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Comparison of Environmental Benefits Between Photovoltaic and Wind Power Based on LCA Method

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Abstract: Since the 21st century, climate change is a global issue that affects every corner of the world and extreme weather occurs frequently. The Paris Agreement proposes that countries should strengthen their response to the threat of climate change. Countries around the world are actively seeking energy transition. Photovoltaic power generation and wind power generation are the most important renewable energy generation methods in the world. These two technologies are pollution-free and zero carbon emission during the power generation process. But from the perspective of the full life cycle, there is still some controversy over the environmental benefits of both at present. This article normalizes and analyzes the input-output data of the cradle to grave process using the LCA methodology, and the results indicate that the environmental impact of photovoltaic power generation throughout the full life cycle is significantly greater than that of wind power generation. Based on the above conclusions, several measures are proposed to improve the ecological benefits of both photovoltaic and wind power generation.

Keywords: Climate change, Photovoltaic power generation, Wind power generation, LCA methodology, The environmental impact

1. Introduction

Since the 21st century, climate change has become increasingly serious. The increasing concentration of greenhouse gases in the atmosphere has led to global temperature rise, an increase in extreme weather, a decrease in biodiversity and so on. Intergovernmental Panel on Climate Change(IPCC)predicts that global greenhouse gas emissions by 2030 may lead to a global temperature rise of over 1.5℃ in the 21st century, and it is difficult to control the temperature rise within 2℃ [1]. Limiting global warming to 1.5℃ or 2℃ requires countries around the world to make every effort to reduce greenhouse gas emissions. As the world’s largest emitter of carbon dioxide, China’s emission reduction policies are also of great concern to countries around the world. On September 22, 2020, General Secretary Xi Jinping announced that China aims to peak its carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060 at the 75th United Nations General Assembly General Debate [2]. According to the "2023 Carbon Dioxide Emissions" report released by the International Energy Agency (IEA), global energy related carbon dioxide emissions will increase by 1.1% in 2023, reaching a historical high of 37.4 billion tons, an increase of 410 million tons [3]. The production and consumption in the energy sector account for 75% of greenhouse

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gas emissions. To reduce carbon emissions, achieve carbon neutrality, and better cope with the impact of climate change, it is crucial to abandon carbon in the energy sector.

To achieve carbon neutrality in energy, countries around the world are vigorously developing renewable energy. The International Renewable Energy Agency (IRENA) states that by the end of 2023, the global installed capacity of renewable energy will reach 3870 GW. Solar energy accounts for the largest share of the global total, with a capacity of 1419GW [4]. Renewable hydroelectricity and wind energy account for most of the remaining capacity, with a total capacity of 1268GW and 1017GW respectively [4]. Solar and wind energy continue to dominate the expansion of renewable energy capacity, accounting for 97.6% of the net increase in all renewable energy in 2023 [4]. The growth of wind and solar energy has brought the highest annual increase in renewable energy generation capacity, as well as the highest percentage increase on record. The proportion and capacity of renewable energy installed worldwide are shown in Fig.1 and Fig.2.

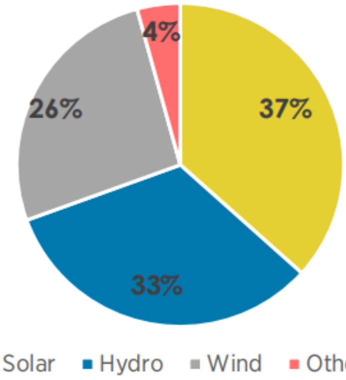

Figure 1: Renewable power capacity by energy source [4].

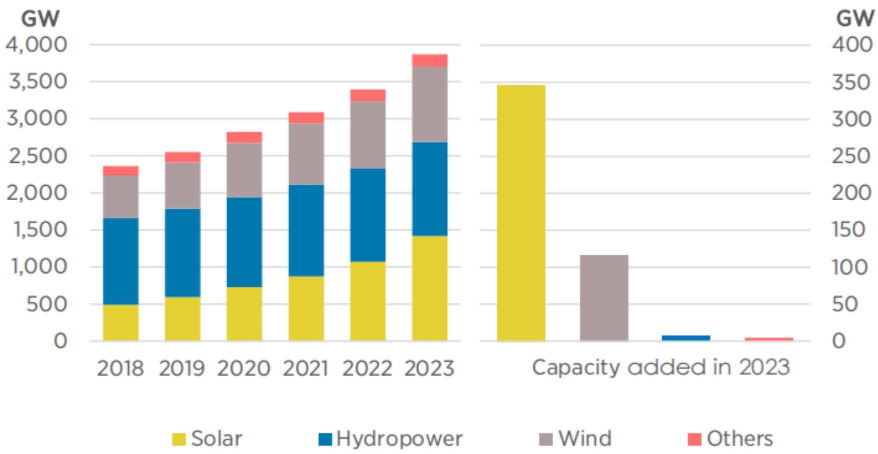

Figure 2: Renewable power capacity growth [4].

