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Original Research

Environmental Impact Assessment of the Photovoltaic Industry Based on LCA

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Abstract

At present, the global energy crisis and environmental problems are worsening, and there is an urgent need to use new energy sources to replace traditional fossil energy sources. Photovoltaic (PV) power generation, as a primary clean energy source, has the potential to become a major energy solution with sustainable development prospects and is suitable for future energy development. Photovoltaic power generation is generally considered to be highly environmentally friendly. However, from a life cycle perspective, PV is not "zero pollution", and the PV industry is more or less likely to produce pollution and cause a certain degree of damage to the ecological environment in terms of the manufacturing of components and equipment, operation, and maintenance; current research has not yet carried out a comprehensive evaluation of the environmental impact assessment of photovoltaic power generation. Therefore, this paper focuses on the photovoltaic industry and the environmentally sound related industry and combines the basis of the life cycle as an entry point, research, and analysis of the photovoltaic industry full life cycle of the various stages of the photovoltaic power generation industry produced by the pollutants for a comprehensive evaluation, including carbon emissions, nitrogen oxides, sulfur dioxide, hazardous wastes, and other 11 kinds of pollutants. Take the polysilicon photovoltaic power generation system as an example to carry out empirical analysis; according to the statistical results, the contribution analysis and sensitivity analysis of the life cycle results show that the stage of photovoltaic power generation with the greatest environmental impact is the production and construction stage of the photovoltaic system. The consumables with the greatest impact on the environment are electricity and aluminum. This paper systematically researches the impact of the whole life cycle of the PV industry on the environment, which to a certain extent fills the gaps of related research, provides analytical methods and theoretical guidance for a deeper understanding of the environmental impact of the PV industry, and the results of the analysis can provide suggestions for the direction of the development of PV power generation.

Keywords: photovoltaic power generation, LCA, environment, pollutants

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Introduction

Energy is an important material basis for the survival and development of human society, but the environmental pollution caused by energy development and utilization is the main reason for the increasingly serious environmental problems [1]. Along with the use of energy, a series of serious environmental problems have followed, mainly including air pollution and ecological damage. Harmful gases such as carbon dioxide, sulfur dioxide, carbon monoxide, nitrides, and fluorides emitted from energy development and utilization can change the composition of the original air, causing pollution and global climate change [2]. Mining, transportation, processing, conversion, and utilization of fossil fuels cause pollution to the atmospheric environment, especially fossil fuel combustion [3]. From China's energy use perspective, large amounts of exhaust gas and dust emitted from coal, oil, and natural gas are the main reasons for the harm to the atmospheric environment [4].

In the face of environmental threats, in recent years, China has made many attempts and explorations in the management of environmental pollution, of which low-carbon energy transformation is an important aspect, with power generation modes transforming from traditional fossil energy power generation to new energy sources such as photovoltaic and wind power [5].

Vigorously growing clean and renewable energy is one of the most important ways to improve the environment [6]. At present, the leading clean energy and renewable energy sources include solar energy, wind energy, hydrogen energy, fuel cell energy, geothermal energy, and so on. This will inevitably eliminate the disadvantages of existing energy utilization due to the advantages of low or harmless emissions. Solar photovoltaic power generation, due to its unique advantages, is known as one of the best energy alternatives to chemical energy sources. Solar energy itself is pollution-free and inexhaustible, effectively reducing the country's energy shortage and pollution [7, 8].

In recent years, with the rapid development of the photovoltaic industry and the continuous advancement of research and exploration related to photovoltaic technology, domestic and foreign scientific researchers have gradually conducted relevant research on the environmental load in the photovoltaic field [9]. Life Cycle Assessment (LCA), as an environmental management tool, is widely used to study the impact of industrial products on the environment [10].

In China, research in the photovoltaic field mainly includes the environmental assessment of the production cycle of photovoltaic modules and the life cycle of photovoltaic power generation systems. Gang et al. summarize the research on applying photovoltaic power generation and solar thermal technology in CSGs. The application of these advanced solar technologies has made great progress [11]. Pu et al. assessed the environmental effects of the photovoltaic (PV) power generation industry in China from 2012 to 2017. They compared the carbon emission results derived from the use of the full life cycle carbon emission factor and the phased carbon emission factor to estimate the carbon emissions of the PV power generation industry based on the subphases of the life cycle. The results show that the carbon emissions from China's PV power generation industry show a steady growth trend, and the use of full life cycle carbon emission factors can ignore 90.77% of the carbon emissions compared with the use of phased carbon emission factors [12].

Using life cycle assessment theory, Guo et al. established a model for calculating carbon emissions from photovoltaic power generation systems during production, transportation, and emission treatment. The four stages of production and construction, transportation, power generation operation, and waste disposal of PV power generation systems were evaluated. The results of calculating the electricity consumption and power generation of the PV power supply chain throughout the life cycle show that the carbon footprint of PV power generation is relatively high in the production and construction stages [13]. Yueqiao has established the model of ammonia co-firing in coal-fired power plants (CFPP), encompassing the whole industrial chain from production to transportation and power generation. The assessment focuses on the economic aspects of ammonia co-firing, specifically emphasizing the opportunities for harnessing abandoned wind and solar resources, and further considers the life cycle assessment (LCA) of environmental impacts [14]. Frischknecht et al. discussed the life cycle inventory and life cycle assessment of PV systems. It focuses on the environmental impacts of PV systems, including resource use, energy consumption, and emissions. Also, the comprehensive assessment of the life cycle of PV systems helps people understand their impact on the environment and provides a reference for developing future sustainable energy policies [15].

There are many international precedents of LCA application in the photovoltaic field. This study introduces an innovative methodology for optimizing the renewable energy sources (RES) mix, specifically wind-based distributed generation (WDG) and photovoltaic distributed generation (PVDG), in smart grids to enhance sustainability and efficiency [16]. Arifin researched the development of a cooling system for photovoltaic panels that solves the problem of high operating temperatures that lead to reduced efficiency, and the results of the research improve the electrical and thermal efficiency of photovoltaic panels [17]. Constantino and Gabriel conducted a life cycle assessment of a group of polysilicon photovoltaic systems installed in northeastern Brazil. After evaluating 10 power plants, the results indicate that in countries relying on fossil fuels, photovoltaic technology may help reduce greenhouse gas emissions [18]. Some scholars have used machine learning models to predict solar

PV power generation. The results show that Random Forest Regression (RFR) and Long Short-Term Memory (LSTM) models outperform others. The findings could help solar PV investors streamline the process and improve solar production planning [19]. Fikri et al. explored the effect of solar electrocoagulation contact time on pH and TSS values of discharged wastewater from a psychiatric hospital wastewater treatment plant (WWTP). The results revealed that the change in solar electrocoagulation contact time significantly affected discharged wastewater's pH and TSS values [20]. Lan Miller implemented quantitative modeling on the parameters of greenhouse gas emissions during the life cycle of photovoltaic power generation. The study found that the impact of temperature-affected emissions is more significant in warm regions, and mainstream photovoltaic power generation's life cycle greenhouse gas emissions are far more limited. Mainstream photovoltaic power in all its forms has significantly lower life cycle greenhouse gas emissions than fossil power [21]. Klugmann-Radziemska conducted a complete life cycle assessment of all photovoltaic system components from production to installation and operation to disposal. The study showed that all photovoltaic system life cycle stages can help alleviate the global warming trend. In the primary production stage, a large amount of energy-recovered materials are used. Reducing energy consumption in producing high-purity crystalline silicon and using recycled silicon materials can help reduce greenhouse gas emissions by 42% [22].

Photovoltaic power generation technology is the first commercialized renewable energy with the largest market share, which has attracted growing attention. Therefore, there has been a rise in the number of relevant research studies on analyzing the environment in the photovoltaic field (especially greenhouse gas emissions) at home and abroad. In Table 1, some representative relevant research situations are summarized from the past five years. Different boundary conditions and evaluation indicators, geographical location, and analysis time of the research objects give rise to the research results [21-27].

In summary, domestic and foreign scholars have analyzed the life cycle of PV module manufacturing, module supply chain, and PV power generation systems through the LCA method. In terms of PV modules, most of the studies mainly focus on the environmental assessment and analysis of the life cycle of different production processes of solar-grade polysilicon, as well as the optimization and cycling process of the PV module supply chain. In terms of PV power generation systems, domestic and international studies have focused on environmental assessment and analysis of the life cycle of different PV power generation systems in terms of greenhouse gas emissions. The research progress on the environmental impacts of the PV industry in recent years is shown in the Table 1.

Table 1. Progress in research on environmental load in the photovoltaic field in the past five years.

