China Electricity Power Research Institute. Currently, he is Vice President in State Grid Information&Telecommunication Corporation,LTD. Therefore,it is valid.	
Penny Hitchin, 2018, High-efficiency, low emissions coal plants: come HELE or High Water	Penny Hitchin is an experienced and established freelance writer specializing in energy and the environment. She has had a long career producing articles, papers, and web- copy. Penny also has a deep knowledge of energy generation, renewable energy technologies, and the politics and economics of new build decommissioning and radioactive waste management. Therefore, this is reliable.	This article shows the conversion efficiency of coal- fired carbon power generation today, and how it may improve in the future
Mehmet Rida Tur, et al, 2018, effect of fault in solar panels on production rate and efficiency	One of the authors is in Batman Üniversitesi Department of Electricity and Energy. He is the doctor of Philosophy. Another is in Nisantasi Üniversitesi Electrical and Electronics Engineering, PhD. So, it is valid.	The external factors that may affect the efficiency of solar energy production are analyzed, and the solar technology used to solve these problems is put forward
Nadarajah Kannan, et al,2016, Solar energy for future world-A review	The authors are in the Department of Agricultural Engineering, Faculty of Agriculture, University of Jaffna, Sri Lanka. Therefore, this is reliable.	Explore the technology to improve the efficiency of solar power generation and the future trend of technology development
Priscila Goncalves Vasconcelos Sampaino, et al, 2017, Photovoltaic solar energy: conceptual framework	The authors are in the Federal University of the Semi-Arido, Brazil. Therefore, Their opinions are valid.	Related to the technical development of solar photovoltaic industry

3. Discussion/ Development

Through relevant literature and research, solar power generation has fully demonstrated potential and advantages in diverse aspects. But, using solar power to generate electricity still has a series of shortcomings and disadvantages. However, in China, whether solar power generation can replace coal power generation is a highly controversial issue. So, I will analyze the following four aspects to discuss:

1.The environmental impact of using solar panel comparing using coal to generate electricity.
2.The energy cost of solar panel and coal-based energy.
3.The policy in China.
4.Land use and development of solar energy.
5.Recovery of solar energy.
6.The technological maturity of solar power generation and coal-fired power generation.
7.The appearance of solar panels.

3.1. Advantages

3.1.1. The environmental impact of using solar panel comparing using coal to generate electricity

Solar power generation and coal power generation have some impact on the environment. In today's world, the greenhouse effect has become one of the most concerned environmental problems. The traditional way of generating electricity, —-burning coal, will generate a plenty of toxic chemical gases. The main gas and particle pollutants produced by coal-fired power generation are CO_2, CO, SO_x and NO_x. When these organic compounds released into the air, they will cause serious air pollution. [5] These main pollutants include greenhouse gases. The greenhouse gases make the land surface and atmosphere warm, leading the glaciers and sea ice to retreating, and it will affect the rainfall and the sea level. [21] And it can cause extreme climate change like heat waves, droughts, floods, stronger storms. [5] These changes will pose a major threat to the world's environmental protection. According to a study conducted in 2009 in India, between 2001 and 2009, carbon dioxide emissions rose from 324 to 499 Mt/year, sulfur dioxide from 2,519 to 3,840 kt/year, and nitric oxide from 948 to 1,539 kt/year. In factories, carbon dioxide emissions average in a range from 0.91 to 0.95 kg/kWh. [19] It is clear that over the course of nearly a decade, emissions of these gaseous pollutants have been rising. Although in today's world, national governments have adopted policies to vigorously promote the reduction of greenhouse

gas emissions, but because of the high emissions, it is obviously unrealistic to reduce these greenhouse gases in a very short time. Besides, coal-fired power generation causes far more pollution to the environment, including water pollution caused by emissions, and the imbalance of ecosystem are also major problems.