Photovoltaic and wind power, as the main forms of power generation, produce electricity that is pollution-free and does not produce carbon emissions during use. However, from the perspective of the full life cycle, there is still some controversy over the environmental benefits of these two technologies. For instance, Wu Jianguo, Wang Siyu, and others proposed that although photovoltaic power generation technology itself is zero emission and pollution-free, the pollutants generated in the production process such as photovoltaic equipment manufacturing still have an impact on the environment [5]. Zhang Xiong also referenced that wind power technology has broad prospects for the development of clean energy, but its construction process can also cause certain impacts and damage to the ecosystem [6]. In this context, the use of life cycle assessment methods to quantitatively and systematically evaluate the environmental impacts of various products, services, and technologies throughout their entire life cycle is of great significance for supporting macro decision-making and mitigating global climate change.

According to the definition of the International Organization for Standardization (ISO), the life cycle assessment (LCA) is a method of summarizing and evaluating the potential environmental impacts of all inputs and outputs of a product (or service) system throughout its pull life cycle [7,8]. It covers the entire life cycle of products, conducts systematic analysis for each link, quantifies and evaluates various environmental impacts, and expands the focus from end processes to the entire industry chain. This helps to comprehensively, systematically, and objectively identify the environmental loads and impacts generated by a product, process, or activity throughout the entire process. LCA methodology has also become one of the key tools for achieving sustainable development and carbon reduction.

This article is based on LCA technology, tracing the ecological and environmental impacts of the production processes of photovoltaic and wind power technologies in the entire industry chain from the perspective of full life cycle assessment, and quantitatively evaluating the environmental benefits of both. Subsequently, the research results are analyzed and targeted recommendations are proposed to provide methodological support for the steady advancement of global energy conservation and emission reduction goals.

2. Research methods

2.1. Research object and range

2.1.1. Research object

This study focuses on photovoltaic and wind power technologies, utilizing LCA methodology to systematically identify their energy consumption and environmental impacts in various production stages. The environmental benefits of both technologies are quantitatively evaluated from a full life cycle perspective and compared. On this basis, targeted suggestions are proposed for the global energy system to reduce carbon emissions from a low-carbon perspective.

2.1.2. System boundary

Determining system boundaries is a key step in using LCA methodology for research. It is determined by various factors such as research purpose and depth, and directly affects the accuracy of subsequent research and evaluation. According to the characteristics of photovoltaic and wind power construction projects, when using LCA methodology for research, quantifying the environmental and economic benefits of both in the process of acquisition and processing should be given attention. At the same time, in this process, we should also consider the consumption of various raw materials during actual construction and operation, the environmental load caused by their production and processing, and the environmental impact caused by the dismantling and scrapping of the power plant.

The system boundary of this study includes the production and transportation stages of raw materials and fuels, construction and installation stages, power plant operation stages, and abandonment and demolition stages, covering the entire production process of photovoltaic and wind power generation technologies from cradle to grave, and conducting a systematic evaluation of the environmental benefits of global photovoltaic and wind power technologies. The system boundaries of the photovoltaic power generation life cycle and the wind power generation life cycle are shown in Figure 3 and Figure 4.