Literature	Years	Location	System boundary	Environmental impact factor	Main results
Photothermal and Photovoltaic Utilization for Improving the Thermal Environment of Chinese Solar Greenhouses: A Review	2023	China	Full life cycle stages	CO_2, SO_2, NOx	The application of these advanced solar technologies has made great progress.
Enabling industrial decarbonization: A MILP optimization model for low-carbon hydrogen supply chains	2024	China	Production and construction stage, power generation operation stage, waste disposal stage	CO_2, CO, SO_2, NOx	Coal-fired thermal power plants have lower environmental costs
Sustainability of photovoltaic technologies in future net-zero emissions scenarios	2022	China	Production and construction stage, component transportation stage, power generation operation stage, waste disposal stage	CO_2, SO_2, NOx	Selecting suppliers reasonably, reducing transportation distances as much as possible, and adopting low-carbon production processes can effectively reduce carbon emissions
Life Cycle-Based Carbon Emission Reduction Benefit Assessment of Centralized Photovoltaic Power Plants in China	2024	China	Production and construction stage, power generation operation stage, waste disposal stage	CO_2, NOx, Chloride	The carbon emission intensity per unit power generation of the photovoltaic module life cycle using pyrolysis recovery technology is lower than the carbon emission level of similar research and my country's current power structure

Adoption of Photovoltaic Systems Along a Sure Path: A Life Cycle Assessment (LCA) Study Applied to the Analysis of GHG Emission Impacts	2018	Brazil	Production and construction stage, component transportation stage, power generation operation stage	Energy payback period, greenhouse gas emission rate	In fossil fuel-based countries, the use of photovoltaic technology may help reduce greenhouse gas emissions
Parametric modeling of life cycle greenhouse gas emissions from photovoltaic power	2019	United States, China, India, Australia, Egypt, Colombia, Germany	Production and construction stage	Greenhouse gas	In terms of photovoltaic module manufacturing, there is a big difference in emissions between China and Europe. The life cycle greenhouse gas emissions of mainstream photovoltaic power generation are much lower than those of fossil energy.
The use of recycled semiconductor material in crystalline silicon photovoltaic module production - A life cycle assessment of environmental impacts	2020	Europe	Production and construction phase, production operation phase, disposal phase	Greenhouse gas	In the primary production stage, reducing energy consumption during the production of high-purity crystalline silicon and using recycled silicon materials can reduce greenhouse gas emissions by 42%.
Are rooftop photovoltaic systems a sustainable solution for Europe? A life cycle impact assessment and cost analysis	2020	Europe	Component transportation stage	Climate change, acidification/ eutrophication, eco-toxicity, resources (fossil fuel), materials, inorganic dust	The impact of the photovoltaic system on the environment depends on the coordination of its installation location and local power. The impact on the environment during the transportation phase is relatively small, and the overall impact on the environment increases with the increase in transportation distance.

As can be seen from the Table 1, in recent years, many scholars in the photovoltaic industry life cycle, photovoltaic power generation on the environment, and other aspects of a large number of studies and contributions, but most of the existing research is focused on the photovoltaic industry at a certain stage of the life cycle of the photovoltaic industry or on the influence of the photovoltaic industry pollution of a number of factors to be investigated for the entire photovoltaic industry throughout all phases of the life cycle of pollutant emission levels, and the various comparisons of the research are less. Therefore, the research contribution of this paper is mainly in the following 2 aspects:

(1) Based on the life cycle theory, construct the life cycle assessment model of the photovoltaic power generation system. Using the utilization of SO_2, NO_x, CO_2, and particulate matter as environmental factors, conduct an environmental evaluation of the whole life cycle of raw material mining and production, transportation and installation, operation and maintenance, transmission and distribution, and decommissioning and disposal, and quantitatively compare the pollutant emission levels at each stage.

(2) Based on the full life cycle analysis of the pollutant emission level of the photovoltaic industry, a sensitivity analysis is carried out to calculate the sensitivity coefficients of various types of pollutants, respectively, and this conclusion is drawn: the future level of development of electrical energy and aluminum will have a greater impact on the emission coefficients of the photovoltaic service life. It has a certain degree of guiding significance and theoretical support for promoting the future sustainable development of photovoltaic power generation.

Theoretical Analyses

General Framework of Life Cycle Assessment

Life Cycle Assessment (LCA) is a process from the collection of raw materials to the production, transportation, sales, use, recycling, maintenance, and final disposal of the product, which is intended for evaluation of a certain product, process, or organized activity and is related to the environmental load at all stages of the entire life cycle [28]. The first thing it needs to handle is to identify and quantify the energy and material consumption and environmental emissions in each stage of the entire life cycle, then evaluate the impact of this consumption and emissions on the environment, and finally identify and evaluate opportunities and measures to reduce these impacts [29]. Life cycle assessment focuses on the research system's environmental impact in the fields of ecological health, human health, and resource consumption [30] (see Fig. 1).

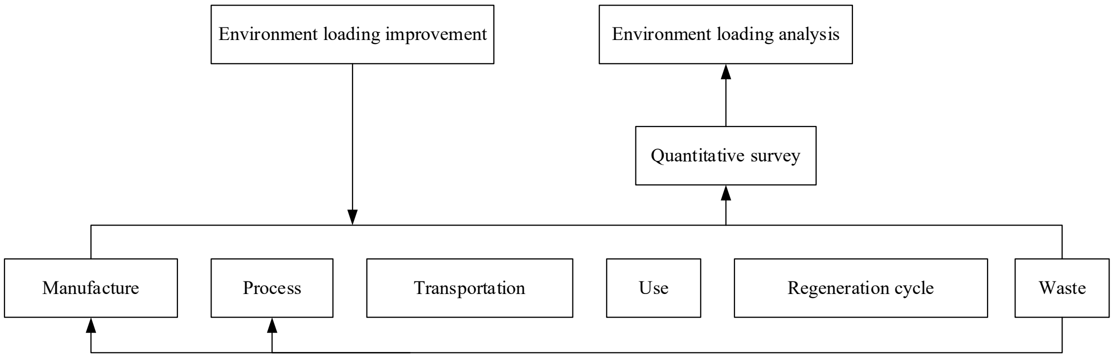

Fig. 1. Basic Ideas of Life Cycle Assessment.

Determination of the Purpose Scope

The first step in life cycle assessment is setting goals and scope. The definition of the goal mainly includes the reason for the project research, the expected application purpose, the targeted audience, and the information needed by the decision maker. The research scope includes the definition of the system, functions, functional units and baseline flows, initial system boundaries, data quality requirements, assumptions and constraints, and reports and appraisal reviews. LCA research is an iterative process. The objectives and scope can be revised or redefined based on the collected data and information and the interpretation of the results in future research. This process is generally expected to cover the following [31].

(1) System boundary definition. Determining the scope of research means defining the system and system boundaries. The boundaries of the life cycle stage, the scope of detail standards, and the scope of time and space of the evaluation object should be clarified in almost all life cycle assessments. The product life cycle stages are shown in the Fig. 2.

(2) Functional unit. Determining the functional unit is the cornerstone of the entire life cycle assessment because the functional unit determines the scale for comparing products. Its main purpose is to standardize the input and output of the product system. All data collected during inventory analysis are expected to be converted into functional units.

(3) Data quality, which determines the quality of the final life cycle assessment results, involves factors such as accuracy, completeness, representativeness, compatibility, and repeatability.

List Analysis

Inventory analysis is an important part of life cycle analysis. It is in the preliminary stage of data collection for life cycle analysis, laying the foundation for life cycle analysis receipts. In inventory analysis, by determining the type of data to be collected, collecting data at each stage of the product's life cycle in accordance with the requirements in the scope of purpose definition, quantitatively describing the logistics and energy flow of the input and output system boundaries, and the collected data is calculated and processed using models and databases to provide references for evaluation, analysis, and data interpretation. Models and databases are often involved to assist analysis. Inventory analysis

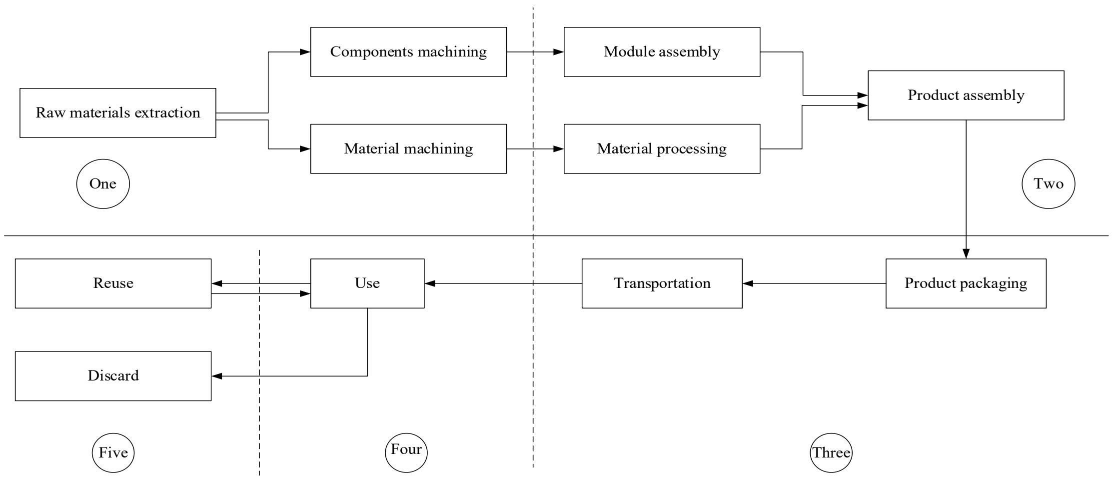

Fig. 2. Product life cycle stages.

mainly comprises the system's life cycle stage division, data type determination, data collection, and preliminary data processing [32]. The scope and input and output of the inventory analysis system are shown in Fig. 3.

Impact Evaluation

The impact evaluation analysis research methods vary with service objects, application purposes, and life cycles. Impact evaluation consists of the following parts: selection, classification, description, and weight determination of evaluation factors [33]. Each part represents a different procedure, but not all life cycle analyses require these components. The impact evaluation should clearly indicate the methodology chosen and the assumptions made.

(1) To make the impact assessment process reasonable and effective, the selection and definition of appraisers should be based on the production process and the mechanism of environmental discharge and pollution.

(2) The classification process allocates the input and output data in the inventory analysis to various evaluation factors. Proper allocation guarantees the accuracy and effectiveness of the evaluation.

(3) The description process is to model the inventory data allocated to various evaluation factors to express the environmental load and resource consumption.

(4) The result of the weight determination is used to compare different evaluation factors to determine the mutual importance of different factors.