Compared with coal, solar power generation has a much smaller environmental impact. Although solar power generation has some impact on the environment in the production process and recycling process, for example, in the production of high purity polysilicon, metallurgical is converted to $SiHCl_3$, and only 25% of $SiHCl_3$ is converted to polysilicon, while the rest will produce a by- product $SiCl_4$. Some photovoltaic materials can also produce harmful gases and heavy metals to pollute the environment. However, there are also experimental studies that show that under the normal operation of the photovoltaic system, there will not only be no emission of heavy metals such as Cd, but also can greatly solve the problem of massive greenhouse gas emissions. [20]

In China, different photovoltaic systems in different regions of solar energy are controlled to have carbon emissions between 9 gCO_2-eq/kWh and 280 gCO_2-eq/kWh. Carbon emissions from central tower power plants are limited to between 21 gCO_2-eq/kWh and 345 gCO_2-eq/kWh. [22] These figures are significantly lower than the above figures for carbon emissions from coal-fired power generation. In the United States, solar and wind power each reduced CO_2, SO_2, NOx and PM2.5 total emissions by 20%, 72%,50% and 46% each between 2007 and 2015, according to one set of figures. [23] These studies have shown that solar power can reduce the risk of greenhouse effect because it is a clean energy source. The data also show that solar power generation must be a wise choice in terms of environmental protection and reducing the greenhouse effect. And solar panels may only be effective if situated in the correct area- south facing for some areas. Most experts believe that solar energy is a feasible way to protect the environment, because emissions are greatly reduced after using solar energy.

3.1.2. The energy cost of solar panel and coal-based energy.

It is inevitable for the cost estimation of the power generation industry to include the cost of generating energy and electricity, as well as a range of costs for emissions treatment. Apparently based on current trends, solar power also presents a huge advantage in terms of cost.

There are many factors affecting the cost of solar energy, including technological innovation, the discovery and use of newer, lower-cost materials, increased production of photovoltaic modules, the lifetime of photovoltaic systems and government policy support.

The experts agree that materials are crucial to reducing the cost of solar cells, and each material has a different degree of cost reduction. Compared with silicon, thin-film solar cells are cheaper.

Polymer solar cells were found to be cheaper and faster than crystalline solar cells, making them a potential competitor. Organic solar cells cost between $48.8 and $138.9 (US dollars) per square meter to manufacture.[20] Therefore, considering the low cost, organic solar cells are a good choice. In addition, if the government can get corresponding policies to encourage the photovoltaic industry, improve the service life of solar panels, and further improve the technology, the cost of solar power generation will further drop significantly and become more competitive in the power generation market.

Under the new energy development policy, it has been calculated that the cost of coal-fired power generation in China in 2020 was between 4.54 cents and 10.8 cents per kilowatt hour. However, the cost of photovoltaic power generation has basically reached 5.7 cents/kwh. (ailden, 2023) As recently as 2000, the cost of photovoltaic power in China was between $0.8 and $2.15 per kilowatt hour. According to the study, between 2000 and 2018, the annual falling of the solar power generation was between 4 cents and 10.7 cents per kilowatt-hour. [17] However, the cost of coal-fired power was 11.73 cents per kilowatt-hour in 2012. Obviously, the cost of coal- fired power has fallen much more slowly than photovoltaic power. In many parts of China, the cost of photovoltaic power generation is now lower than that of coal, and this trend is set to spread to the whole country. In 2020, photovoltaic power generation in China has 78.6% of the potential to be equal to or lower than the cost of local coal power generation. [15] Judging from the trend of the past few years, and the current Chinese government's strong push for sustainable energy policies, the cost of photovoltaic power generation will continue to fall. In the coming years, the cost of coal power will be much higher than the cost of photovoltaic power. And it is estimated that by 2060, photovoltaic could provide 43.2% of medieval electricity demand for less than 2.5 cents. [15]. The research findings all state that energy cost of solar is falling. This could be economies of scale that as more people have solar panels the costs of the panels keep falling.