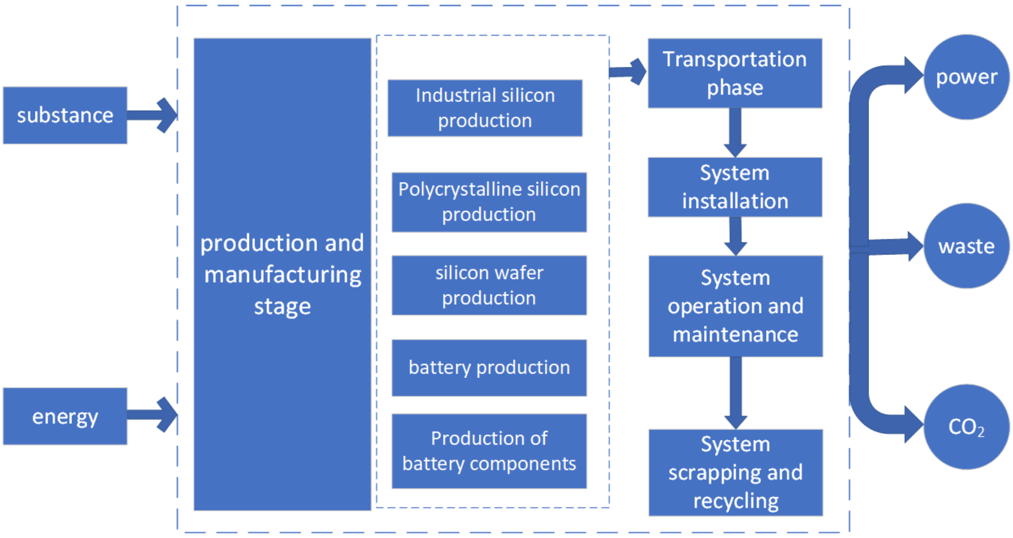

Figure 3: Boundary of photovoltaic power generation system.

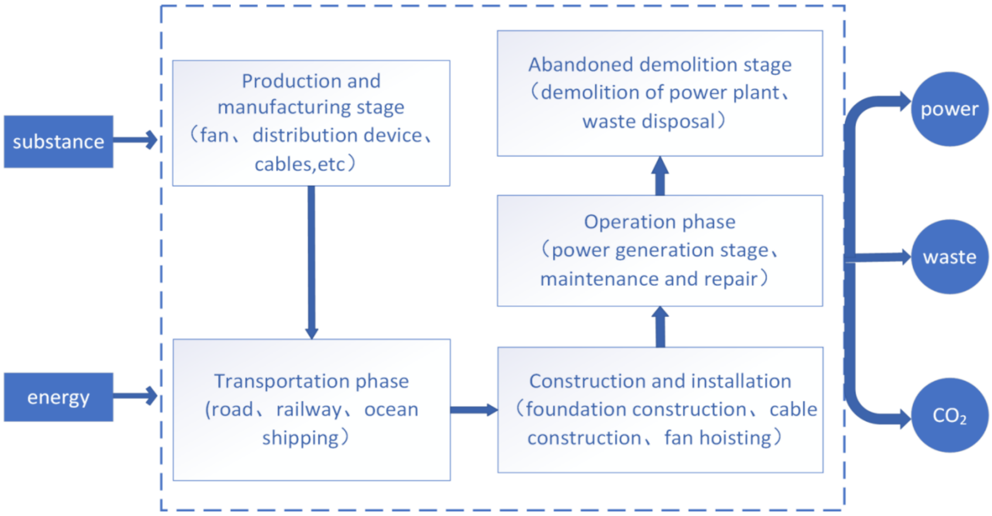

Figure 4: Boundary of wind power generation system.

2.2. Functional unit

In the process of LCA, to ensure the comparability of the final results, the benchmarks for measuring inputs and outputs of the systems should be unified. Functional units are the fundamental measurement method used to quantify the performance of product systems and are crucial for subsequent research. The functional unit selected for the LCA of photovoltaic and wind power generation in this study is 1KWh (power generation).

2.3. Life Cycle Inventory

Life Cycle Inventory Analysis (LCI) is an important step in conducting LCA. It is a quantitative technical process for the use of resources, energy, and waste discharge into the environment throughout the entire life cycle of a studied system, such as a product, process, or activity. Its core is to establish inputs and outputs based on functional units. The material and energy consumption of the two power generation methods are shown in Table 1, and the waste generated is shown in Table 2.

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Table 1: Material and energy consumption generated by photovoltaic and wind power generation [9].

resources	Photovoltaic power generation	Wind power generation
Raw coal(MJ/kWh)	6.72	0.55
Crude oil(MJ/kWh)	0.16	0.011
Natural gas(MJ/kWh)	0.045	0.0061
Freshwater(kg/kWh)	1.35	0.14
Original iron ore(kg/kWh)	0.0028	0.0028
Original copper mine(kg/kWh)	8.96E-7	3.25E-5
Limestone(kg/kWh)	0.000029	—

Table 2: Waste generated from photovoltaic and wind power generation (unit:kg/kWh) [9].