Data Interpretation

Data interpretation is a comprehensive explanation of the data quality and analysis results of the inventory analysis and the conclusion of the evaluation analysis based on the inventory analysis and evaluation analysis of the life cycle analysis [34]. Fig. 4 shows the relationship between the interpretation phase and the other phases of life cycle assessment. Data interpretation provides technical support and a reference basis for decision-makers and policymakers in the form of conclusions and recommendations and meets the requirements set out in the purpose scope.

Data interpretation refers to redefining the data in the research according to the research requirements, which requires repeated collection of certain data to conduct sensitivity analysis on the research results. It has an important role in finding the most important stages and influencing factors of environmental pollution and impact on the entire life cycle of the product, based on the results of inventory analysis and evaluation analysis. It provides effective technical support for researchers and policy departments.

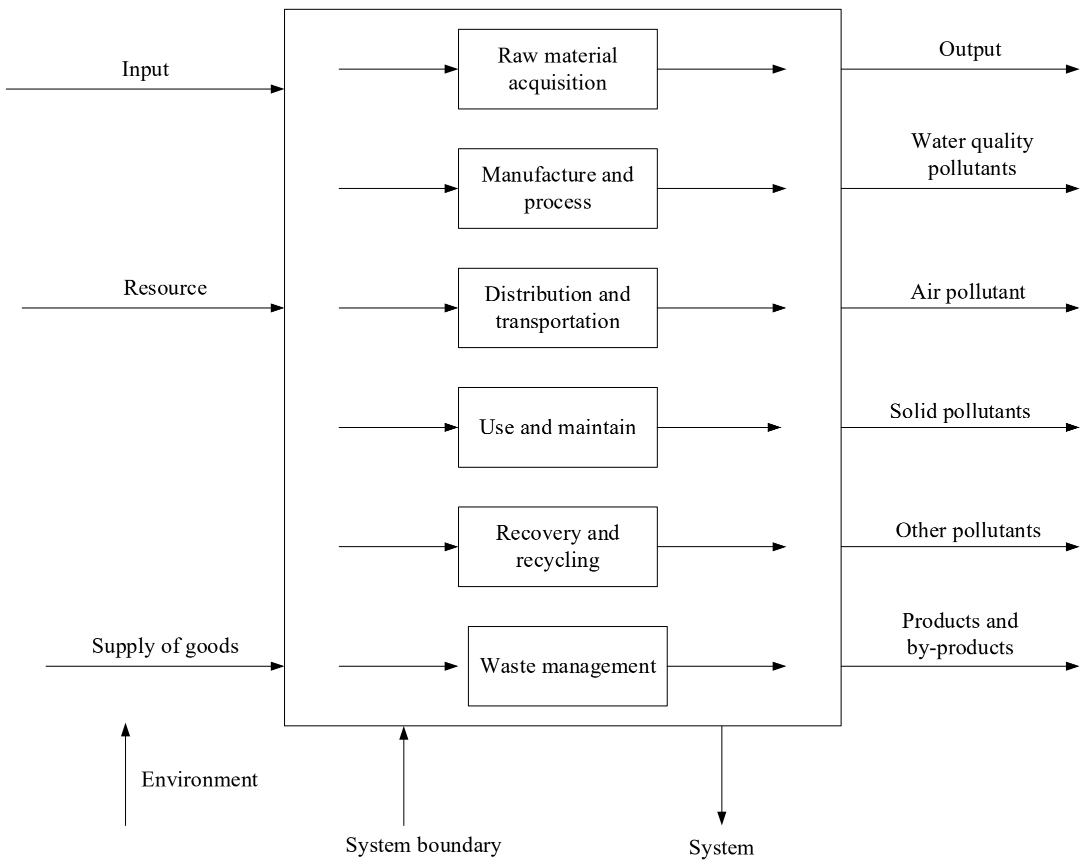

Fig. 3. Scope and input and output of the inventory analysis system.

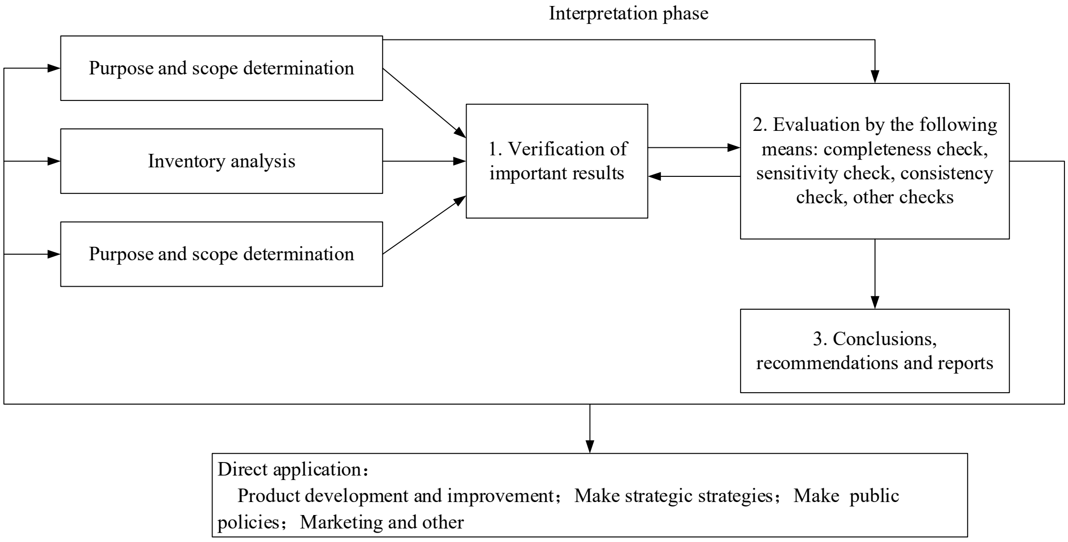

Fig. 4. The relationship between the life cycle assessment interpretation stage and other stages.

Construction of a Life Cycle Assessment Model for Photovoltaic Power Generation Systems

In recent years, crystalline silicon solar cells, made of polycrystalline silicon, with maximum productivity and utilization, whose output accounts for more than 85% of the current world's total solar cell output, with a market share as high as 90% in China. According to the characteristics of life cycle assessment and the whole life cycle process of polycrystalline silicon photovoltaic system grid-connected power generation, the basic model of the whole life cycle research and evaluation of the polycrystalline silicon photovoltaic system is constructed, as shown in Fig. 5. As a macro model, the life cycle process research model is not suitable for specific microcalculation processes and plays a role in guiding the actual research work of the polysilicon photovoltaic power generation system's full life cycle inventory data analysis, impact evaluation, and improvement evaluation.

Impact assessment generally involves three major aspects: resource consumption, ecological environmental impact, and human health impact. Life cycle impact assessment is usually defined as a "three-step" model of classification, characterization, and quantification, in which the life cycle inventory provides a detailed description of basic flows such as resource consumption and environmental emissions. Then, the impact assessment is classified, characterized, and normalized weighted according to impact types via different methods.

This study considered the raw material mining and production, transportation and installation, operation and power transmission and distribution, and decommissioning recovery phases of the polycrystalline silicon photovoltaic power generation system throughout the life cycle. A quantitative model was constructed, including seven characteristic indicators, including primary energy consumption (PED, kgce), sulfur dioxide (SO_2, kg), nitrogen oxides (NO_x, kg), carbon dioxide (CO_2, kg), and particulate matter, most of which are listed substances and do not require characterization factors. The quantitative model is as follows:

$$P_{ij} = DP_{ij} + GP_{ij} * G_i \tag{1}$$

$$UP_j = \frac{P_1 + P_2 + P_3 + P_4}{PG} \tag{2}$$

$$PG = SR * A * CE * PE \tag{3}$$

i represents the various stages of the life cycle of the photovoltaic power generation system; j represents the types of pollutants discharged during the life cycle of the photovoltaic power generation system; P_{ij} is the total emission of the j phase pollutant in the i phase stage of the photovoltaic power generation system life cycle; DP_i is the direct emission of the j phase pollutant in the i phase stage of the photovoltaic power generation system life cycle; G_i is the energy consumption in the i phase of the life cycle of the photovoltaic power generation system; GP_{ij} is the emission coefficient of the j phase pollutant corresponding to the energy consumption in the i phase of the photovoltaic power generation system life cycle; UP_j is the emission coefficient of the j phase pollutant; *PG* is the actual annual power generation of a 1MWp photovoltaic power generation system; *SR* is the annual average solar radiation of a 1MWp photovoltaic power generation system; *A* is the total area of a 1MWp photovoltaic power generation system battery; *CE* is the photoelectric conversion efficiency; *PE* is the actual power generation efficiency.