3.1.3. The policy in China

In recent years, China has attached great importance to the utilization of energy. First, China is now the world's largest emitter of carbon dioxide. Second, with the continuous development of China's industrialization, the Chinese government has begun to pay more and more attention to environmental protection. Therefore, China has introduced a series of sustainable energy policies, possibly because of the sustainable development path, and the rapid development of China's photovoltaic industry: China's photovoltaic industry provides more than 70% of solar photovoltaic modules to the global market, [41].

Research shows that when the energy structure adjustment policy is implemented, carbon dioxide emissions in 2030 will be reduced by 11.3%-22.8% compared with the baseline case. With the energy intensity reduction policy, carbon dioxide emissions will be reduced by 33.3 percent in 2030 and 47.8 percent in 2050 compared to the baseline scenario. This also shows that the key to realizing the Sustainable Development Goals is to adjust the energy structure and reduce energy intensity to reach the peak of

carbon dioxide emissions. [13] The government will also shift its energy focus from coal to sustainable energy systems. Coal power is at a disadvantage in terms of government support.

China's goal of becoming carbon neutral by 2060 requires a green power system dominated by renewable energy. By estimating supply and demand, land use and government policies for various forms of power generation, the authors hope that policymakers will accelerate the use of complementary solar and wind power as primary energy sources to achieve China's carbon neutral goal. [28]

From 2000 to 2010, the Chinese government has issued nearly 109 policies to encourage and promote the photovoltaic industry and the use of sustainable energy in China. [2] Although the promulgation of these policies did promote the development of solar power generation, more than 100 policies in a decade also meant that the policy was updated too quickly, and it was easier and more frequent to emerge new policy issues. In 2005, the Chinese government passed the China Renewable Energy Law to encourage the use of renewable energy. This article includes the following regulations: 1. Photovoltaic power generation is all purchased by power companies, and grid-connected services are sufficient. (2) In order to encourage the development of solar energy, set higher than conventional electricity prices, investors should be guaranteed. It's great because it allows people to profit from it. 3. The central government provides certain subsidies to the renewable resources industry. This promotes sustainable development and thus indirectly promotes the photovoltaic industry. (4) The central government encourages renewable energy generation and undertakes initial investment and medium-term maintenance. 5. The price of photovoltaic power generation for end users is the same as that of conventional power generation. [2] In 2018, the Chinese government issued 513 New Policies to guide the photovoltaic industry to a more sustainable and efficient development path.[17] In terms of policy support, solar power also has a big advantage.

These studies demonstrate the importance China attaches to the use of photovoltaic systems and solar energy. This may be due to the increasing number of people starting to use and pay attention to solar panels and getting the attention of the government, as well as the crisis caused by China's huge carbon emissions. These policies have given people great concessions, making it easier to accept solar panels. But these policies should be more humane. For example, different policies are formulated in different industries to meet the needs of different groups of people. This has also accelerated the spread of solar panels to the general population, probably because China produces more solar panels than any other country, and the development of solar energy has also boosted employment in China.

3.1.4. Land use and development of solar energy

Utility-scale solar development requires a lot of land, and large-scale installation can have a negative impact on the environment. [37] As with coal, since any unpredictable or overlooked land or soil factor can affect the performance of a PV system, solar infrastructure often requires significant modifications to the landscape, as well as grading and clearing of vegetation. Such as clearing vegetation, leveling the land, compacting the soil, etc. These will lead to erosion of top or deep soils and loss of biodiversity. [32] In the United States, utility-scale solar supply has been found to account for 0.6% of the country's land area. The amount of land used for solar photovoltaic (cadmium) is 12.6 square meters per megawatt-hour. Solar photovoltaic (silicon) has a land area of 3 square meters per megawatt hour. Coal-fired power requires an even larger area of 15 square meters per megawatt-hour. As utility-scale solar installations continue to expand, they still do not pose a significant threat to the loss of agricultural land. This may be due to the fact that solar photovoltaics occupy less space than coal power, and there are fewer pollutants, and people think that solar panels can be installed at the same time with livestock farming, so as to bring double benefits to the local people. Solar energy, combined with local grasses and pollinators, can provide an opportunity for overused soils to recover. In the long run, the above situation shows that solar energy is more efficient in terms of land use and will not have a serious impact on other industries in the short term.