Emissions	Photovoltaic power generation	Wind power generation
CO2	0.034	0.035
CO	0.00017	8.56E-5
SO2	0.0013	0.00017
NOX	0.0012	0.00011
CH4	0.0014	0.00012
PM2.5	0.00042	3.84E-5
N2O	6.97E-6	5.64E-7
COD	5.73E-5	1.42E-5
Fly ash	0.046	0.0038
Lead	1.77E-8	1.53E-8
NH3	2.17E-6	5.39E-7
Waste water	0.25	0.030
Sludge	1.85E-8	1.52E-9
Slag	0.0068	0.0018

2.4. Data processing

Normalization is an important step in the process of life cycle assessment, which aims to eliminate the influence of dimension and unify different data on a comparable basis, facilitating our subsequent evaluation. In this step, the obtained data is converted into relative values, usually by dividing each data by a benchmark or average. By normalizing, the contribution of each stage to the environmental impact can be analyzed and compared more clearly, which facilitates subsequent research.

The normalization formula is as follows:

$$N_L = \frac{{m_i}^{LC}}{N_i} \tag{1}$$

where, NL is the normalized inventory substance index formula, Ni is the normalized baseline value as seen in Table 3, and ${m_i}^{LC}$ is the emission amount of a certain inventory substance.

Table 3: The normalized baseline value [9].

List of substances	Unit	Numerical value
CO2	KgCO2eq	7.28E+11
water consumption	Kg	1.45E+14
SO2	KgSO2eq	2.02E+10
NOX	Kg	1.98E+10

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Table 3: (continued).

COD	kg	6.92E+09
NH3·N	kg	1.09E+10
Primary Energy Demand (PED)	MJ	2.56E+13

The results of normalizing the above data are summarized in Table 4.

Table 4: Normalization results of inventory data.

List of substances	Photovoltaic power	Wind power
Greenhouse gas (GHG)	4.67E-14	4.81E-14
Industrial water consumption	9.34E-15	9.69E-16
Acidification potential(AP)	6.43E-14	8.41E-15
NOX	6.06E-14	5.56E-15
Chemical oxygen demand(COD)	8.28E-15	2.05E-15
NH3`N	8.38E-16	1.01E-16
Primary Energy Demand(PED)	8.02E-14	2.22E-14
Total	2.70E-13	8.74E-14

3. Result

According to the final data in Table 4, the environmental impact of photovoltaic power generation throughout its entire life cycle is significantly greater than that of wind power generation. And comparing Fig.5 and Fig.6, there are differences in the structure of factors that contribute to the impact of the two technological environments. For photovoltaic power generation technology, primary energy consumption (PED), acidic substances, nitrogen oxides, and CO2 emissions constitute the vast majority of its environmental impact throughout its entire lifecycle. Therefore, it can be inferred that in the photovoltaic power generation process, the consumption of energy such as raw coal, crude oil, and natural gas, as well as the emission of various waste gases, are the main links that cause environmental impact throughout its entire lifecycle, including production and operation. According to Fig.6, carbon dioxide emissions account for 55.04% of the environmental impact of wind power generation technology, indicating that carbon dioxide gas emissions are the main factor causing the environmental impact of wind power generation.

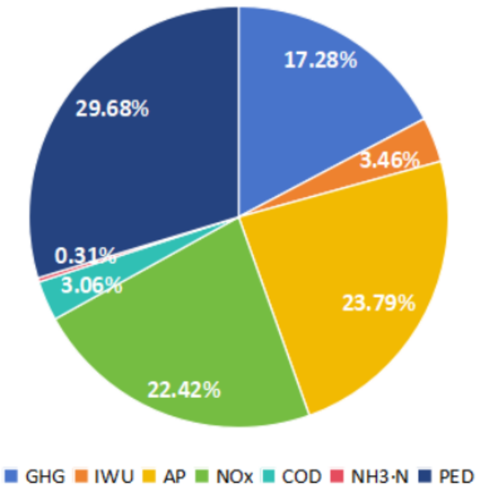

Figure 5: Proportion of substances in each list of photovoltaic power generation.