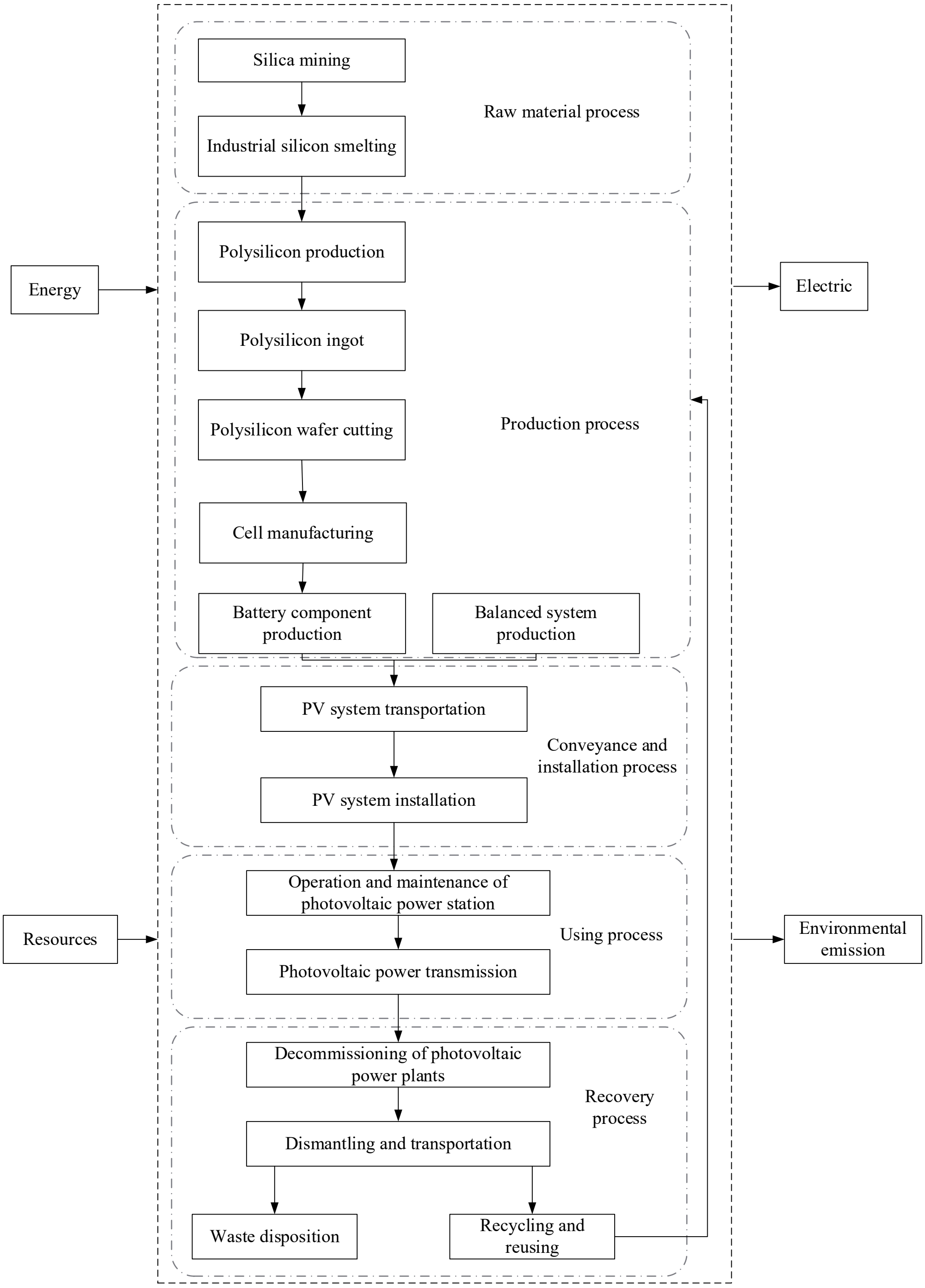

Fig. 5. Schematic diagram of the full life cycle assessment model of the polysilicon photovoltaic power generation system.

Material and Methods

Research Objectives and Scope

Research Goals and Significance

With the development of technology and the decrease in production costs, solar power generation has become a promising renewable energy technology with wide applications and has received widespread attention worldwide. Photovoltaic technology, a branch of solar power generation, has negligible environmental impact. However, from the perspective of the entire life cycle, its production, transportation, operation, and decommissioning disposal stages, there is great energy consumption, greenhouse gas emissions, and pollutants. In this section, life cycle background data are adopted as a reference to quantify the energy and environmental impacts of photovoltaic systems, accurately identify the environmental impacts of each life cycle stage, clarify the environmental benefits of photovoltaic power generation, and eliminate people's doubts about the environmental issues of photovoltaic power generation. It can provide a scientific basis and theoretical reference to the decision-making of relevant departments and the technological improvement of photovoltaic power generation enterprises.

Research Object and System Boundary

According to the types of raw materials, solar cells can be categorized into silicon solar cells, multiple compound thin-film solar cells, polymer multilayer modified electrode solar cells, nanocrystalline solar cells, and organic solar cells. In China, silicon solar cells are currently well-refined and occupy a dominant position in applications. Silicon solar cells enjoy a market share of about 98% in China, taken as the research object.

This section mainly analyzes the photovoltaic grid-connected power generation of crystalline silicon solar cells. In order to accurately calculate the types of pollutants and emissions during the life cycle of photovoltaic power generation, it is first necessary to determine the boundaries of the industrial chain, as shown in the Fig. 6.

As shown in the Fig. 6, according to the technical characteristics and relevance of each link of the photovoltaic system, it can be divided into four stages: production, transportation and installation, operation and power transmission and distribution, and power station decommissioning. The pollutants in the production stage mainly come from the production chain of silicon's main material, and the production and transportation of various auxiliary materials have a negligible amount of pollutant emissions during the production stage. Therefore, the production stage mainly considers the production of photovoltaic power generation systems, including quartz sand mining, industrial silicon production, high-purity polysilicon, polysilicon ingot production, polysilicon wafer cutting, cell manufacturing, cell module production, and balance system production. The transportation and installation stage mainly considers the pollutants generated by the consumption of diesel fuel during the transportation of the photovoltaic power generation system. The installation stage only consumes a small amount of electricity, and the environmental impact is negligible. In the operation and power transmission and distribution stage, solar cells directly convert solar energy into electrical energy, which is a completely clean process. However, power loss in the power transmission

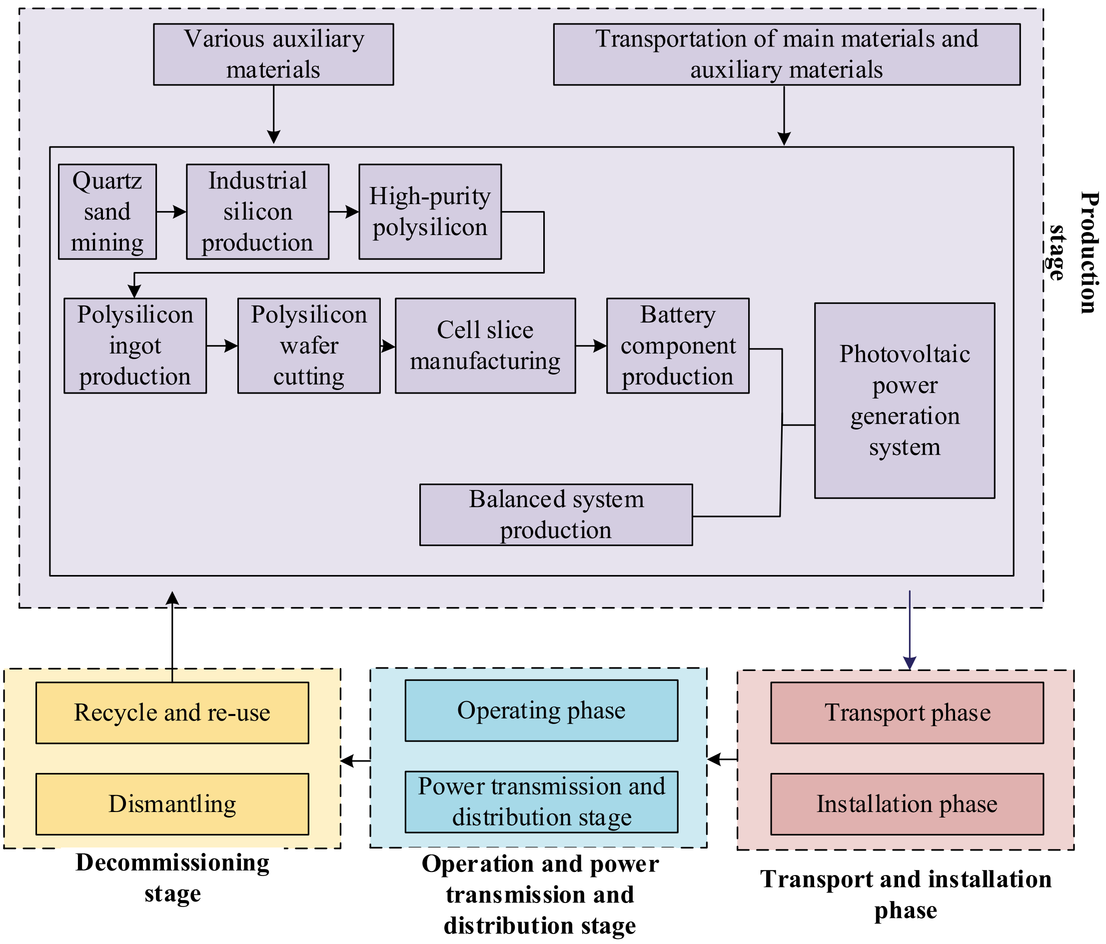

Fig. 6. Technical characteristics and correlation of each link of the photovoltaic system.

and distribution stage will lead to the production of pollutants. The decommissioning stage of the power station is divided into dismantling, treatment, and recycling. The dismantling and treatment of photovoltaic panels will generate some pollutants. Some materials are recyclable in the decommissioning stage, and pollutants will also be generated during the recycling process.

The pollutant emissions involved in this study fall into two categories: direct and indirect. Direct emissions refer to the emissions from raw material mining, power station construction, operation, and decommissioning processes. Indirect emissions refer to the emissions from material processing to product molding experienced by various product elements (equipment, raw materials, and energy) involved in the construction, operation, and decommissioning process before becoming the product form used by this system.