3.2. Disadvantages

3.2.1. Recovery of solar energy

The life of solar panels and component recycling will also be a serious problem and challenge. If the solar panel is not properly recycled after the end of its service life, it will have a great impact on the environment. The average lifespan of a solar panel is 20 to 30 years. And today, as governments push for sustainable development, solar adoption is rising exponentially. According to the study, by 2050, if not properly recycled, 60 million tons of solar waste will be generated, and the photovoltaic waste stream is expected to reach 60-78 tons. [30] Solar panels also contain lead (Pb) cadmium (Cd) and other harmful chemicals, so if the entire panel cracks, these chemicals will not be removed. Because of the huge impact of solar energy recycling on the environment, people have also begun to focus on the recycling of solar panels. There are three main recycling processes:

(1) Physical separation: The panel is removed mainly by removing theenclosed aluminum frame as well as the junction box and recessed cables, but this method can only be used for the external junction box located outside the main body of the solar panel. (2) Thermal and chemical treatment: These methods can make the solar silicon panel be effectively used after the recycling process, but in the process will produce toxic gases, and consume a lot of energy. [29] However, the more pessimistic is that the cost of recycling is also high. It costs between $20-30 to recycle a panel. [33] Also, China has no strong policies related to recycling, and the environmental protection department has not focused on waste recycling. [29] Therefore, China should go further and promote

the solar panel recycling policy. According to the above research, China's solar panel recycling into a very not optimistic trend, one is the government for the recycling of solar panels is not enough attention, the second is not enough investment, technology is difficult to meet the required requirements, resulting in solar panel recycling has become the short board of China's solar industry.

3.2.2. The technological maturity of solar power generation and coal- fired power generation

With the increasing emphasis on solar energy in today's world and the desire for further government support and market dominance, it is essential to improve the technical deficiencies and loopholes of photovoltaic power generation. The technological maturity of solar power generation can be judged by its improved efficiency, as well as its cost and environmental impact. For the development of solar power generation, efficiency has always been the focus of attention. So people have been working on ways to make solar energy more efficient. And the factor that affects the efficiency, material selection accounts for a large proportion. However, it is not only the influence of materials, but also the influence of external factors. As the technology matures, costs will come down and the environment will improve, meaning solar will be competitive as an alternative to coal.

In recent decades, the efficiency of solar energy materials has been further developed, and each material has been more or less efficient. But the drawback is that every material has its limits, and today's solar cells are not very efficient at conversion. That efficiency is between 15% and 20%, compared with about 40% for the most efficient solar panels. [9] However, coal is still the world's dominant form of electricity generation today, and its high efficiency accounts for a large proportion of that. Coal-fired power plants around the world typically produce electricity at an efficiency of 33%, while higher coal-fired plants can produce electricity at an efficiency of 45%. [8] This figure far exceeds the efficiency of current solar cells. So finding more efficient ways to replace coal with solar power is a priority.