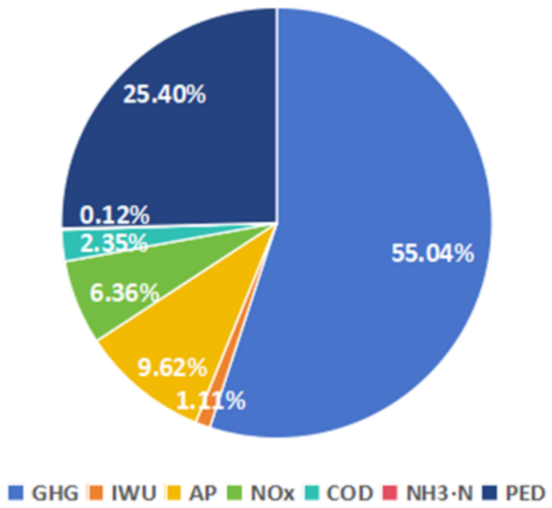

Figure 6: Proportion of substances in each list of wind power generation.

In addition, according to the analysis and observation of Fig.7, there is not much difference in carbon dioxide emissions between the two technologies. However, photovoltaic power generation has an order of magnitude higher acidification potential, nitrogen oxide emissions, and industrial water consumption than wind power generation. Moreover, the primary energy consumption of the former is much higher than that of the latter, indicating that photovoltaic technology requires more material and energy consumption in the production and use process, and it will have a greater impact on the environment throughout the entire life cycle of production, transportation, and operation.

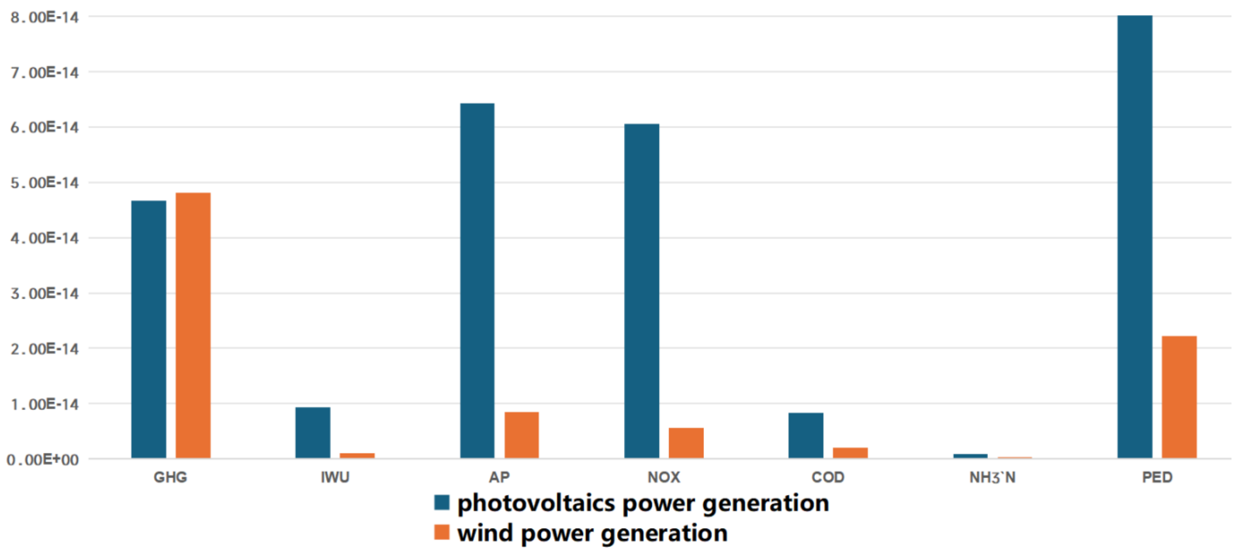

Figure 7: Proportion of each substance list for two power generation technologies.

4. Discussion

4.1. Comparison and analysis

On the basis of previous research, this article uses LCA methodology to comprehensively evaluate the environmental benefits of photovoltaic power generation technology and wind power generation technology throughout their full life cycle. After searching for data, conducting inventory analysis, and normalizing, it was found that the overall environmental benefits of photovoltaic power generation technology are lower than those of wind power generation technology. However, Wu Chenhao mentioned that the environmental impact potential of photovoltaic power generation technology is lower than that of wind power generation, and the ecological efficiency and overall benefits of the former are higher than those of the latter, which is significantly different from the results of this paper [10]. Through analysis, it was found that this difference occurred because Wu Chenhao not only evaluated the environmental benefits of several power generation technologies throughout their entire life cycle from a time scale in the article, but also considered the economic benefits of various power generation technologies from an economic perspective, thus constructing an ecological benefit evaluation model and drawing conclusions. However, this article uses the traditional LCA methodology to compare the input and output of the two technologies throughout their entire life cycle, considering their energy and material consumption as well as waste emissions in production and operation processes, leading to different conclusions.