List Analysis of Each Stage of the Photovoltaic System Life Cycle

Production Stage of the Photovoltaic System

(1) Quartz sand mining

The general production process of quartz sand is as follows:

1) Crushing: After the stone is mined, it is crushed by the coarse crusher. 2) Separation: The crushed stones are transported by a belt conveyor to a fine crusher for further crushing and then separated by a vibrating screen. The stone material that meets the feed size of the sand-making machine is sent to the sand-making machine for sand-making, that is, ordinary quartz sand. 3) Selection: The stones from the sand-making machine are further selected, and the quartz sand with higher silicon content is separated to form refined quartz sand. 4) Processing: The selected quartz sands are further processed, such as pickling, purification, etc., to produce different types of quartz sand manufacturing products, such as pickling quartz sand, silica powder, etc.

By reviewing the literature [35, 36], the energy consumption required to produce 1 kg of industrial silicon, as well as the pollution caused by direct production and indirectly produced by energy consumption, are as described in Table 2.

(2) Industrial silicon production

The commonly used industrial silicon in industrial silicon production is produced by reducing SiO_2 with coke. Under normal circumstances, industrial silicon yields between 80-85%. In this process, CO, SiC, CO_2, C_2H_6, and other gases will be released. Every 1 kg of industrial silicon (MG-Si) reacts with oxygen to produce 6.0 kg CO_2, 0.008 kg SiO_2, and 0.028 kg SO_2. These gases are processed by a filter and discharged into the atmosphere. According to related literature, the energy consumption required to produce 1 kg of industrial silicon, as well as the pollution caused by direct production and indirectly caused by energy consumption, are as described in Table 3.

(3) Production of solar-grade polysilicon ingots

The production of solar-grade polysilicon adopts metallurgical methods, including four main processes: slag refining, pickling, directional solidification, and electron beam refining. The process of preparing solar-grade polysilicon by metallurgical method and the flow chart of sewage discharge are shown in the Fig. 7, which includes the directional solidification and ingot casting process; that is, the directional solidification of

Table 2. Pollutants produced per kilogram of industrial silicon (MG-Si) produced.

Link	Energy consumption (kWh)	Pollutants	Direct discharge (g)	Indirect emissions (g)	Total (g)
Quartz sand mining	0.48	CO_2	–	284.16	284.16
		Particulates	-	0.014	0.014
		SO_2	-	0.068	0.068
		NO_X	-	0.066	0.066
		SiO_2 (dust)	0.185	-	0.185

Table 3. Pollutants produced per kilogram of industrial silicon (MG-Si) produced.

Link	Energy consumption (kWh)	Pollutants	Direct discharge (g)	Indirect emissions (g)	Total (g)
Production of industrial silicon	11.37	CO_2	6000	6731.04	12731.04
		Particulates	-	0.34	0.341
		SO_2	28	1.56	29.560
		NO_X	-	1.609	1.609
		S_iO_2	8	-	8

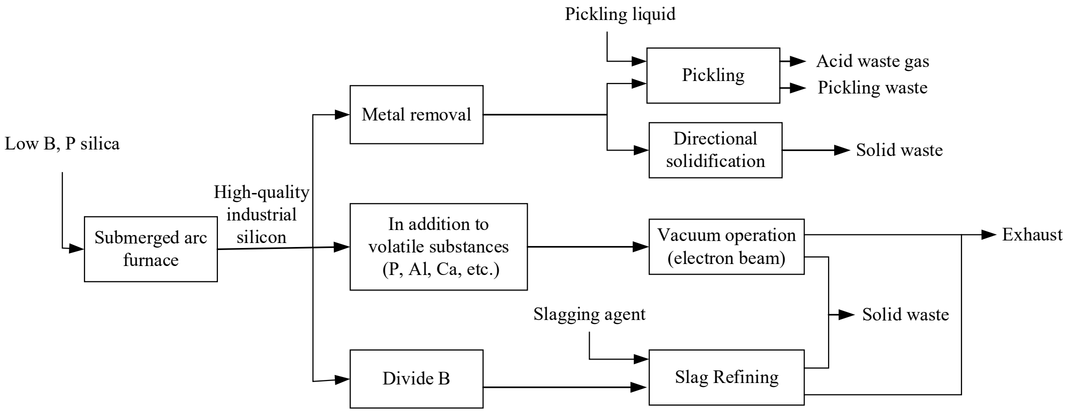

Fig. 7. Solar-grade polycrystalline silicon ingot production flow chart.

polysilicon is divided into two steps, with the purpose of purification and ingot casting.

The energy consumption required to produce 1t of solar-grade polysilicon, as well as the pollution caused by direct production and indirectly produced by energy consumption, are as described in Table 4.

(5) Polysilicon wafer cutting

The main raw material used in the cutting process of polycrystalline silicon wafers is polycrystalline silicon ingot, and the auxiliary materials include pure water, steel wire, polyethylene glycol, silicon carbide, glass, glue, lactic acid, citric acid, and cleaning agent. During the slicing process of polycrystalline silicon ingots, due to broken ingot squares, cutting heads and tails, chamfering, wire cutting, and waste silicon wafers, the loss of silicon ingots is 25-50%, and the average value is 37.5%. The slicing mortar is used as a cutting fluid, mainly containing polyethylene glycol and SiC particles. They and silicon waste constitute waste-cutting fluid. After converting the relevant data from several groups of documents, the weighted average is investigated and calculated, and the data list of the polysilicon wafer-cutting process is listed in Table 5.

(6) Cell manufacturing

See the Fig. 8 for details of material input and pollution during the cell manufacturing process.

Due to the well-refined and transparent cell manufacturing process, the actual process data of cell manufacturing in this article is mainly derived from literature, which is calculated by weighted average after converting multiple sets of data in the literature (see Table 6).

(7) Production of battery components

The material input and sewage discharge during the production process of battery components are shown in the Fig. 9. The actual process data of the battery module production in this article mainly comes from literature, which is obtained by weighted average after converting multiple sets of data in the literature. The Table 7 shows the data list of the battery module production process.

(8) Balanced system production

The balance system is regarded as part of the photovoltaic power generation system, including supporting components and the structure and equipment needed to transmit photovoltaic power to the local grid. The bracket system is mainly composed of aluminum

Table 4. Pollutants produced per 1.00 t of solar-grade polycrystalline silicon ingot produced.

Link		Energy consumption (kWh)	Pollutants	Direct discharge (g)	Indirect emissions (g)	Total (g)
Solar-grade polycrystalline silicon ingot production	Solar-grade polysilicon production	41089.11	CO_2	-	24324753	24324753
			Particulates	-	1232.673	1232.673
			SO_2	-	5814.109	5814.109
			NO_X	-	5637.426	5637.426
			CaF_2	162380	-	162380
	Directional solidification ingot	11883.00	CO_2	-	7034736	7034736
			Particulates	-	356.49	356.49
			SO_2	-	1681.445	1681.445
			NO_X	-	1630.348	1630.348

Table 5. Pollutants produced per polysilicon wafer produced.

Link	Energy consumption (kWh)	Pollutants	Direct discharge (g)	Indirect emissions (g)	Total (g)
Cutting of silicon wafer (taking the production of a polycrystalline silicon wafer as an example)	0.64	CO_2	-	378.88	378.88
		Particulates	0.0046	0.0192	0.0238
		SO_2	0.0126	0.0906	0.1032
		NO_X	0.003	0.0878	0.0908
		Polyethylene glycol	20.4	-	20.4
		Silicon carbide	20.08	-	20.08
		CaF_2	0.22	-	0.22
		Lactic acid (hazardous waste)	0.93	-	0.93
		Citric acid (hazardous waste)	0.62	-	0.62
		COD	3.12	-	3.12

and stainless steel. Different photovoltaic power plants use aluminum and stainless steel in different ratios. It is assumed that the mass ratio of the aluminum bracket and the stainless steel bracket is 1:1. Research shows that the overall mass of the bracket in the ground-mounted balance system is 16,821 kg/MWp, and the overall mass of the junction box is 1,385 kg/MWp. Based on this, it can be estimated that the amount of brackets in the balance system of the 1MWp photovoltaic system is 16.82 t (in which the aluminum bracket and the stainless steel bracket are both 8.41 t), and the amount of junction boxes is 1.39 t. Assuming that the mass of the cable in