3.2.2.1. The materials

At present, studies have shown that in the market, the solar government technology is generally divided into three generations: the first generation of crystalline silicon technology is divided into the use of single crystal wire form and polycrystalline form. Monocrystalline silicon is about 15 percent more efficient than polysilicon, which costs less. For monocrystalline silicon, in the 1950s it was 15% efficient, by the 1970s it was 17% efficient. By 2010, its efficiency had increased to 24.7 percent, and by 2013, it's consistently growing to 28%. The efficiency of polycrystalline solar cells is relatively low, but has reached 19.8% by 2013. And crystalline silicon is highly popular in the commercial PV market due to its abundant, stable, nontoxic silicon, high efficiency, ideal for the Earth's solar spectrum. It accounts for about 90% of the market share of solar cells. But because of its high cost, people will further find more reliable, but cheaper, materials to replace the crystalline materials. Second generation of thin-film PV technologies including amorphous silicon and micro- amorphous silicon, cadmium telluride (CdTe) and cadmium sulphide (CdS), copper indium selenide (CIS) and copper, indium gallium dieseline. By 2010, the thin-film technology had an efficiency of about 19.9 percent. The subdivisions are: Cadmium telluride (CdTe) and cadmium sulphide (CdS) are much more efficient, up to 15%. Cadmium (Cd) is a toxic non-essential excess metal that exists in the natural environment as a pollutant from agricultural and industrial sources. Once ingested, it can cause a variety of serious diseases, posing a threat to human and animal health. [31] However, studies have also shown that toxic cadmium can be controlled by temperature and concentration. [32] The component efficiency of copper indium selenide (CIS) and copper, indium gallium dieseline is nearly 13%, and its battery efficiency is 20%. But the degradation rate of CIS is very low, only 10%. [20] However, the power generation efficiency of this technology is low and the materials used have a negative impact on the environment. [20] Third generation organic photovoltaics, which have the advantage of having the same conversion efficiency as silicon but at a lower cost and higher yield, are not yet widely available. [10]

However, the conversion efficiency of silicon solar cells has reached its limit, at only 30%. This means that people will need to search for more reliable materials with higher conversion efficiency, and perovskite has this potential and is the focus of research in the world today. By 2020, perovskite efficiency has increased from 3.8 percent to 25.5 percent in just 10 years. The data show that single-layer efficiency can reach 33%, double-layer efficiency can reach 45%, and triple-layer efficiency can reach 51%. [11] In addition, the cost of this material is not high. The discovery of this material not only fills in some of the shortcomings of other materials, but most importantly, it solves the biggest efficiency problem that solar cells have ever had. But even with the high efficiency of perovskite solar cells, there are still many disadvantages. It contains Pb, Sn and other toxic substances, and it also has a short life span. [32] With its rapid development rate and great potential, if it is put into the commercial market on a large scale, the efficiency of solar cells will be greatly improved in the near future. And when solar cells become more efficient than coal, solar power is likely to displace coal on a large scale.

3.2.2.2. Other factors

Of course, photovoltaic efficiency is not only affected by materials, but also by other factors. But these factors are often negative. The use of solar energy is influenced by many external factors, such as day and night, seasons, geographical latitude, altitude and climate. Because solar energy can’t be consistent as an energy source, these limitations of natural conditions will lead to instability of solar power generation. Studies show that the sun's radiation is greatest when the weather is clear at noon, as it is in summer, but on an annual average, it is only one-fifth as high as it is when generating electricity at noon. Winter is only about half of the normal occurrence point, cloudy days often only one-fifth, so the energy flux density is extremely low. These are problems that coal does

not have. And these problems are objective and unavoidable, so energy storage is also solar power generation and will face major improvements. However, building energy storage systems will also increase the total cost of technology. [32] And so far in China, energy storage is one of the weak links in solar energy utilization. Lithium-ion batteries are the main way to store electrical energy. Although it has a longer life, this approach is expensive, with the cost of building a solar-plus-storage plant ranging from $380 per kilowatt-hour (which can provide four hours of electricity) to $895 per kilowatt-hour (which provides a 30-minute system). (Solar Energy Technologies Office, 2019) And lithium batteries are equally harmful to the environment, when it is disposed of, it becomes electronic waste. And, coal power has a big advantage. Electricity can be generated by burning coal in any state, without the need to fight intermittency like solar power. Today, the world's coal reserves are also very large. Studies have shown that there are still 200 years of coal use. [34]

But further analysis of these factors has also been carried out, and some solutions have been offered. For the environment, there are dust, shading, solar irradiance and environmental humidity. The rest are components, as well as the effects of solar cell temperature.