4.2. Suggestions

Based on existing research and the above analysis, combined with the status of photovoltaic and wind power generation, the following suggestions are proposed:

4.2.1. Develop policy support

Governments of various countries should scientifically plan wind resource rich areas, reasonably layout wind power projects, determine suitable locations for wind farm construction, avoid resource waste and environmental impact, and introduce relevant policies to increase research and development investment in wind power technology, and encourage enterprises and investors to increase investment in the wind power field. Taking Pingtan in Fujian, China as an example, due to its location at the entrance of the Taiwan Strait, the "narrow tube effect" is obvious, making it one of the regions with the richest wind energy resources in China. With substantial support from the local government and tailored to local conditions, a wind power experimental group was established in the 1970s to initiate the development of wind turbines, which began commercial development in the 1990s.Subsequently, attracted by local policies and wind energy advantages, a series of energy groups participated in the construction of wind power projects in Pingtan and formed a wind power industry chain. As of now, Pingtan Island has entered the era of "deep all green electricity" [11].

4.2.2. Technology innovation to improve existing problems

Photovoltaic power generation projects should adopt low-carbon and environmentally friendly construction methods as much as possible in construction and operation, and adopt advanced waste disposal technologies and measures to effectively dispose of waste materials such as solar panels to reduce their impact on the environment. Scientists around the world are also accelerating research on the recycling of discarded photovoltaic panels. For example, Bruton proposed a method of using inorganic acid-base dissolution to treat photovoltaic panels, which is simple to operate, has a short process, and has low energy consumption [12].Klugmann Radziemska proposed using the "heat treatment chemical dissolution" method to treat scrapped photovoltaic panels, which can successfully recover clean silicon chips [13].In addition, when the components of scrapped photovoltaic panels are completely separated, valuable metals in the solar cells can be recycled, thereby reducing the environmental impact of photovoltaic power generation technology.

4.2.3. Improvement of energy utilization efficiency

In the above analysis, it can be seen that both photovoltaic power generation and wind power generation consume a large amount of primary energy throughout their entire life cycle. Therefore, when utilizing both photovoltaic and wind power technologies, we should reasonably arrange the layout of photovoltaic modules and wind turbines to avoid shadows and wind resistance affecting wind power efficiency and improve overall energy output. Meanwhile, with the continuous development of energy storage technology, the two technologies of photovoltaic and wind power can be combined, such as using PEDF technology [14], which combines photovoltaic power generation, energy storage, direct current, and flexibility. Firstly, solar energy is converted into electrical energy through photovoltaic panels, and then excess electricity generated during the day is stored using energy storage devices, thus achieving continuous energy supply to electrical equipment at night or on cloudy days. Then, through direct current distribution, the direct current electricity generated by photovoltaic power generation is directly transmitted to the electricity consuming area, solving the problem of energy loss in traditional alternating current electricity conversion process. Finally, intelligent flexible electricity use function is adopted, and various electricity demands are flexibly adjusted and managed through intelligent control system. This system greatly improves energy utilization efficiency and enhances power generation efficiency [15].

5. Conclusion

Against the backdrop of rapid global climate change, countries around the world are seeking changes in their energy structure. Photovoltaic power generation and wind power generation are currently the most important renewable energy generation methods, and their environmental benefits have gradually become the focus of attention for countries around the world. This article starts from the perspective of the entire life cycle, and based on previous research, uses LCA methodology to normalize the input-output quantities of the two during the entire life cycle process. Through comparative analysis, it is found that from the perspective of the entire life cycle, the environmental impact of photovoltaic power generation is significantly greater than that of wind power generation. Based on this article and existing research, suggestions are proposed for the development of current photovoltaic and wind power technologies. Meanwhile, due to the different scope and perspectives considered, this article found differences in research results when compared with previous studies. In future research, refining data and evaluating photovoltaic and wind power technologies from multiple perspectives will become the direction of efforts.

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