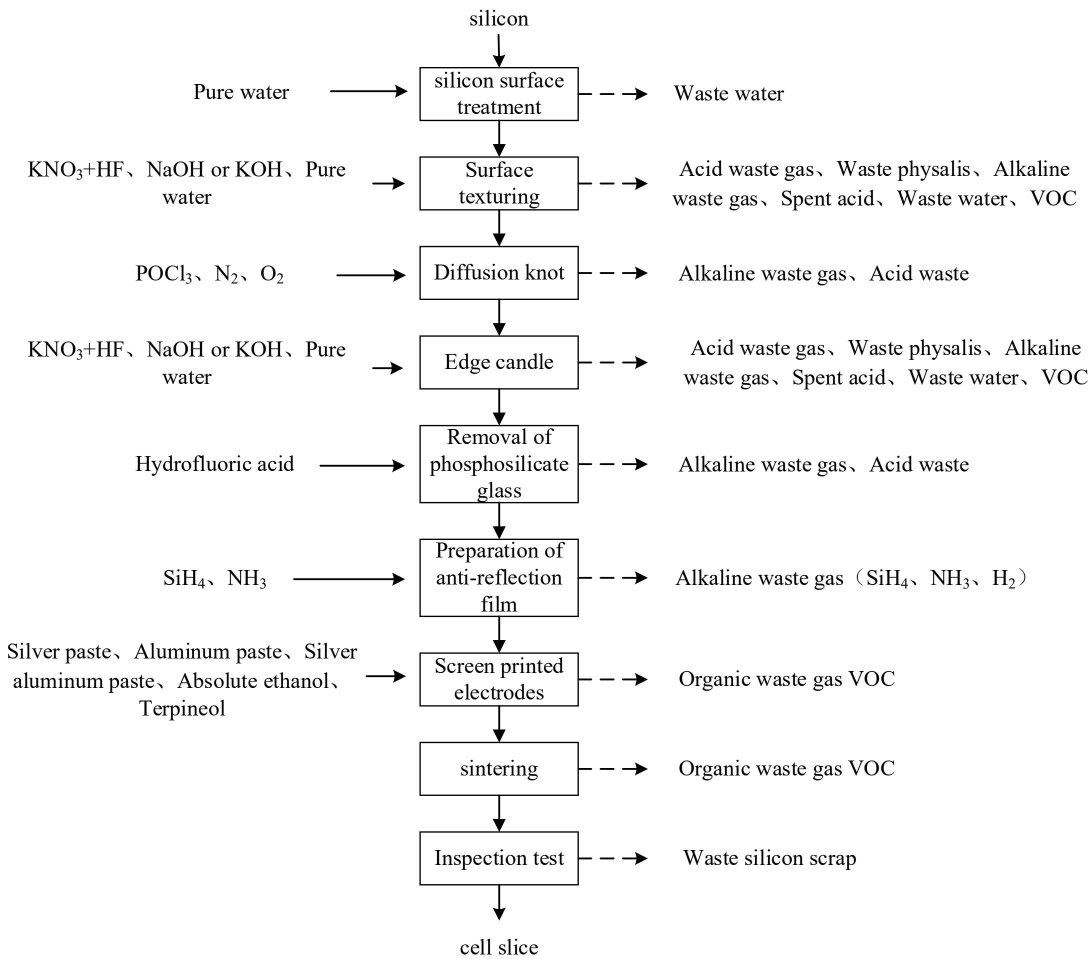

Fig. 8. Flow chart of cell manufacturing.

Table 6. Pollutants produced per cell produced.

Link	Energy consumption (kWh)	Pollutants	Direct discharge (g)	Indirect emissions (g)	Total (g)
Cell manufacturing	0.55	CO_2	-	325.6	325.6
		Particulates	-	0.0165	0.0165
		SO_2	-	0.0778	0.0778
		NO_X	0.12	0.0755	0.1955
		COD	0.12		0.12

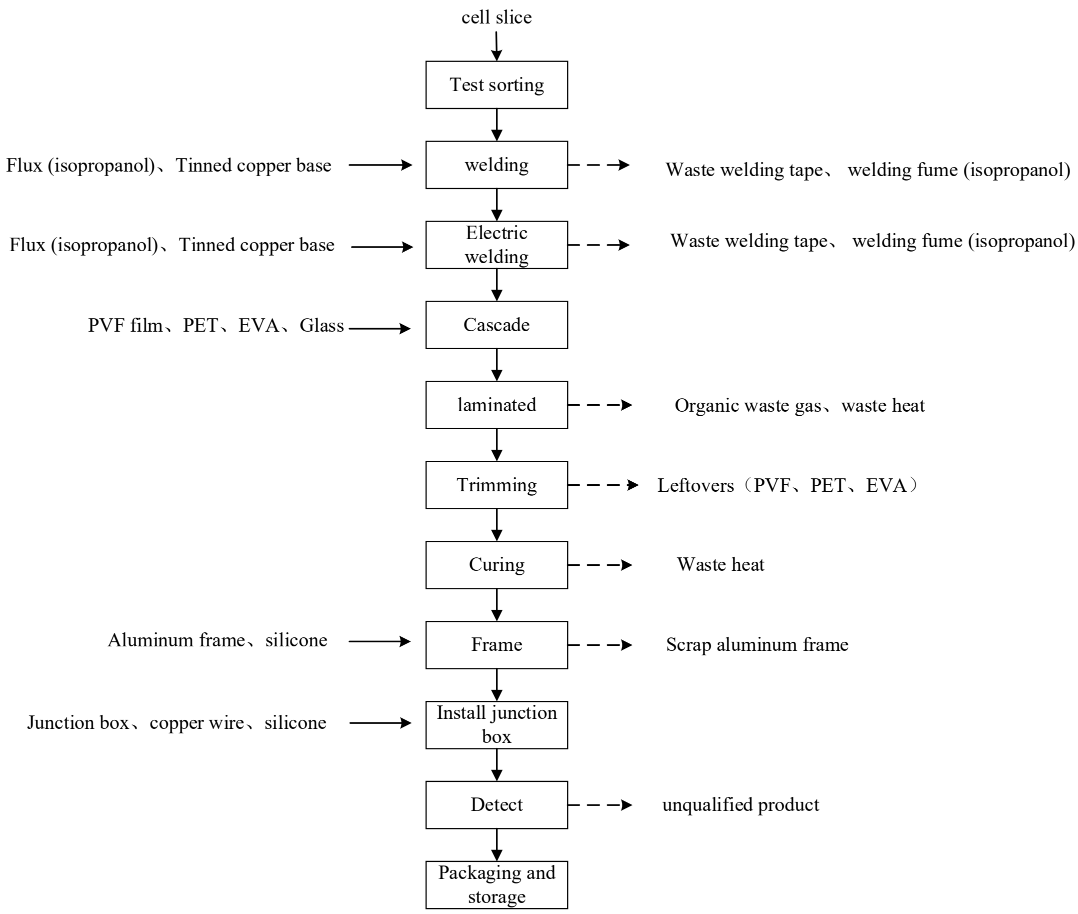

Fig. 9. Production flow chart of the battery module.

Table 7. Pollutants produced per battery pack produced.

Link	Energy consumption (kWh)	Pollutants	Direct discharge (g)	Indirect emissions (g)	Total (g)
Battery component production	11.90	CO_2	-	7044.8	7044.8
		Particulates	-	0.357	0.357
		SO_2	-	1.6327	1.6327
		NO_X	-	1.6839	1.6839

the balanced module of the 1 kWp photovoltaic system is 7.36 kG (including 4.36 kg of copper and 3 kg of insulation protection layer), the amount of cable in the balanced system of the 1 MWp photovoltaic system in this paper is estimated to be 7.36 t.

Table 8. Pollutants produced by MWp balance system.

Link	Energy consumption (kWh)	Pollutants	Direct discharge (g)
Balance system	Aluminum (8.41 t)	CO_2	127243.3
		Particulates	46255
		SO_2	287622
		NO_X	117740
	Stainless steel (8.41 t)	CO_2	38686
		Particulates	327.99
		SO_2	403.68
		NO_X	1892.25
	Copper (1.39 t)	CO_2	4865
		Particulates	258.54
		SO_2	1549.85
		NO_X	542.1

In summary, the main consumables considered for the balance system are aluminum 8.41 t, stainless steel 8.41 t, and copper 1.39 t. The amount of pollutants discharged is shown in the Table 8.

According to the above research, every production of a 1MWp photovoltaic system requires 8.25 t quartz sand mining, 6.60 t of industrial silicon, 5.38 t of solar-grade polysilicon, 5.32 t of polysilicon ingot, 260869.57 of polysilicon wafers, 260869.57 solar cells, and 4347.83 solar modules. The pollutant emissions produced by photovoltaic systems that produce 1 MWp are shown in the Fig. 10.

Transportation and Installation Stage

Among the intermediate products in the life cycle of the photovoltaic system, the weight of the photovoltaic system far exceeds the products of other intermediate processes. At the same time, considering the vertical integration trend of the photovoltaic industry chain, only the transportation energy of the photovoltaic system to the installation site is calculated. The environmental impact caused by consumption and other transportation processes is negligible [37].

Assuming that the photovoltaic system is transported by road, the transportation means is a heavy diesel

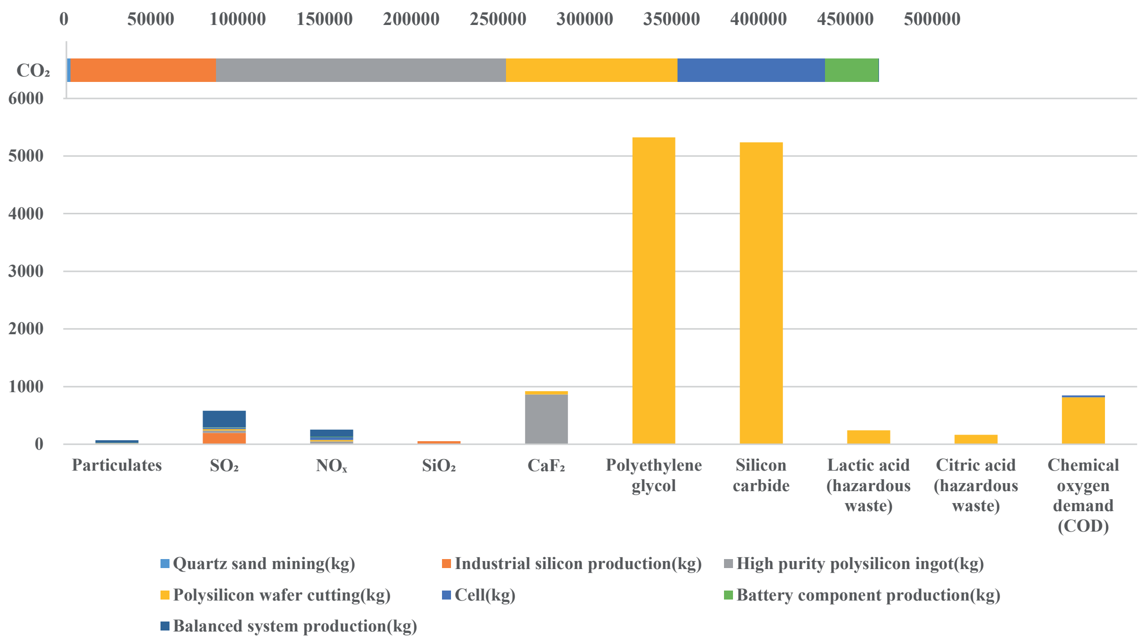

Fig. 10. Pollution discharge of photovoltaic system in the production stage.

truck (10 t), the transportation distance is 200 km, and the weight of the 1 MWp grid-connected photovoltaic system is about 136.43 t. Based on a fuel consumption of 20 L per 100 km, a total of 560 L of diesel was consumed. According to the reference, there is an energy consumption of 0.15 kWh/Wp for installing and constructing a photovoltaic system and 150,000 kWh for installing and constructing a 1 MWp photovoltaic system.