The research shows that :1. Solar radiation is an important factor affecting photovoltaic power generation. The solar irradiance of a photovoltaic module varies with the position of the module. [20] For every 1 degree south of the azimuth, there is a loss of 0.08%. With the increase of solar energy irradiance, the output power of photovoltaic panels also increases. [27] 2. High temperature has a great impact on the utilization efficiency of solar energy. With the increase of temperature, the reverse saturation current increases, Voc decreases, the filling coefficient decreases, and the solar cell volume decreases. [20] For every 1 degree increase in the operating temperature, the battery voltage is reduced by about 2.2mV, and the voltage of the crystal PV cell is reduced by 0.5%. [27] 3. For dust and dirt, the sunlight on the photovoltaic module will be blocked. As a result, the short circuit current will be reduced, thus affecting the efficiency of the photovoltaic module. When the dust of 20g/m2 is collected on the photovoltaic panel, the short-circuit current will be reduced by 15-20%, the open-circuit voltage will be reduced by 2-6%, and the efficiency will be reduced by 15-35%. [27] According to statistics, according to the photovoltaic system, the power rate is between 10%-70%. Of course, the authors propose that distributed MPPT (maximum power point monitoring) technology can provide a single DC-DC converter layer for each sub-PV module string, thus reducing the loss of solar power plants. [12] If these problems are solved, solar energy will be more efficient, making it more competitive in the power generation market.

3.2.3. The appearance of solar panels

Some people simply don't like the appearance of panels. In the past, they had heavy aluminum frames with white backgrounds and exposed wires, but now their designs are sleek and more family-friendly. Although the appearance of solar energy design is indeed a major drawback of solar energy, there are many people who do not want to install solar panels because of this. But in other ways solar has a huge advantage. Compared with the ugly appearance, solar panels can reduce electricity bills, prevent the rise of energy costs, get a lot of money, increase fiscal revenue, and thus bring economic benefits. Make your personal energy independent. [38] Also, solar panels greatly reduce environmental pollution. In general, the decision to install a solar panel should not depend on its appearance.

4. Conclusion

In conclusion, solar power does have great potential to replace coal power generation, but due to the limitations of solar energy. This will be a time-consuming process that will take decades. Most experts agree that solar will be part of the solution in suitable areas.

In general, solar power shows unquestionable potential in the future energy development. In the case of decreasing fossil fuels, solar energy has become an important part of human energy use and has been developed. Solar energy is a renewable energy, compared with non-renewable energy such as coal, solar energy will not produce any greenhouse gases after use, and the impact on the environment is minimal and extremely long-term. Solar energy is available everywhere and can be directly exploited and utilized. In China, energy storage is rich and widely distributed, which can make full use of solar energy resources and improve solar power generation technology. These characteristics make solar energy occupy a dominant position in the development of energy.

At present, the greenhouse gas generated by coal power generation is huge and the environmental pollution is serious. If we want to protect the environment, we must change this status quo. Therefore, China puts forward the strategy of sustainable development and changes the energy structure. In order to smoothly shift its energy system to renewable energy, the Chinese government has further proposed the development goals of carbon peak and carbon neutrality, which have further promoted the development and utilization of renewable energy. In recent years, the Chinese government has issued many policies to support solar power generation, which has further developed rapidly. The cost of solar power continues to fall, and the technology is also rapidly maturing, which proves that solar power has great potential.

However, solar power generation technology still has many problems and limitations. Among them, solar energy is decentralized, and although the total amount of solar radiation reaching the Earth is large, the energy flux density is very low. Therefore, in the use of solar energy, to get a certain amount of converted power, often require a considerable area of collection and conversion equipment, the cost is extremely high. Solar energy is also affected by natural conditions such as day and night, seasons, geographical latitude, and altitude. So, the amount of solar irradiance that reaches a certain region is intermittent and unstable. This

makes it difficult to use solar energy on a large scale, in order to make solar energy a continuous and stable energy source, it is necessary to store energy through batteries for use at night and on cloudy days. However, the batteries used for energy storage are mainly lithium batteries, lithium batteries have no small impact on the soil and the environment, and the Chinese government does not pay attention to solar energy storage, making energy storage a weak link in the utilization of solar energy. Due to low efficiency and high cost, the current laboratory utilization efficiency does not exceed 30%, in general, the economy of solar energy cannot compete with conventional energy, so the development of solar power is also subject to economic constraints. Recycling of solar panels is also a big problem today. The life of solar panels is only 25-30 years, and the replaced solar panels are difficult to be decomposed by nature, resulting in a lot of pollution.

In my opinion, the most important thing for solar power generation is to focus on improving efficiency, which has been a bottleneck that has been unable to break through since the development of solar power generation. Since the conversion efficiency of solar panels is still not high, future studies should focus on exploring the factors that affect the efficiency of solar panels and avoid them. Low cost, low pollution and high efficiency conversion materials should be explored. Second, the Chinese government should introduce policies to support and promote the recycling and storage of solar energy. Today's attention to solar panel recycling is low, but this is one of the big drawbacks of solar energy. So future research should focus on evaluating the recycling of solar energy, because it has not yet been achieved. As solar technology continues to advance, some problems that seem inevitable to us today may be solved in the future. Even if these problems cannot be completely solved in the future, they will certainly be improved and greatly reduce the adverse effects of all aspects of solar power generation technology. Therefore, based on my research, I believe solar power generation is highly likely to replace coal power generation on a large scale by 2060.

References

[1] Max. (2023). Advanced guide: How does coal energy work. *Linquip*. Retrieved from https://www.linquip.com/blog/how-does-coal-energy-work/#:~:text=1%20A%20machine%20called%20a%20pulverizer%20grinds%20the,energy%20that%20spins%20the%20turbine%20engine.%20More%20items.

[2] Liu, L., et al. (2010). Solar energy development in China—A review.

[3] Zhang, Y., et al. (2020). Solar energy potential assessment: A framework to integrate geographic, technological, and economic indices for a potential analysis.

[4] Yang, Y., et al. (2020). Potential of unsubsidized distributed solar PV to replace coal-fired power plants, and profits classification in Chinese cities.

[5] Vamvuka, D. (1999). Environmental impacts of coal utilization on the ecosystem.

[6] Clean Energy Ideas. (2019). Positive environmental impacts of solar energy. *Clean Energy Ideas*. Retrieved from http://www.clean-energy-ideas.com/solar/solar-energy/environmental-impacts-of-solar-energy/#:~:text=Positive%20Environmental%20Impacts%25.

[7] Prehoda, E. W., et al. (2017). Potential lives saved by replacing coal with solar photovoltaic electricity production in the U.S.

[8] Hitchin, P. (2018). High-efficiency, low-emissions coal plants: Come HELE or high water. *GE Power*. Retrieved from https://www.ge.com/power/transform/article.transform.articles.2018.mar.come-hele-or-high-water.

[9] Church, B., et al. (2023). Solar panel efficiency. *Consumer Affairs*. Retrieved from https://www.consumeraffairs.com/solar-energy/how-efficient-are-solar-panels.htm.

[10] Sampaio, P. G. V., et al. (2017). Photovoltaic solar energy: Conceptual framework.

[11] Dodd, G. (2021). Advances in solar panel technology. *University of Sydney*. Retrieved from https://www.sydney.edu.au/news-opinion/news/2021/05/25/advances-in-solar-technology.html.

[12] Tur, M. R., et al. (2018). Effect of faults in solar panels on production rate and efficiency.