According to statistics, the pollutant emissions during the transportation and installation phase of the photovoltaic system are shown in the Fig. 11.

Operation and Power Transmission and Distribution

Photovoltaic power generation is a photovoltaic conversion process. In theory, the power generation process itself does not require energy consumption, but the actual photovoltaic power plant has a service life of about 25 years. The replacement rate of photovoltaic modules is generally less than 0.1%; the pollutants generated during the photovoltaic operation phase are 0.1% of the total emissions during the production phase [38].

The power generated by the photovoltaic system must inevitably be transmitted to users through the public grid with power loss. According to statistics from the National Energy Administration, the average loss rate of power transmission across the public grid in 2018 was 6.21%; that is, the pollutants generated in the power transmission and distribution stage were 6.21% of the total emissions in the previous stage. From the perspective of end users, this power transmission loss should be included in the life cycle assessment results of photovoltaic system power generation. According to statistics, the pollutant emissions during the photovoltaic system operation and power transmission and distribution stage are shown in the Fig. 12.

Decommissioning Disposal Stage

The boundary of the photovoltaic panel decommissioning disposal analysis system includes three subsystems: equipment disassembly, heat treatment of decommissioned photovoltaic panels, and subsequent recycling of recyclable parts [39, 40]. Generally speaking, the first step in recovering and recycling photovoltaic panels requires disassembling them into their main components. The next step is to remove the EVA layer and separate the glass from the silicon cell. The most common method to decompose the EVA layer is heat treatment.

The following is an example of photovoltaic panels per m^2 to analyze the pollutant emissions generated by dismantling and recycling (Table 9). Metal waste can be treated, which can reduce emissions to zero. According to the literature, the dismantling and recycling of photovoltaic panels per m^2 requires an energy consumption of 69.45 kWh as an integral part of the energy consumption in each link; all energy consumption is calculated in the dismantling process [41, 42].

The area of photovoltaic panels required for a 1MWp photovoltaic power station is about 6965 m^2. Therefore, the pollutants discharged during the decommissioning and disposal stage of a 1 MWp photovoltaic power station are shown in the Fig. 13.

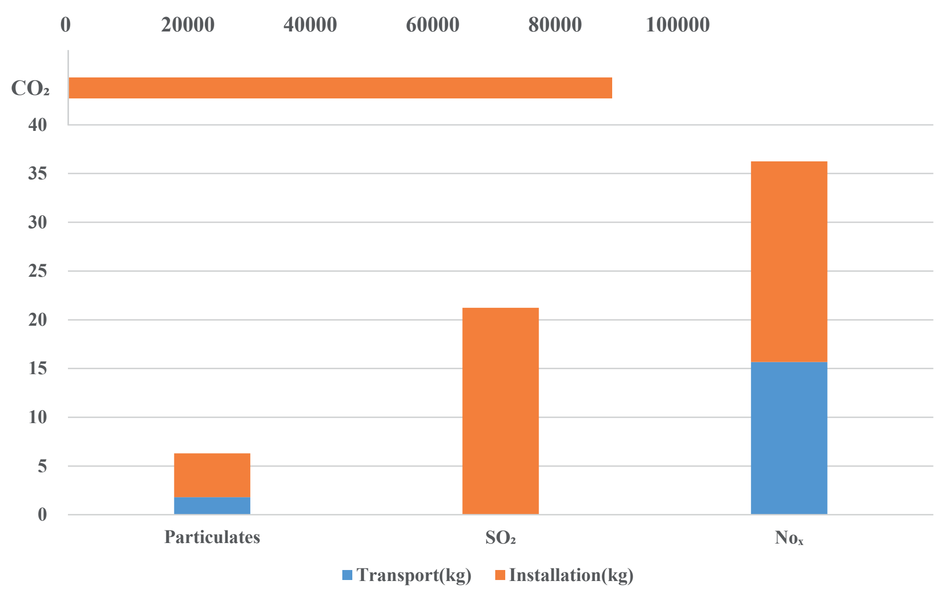

Fig. 11. Pollution discharge during transportation and installation of photovoltaic system.

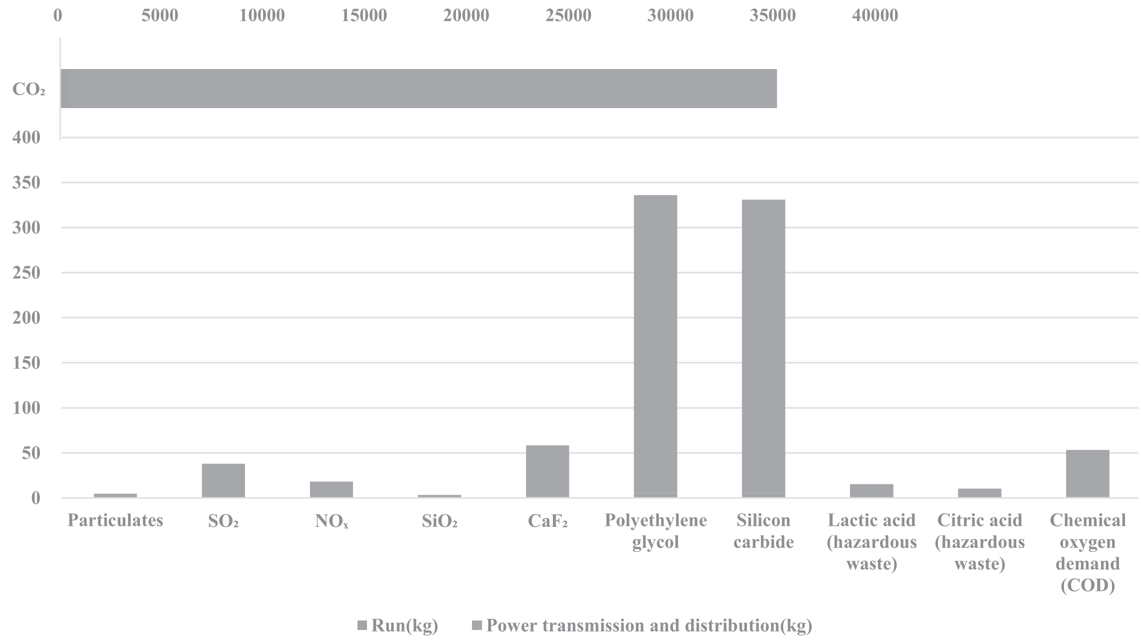

Fig. 12. Pollution discharge in photovoltaic system operation and power transmission and distribution stage.

Table 9. Pollutant emissions per m[2] of photovoltaic panels in the decommissioning and disposal stage.

Stage	Link	Consumption (kWh)	Pollutant status	Pollutants	Direct discharge (mg)	Indirect discharge (mg)	Total
Decommissioning disposal	Photovoltaic panel disassembly treatment	69.45	Gaseous	Particulates	-	2083.5	2083.5
				SO_2	-	9827.175	9827.175
				NO_X	0.41	9528.54	9528.95

Results and Discussion

Life Cycle Impact Assessment

According to data released by the National Energy Administration, there was a 224.3 billion kWh output in China's total photovoltaic power generation in 2019, with an installed capacity of 204.3 million kW. Therefore, the average annual power generation of photovoltaic systems of 1 MWp is 1097895 kWh. Assuming a calculation based on the lifetime of the photovoltaic system for 25 years, there is 27,447,381 kWh of electricity generated during the entire life cycle of the photovoltaic power generation system. Thus, the total pollutant emission and the kWh emission coefficient of a 1 MWp photovoltaic system during the whole life cycle are shown in the Table 10.

Analysis of Life Cycle Results

Contribution Analysis

By analyzing the boundary conditions of the whole life cycle of photovoltaic and using silicon solar cells as the research object, an analysis of the pollutant emissions in the four life stages of photovoltaic production, transportation, installation, operation in power transmission, and distribution, and decommissioning is conducted. Secondly, through the analysis of the phase list of the whole life cycle of the photovoltaic system, combined with the whole life cycle power generation of the 1MWp photovoltaic power generation system, the total life cycle pollutant emission and the pollutant emission coefficient of the 1 MWp photovoltaic power generation system are calculated. According to the emission coefficient of photovoltaic power generation pollutants, each stage's pollutant emission comparison chart is drawn as in the Fig. 14.

According to this Fig. 14, the highest level of pollutant emissions in the production stage accounted for 54% of the emissions during the whole life cycle. At this stage, the percentages of various pollutants discharged in the whole life cycle are: 53%, 73%, 82%, 68%, 94%, 94%, 94%, 94%, 94%, 94%, and 94%. In addition, the pollutant emission level in the decommissioning stage takes second place, at 32%. The pollutant emission levels in the transportation, operation, transmission, and distribution phases accounted for 10% and 4% of the full life cycle, respectively.