[13] Wang, Y., et al. (2014). The economic impact of emission peaking control policies and China's sustainable development.

[14] Yang, X., et al. (2010). A comprehensive review on the development of sustainable energy strategy and implementation in China.

[15] Harvard John A. Paulson School of Engineering and Applied Sciences. (2021). Solar energy can be cheap and reliable across China by 2060.

[16] Yan, J., et al. (2019). City-level analysis of subsidy-free solar photovoltaic electricity price, profits and grid parity in China.

[17] Kannan, N., et al. (2016). Solar energy for future world: A review.

[18] Mittal, M. L., et al. (2014). Decadal emission estimates of carbon dioxide, sulfur dioxide, and nitric oxide emissions from coal burning in electric power generation plants in India.

[19] Tyagi, V. V., et al. (2013). Progress in solar PV technology: Research and achievement.

[20] Ramanathan, V., et al. (2009). Air pollution, greenhouse gases and climate change: Global and regional perspectives.

[21] Wu, X., et al. (2021). Is solar power renewable and carbon-neutral: Evidence from a pilot solar tower plant in China under a systems view.

[22] Millstein, D., et al. (2017). The climate and air-quality benefits of wind and solar power in the United States.

[23] Ritchie, H. (2022). How does the land use of different electricity sources compare? *Our World in Data*. Retrieved from https://ourworldindata.org/land-use-per-energy-source.

[24] Solar Energy Industries Association (SEIA). (n.d.). Land use & solar development. Retrieved from https://www.seia.org/initiatives/land-use-solar-development#:~:text=Land%20Use.%20%26.%20Solar%20Development.%20As%20the%20industry,the%20environment%20and%20a%20boon%20for%20local%20communities.

[25] Solar Energy Industries Association (SEIA). (2019). Solar and agricultural land use can occur harmoniously. Retrieved from https://www.seia.org/sites/default/files/2019-11/Solar%20Ag%20Land%20Usage%20FactSheet%202019-PRINT.pdf.

[26] Fouad, M. M., et al. (2017). An integrated review of factors influencing the performance of photovoltaic panels.

[27] Liu, L., et al. (2022). Potential contributions of wind and solar power to China's carbon neutrality.

[28] Chowdhury, M. S., et al. (2020). An overview of solar photovoltaic panels' end-of-life material recycling.

[29] Divya, A., et al. (2023). Review on recycling of solar modules/panels.
[30] Genchi, G., et al. (2020). The effects of cadmium toxicity.
[31] Rabaia, M. K. H., et al. (2021). Environmental impacts of solar energy systems: A review.
[32] Atasu, A., et al. (2021). The dark side of solar power.
[33] Gaille, L. (2017). 14 advantages and disadvantages of coal.
[34] UL Research Institutes. (2022). Environmental impacts of lithium-ion batteries. Retrieved from https://ul.org/research/electrochemical-safety/getting-started-electrochemical-safety/environmental-impacts.
[35] U.S. Department of Energy. (2019). Solar-plus-storage 101. Retrieved from https://www.energy.gov/eere/solar/articles/solar-plus-storage-101.
[36] Choi, C. S., et al. (2020). Effects of revegetation on soil physical and chemical properties in solar photovoltaic infrastructure.
[37] Kinkaid, M. (2021). Solar panels: Are aesthetics more important than the environment?
[38] Xi, J. (2014). We will actively promote China's revolution in energy production and consumption. Retrieved from http://china.cnr.cn/NewsFeeds/201406/t20140613_515664282.shtml.
[39] Xi, J. (2020). Xi Jinping's speech at the Climate Ambition Summit (full text). Retrieved from http://www.qstheory.cn/yaowen/2020-12/13/c_1126854050.html.
[40] Xinhua News Agency. (2021). Retrieved from https://www.gov.cn/xinwen/2021-03/31/content_5597134.htm#1.