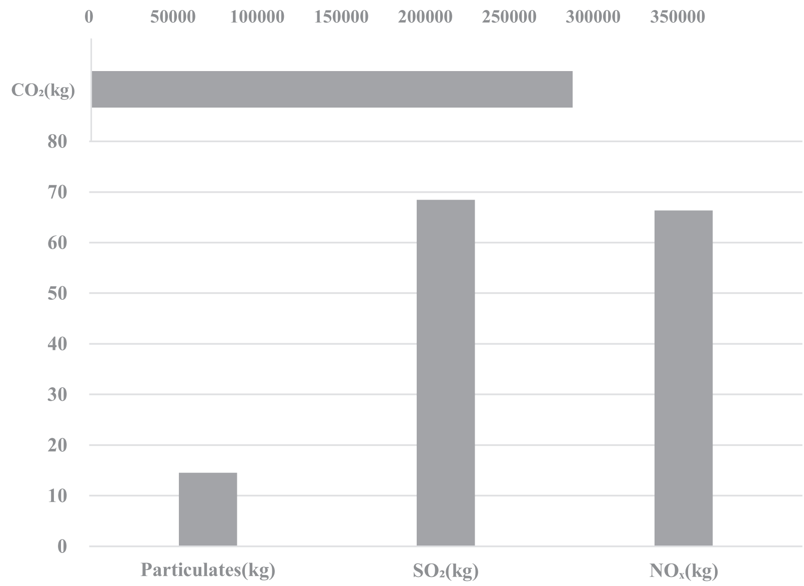

Fig. 13. Discharge status of photovoltaic system in the decommissioning and disposal stage.

Table 10. 1 MWp photovoltaic system total pollutant discharge and discharge coefficient.

Number	Pollutants	Total (kg)	Pollution coefficient (g/kWh)
1	CO_2	878023.4844	31.9893
2	Particulates	95.3298	0.0035
3	SO_2	707.0111	0.0258
4	NO_X	372.8044	0.0136
5	S_iO_2	57.7576	0.0021
6	CaF_2	979.4412	0.0357
7	Polyethylene glycol	5657.8715	0.2061
8	Silicon carbide	5569.1205	0.2029
9	Lactic acid (hazardous waste)	257.9324	0.0094
10	Citric acid (hazardous waste)	171.9549	0.0063
11	COD	898.6031	0.0327

Sensitivity Analysis

The sensitivity factor is an uncertainty analysis method. The discharge of a certain pollutant from a power supply E_j is the sum of the discharge of such pollutants from each power supply stage. If the pollutant discharge coefficient of various consumables is expressed as x_j, E_j can be expressed as a function of x_j, which is $E_j = g(x_{11}, ..., x_{ij}, ..., x_{nm})$. When all the pollutant coefficients change from x_1, ..., x_i, ..., x_n to x'_1, ..., x'_i, ..., x'_n, the amounts of change are Δx_1, ..., Δx_i, ..., Δx_n respectively. The kinds of pollutants will inevitably change, and the discharge of other kinds of pollutants will also occur accordingly from E_j to E_j'. Then $\Delta E_j = E_j' - E_j$ represents the amount of change caused by changes E_j in all factors. The Taylor expansion using multiple functions is:

$$\Delta E_j \approx \frac{\partial E_j}{\partial x_1}\Delta x_1 + \cdots + \frac{\partial E_j}{\partial x_i}\Delta x_i + \cdots + \frac{\partial E_j}{\partial x_n}\Delta x_n \quad (4)$$

To analyze the influence degree of the fluctuation in the pollutant coefficient on the amount of pollutant discharge, the pollutant coefficient of a certain material varies with objective conditions such as the improvement of the material and technology used, but this does not determine the pollutant coefficient of other materials. Therefore, the other parameters vary with parameters x_i; that is, $\Delta x_i \neq 0$. ΔE_j, as a variation of E_j, is the influence value of Δx_i on E_j, which is expressed as:

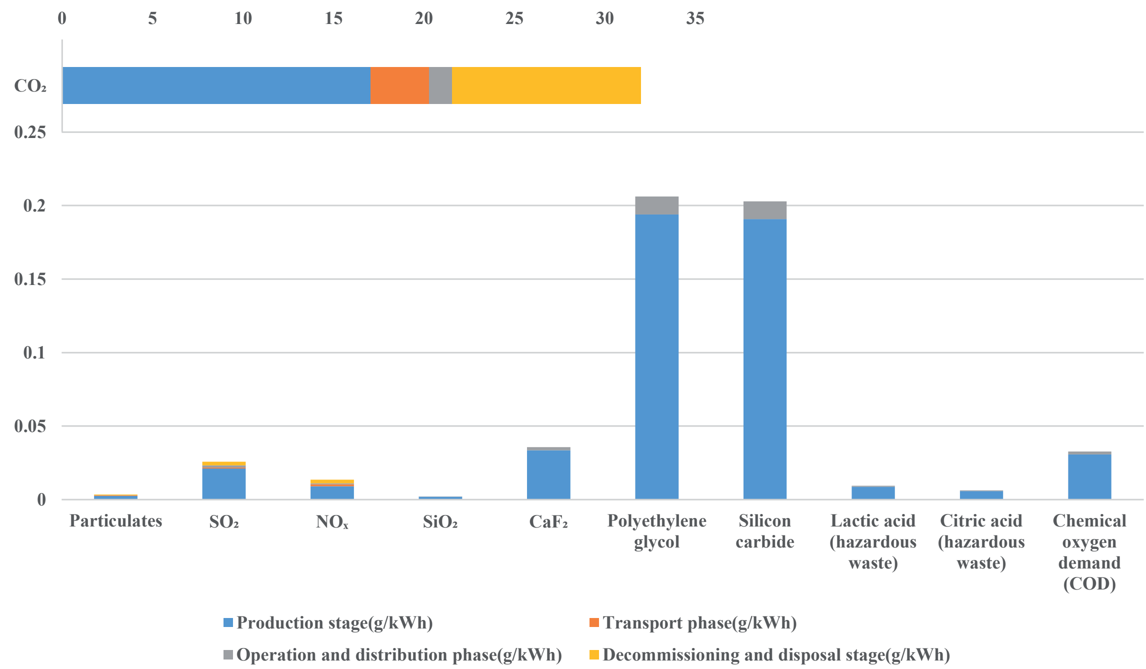

Fig. 14. Pollutant emissions at each stage of the MWp photovoltaic power generation system.

$$\Delta E_{j,x_i} = \frac{\partial E_j}{\partial x_i}\Delta x_i \tag{5}$$

Then Equation $\Delta E_j = \sum_{i=1}^{n} \Delta E_{j,x_i}$ defines the ratio of the rate of change of E_j to the rate of change of factor x_i as the sensitivity factor S_{ji} of E_j to x_i. Then there is:

$$S_{ji} = \frac{\Delta E_{j,x_i}/x_i}{\Delta x_i/x_i} = \frac{(\frac{\partial E_j}{\partial x_i})\Big/x_i}{\Delta x_i/x_i} = \frac{\partial E_j}{\partial x_i} * \frac{x_i}{E_j} \tag{6}$$

j indicates the type of pollutants. i, the type of consumables (energy consumption), and S_{ji}, the sensitivity of a certain pollutant E_j to the pollutant coefficient x_i of a certain material. As can be seen from formula (4-3), the pollutant sensitivity factor S_{ji} of the parameter is a partial derivative $\frac{\partial E_j}{\partial x_i}$ of a certain pollutant E_j to the factor of a certain consumable's contamination x_i, which represents the function of the relationship between the pollutant coefficient x_i and the pollutant E_j. The pollutant coefficient sensitivity factor proposal provides an effective research method for determining the importance of the pollutant coefficient of different measurement consumables on the pollutant calculation results.

Due to the diversity of pollutants in the service life of the power supply, there are many kinds of consumables, and the pollutant coefficient sensitivity factor can be expressed as:

$$S_{ji} = \begin{pmatrix} S_{11} & \cdots & S_{1i} & \cdots & S_{1n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ S_{j1} & \cdots & S_{ji} & \cdots & S_{jn} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ S_{m1} & \cdots & S_{mi} & \cdots & S_{mn} \end{pmatrix} \tag{7}$$

Table 11. Photovoltaic energy consumption sensitivity factors.

Supplies	CO_2	SO_2	NO_X	Particulates
Aluminum	0.0834	0.3652	0.0221	0.0424
Stainless steel	0.0211	0.0005	0.0035	0.0030
Copper	0.0028	0.0062	0.0032	0.0074
Diesel (transportation)	0.0124	0.0000	0.0294	0.0164
Electricity	0.3542	0.1427	0.2044	0.2182

During the entire life cycle of a photovoltaic power station, the main consumables required are electricity, aluminum, stainless steel, copper, and diesel. The pollutants produced by these consumables mainly include CO_2, SO_2, NO_X, and particulate matter. The sensitivity factors of these pollutants are calculated, respectively, with the results shown in the Table 11.

According to the calculation, electric energy has the greatest impact on the CO_2 emission coefficient during the service life of the photovoltaic power station, with a sensitivity factor of 0.3542; aluminum has the greatest impact on the SO_2 emission factor during the service life of the photovoltaic power station, with a sensitivity factor of 0.3652; electric energy has the greatest influence on the NO_X emission coefficient, with a sensitivity factor of 0.2044; electricity has the greatest influence on the emission coefficient of particulate matter, with a sensitivity factor of 0.2182. Therefore, the development level of electric energy and aluminum in the future will have a greater impact on the emission coefficient of the service life of photovoltaics.

Conclusions

Photovoltaic power generation is generally considered a more environmentally friendly alternative. Still, its environmental protection potential shouldn't only be determined by the operating phase of photovoltaic power plants; the entire life cycle must also be considered. Therefore, this article uses life cycle assessment methods to analyze the environmental conditions of photovoltaic power generation systems, involving four stages of photovoltaic system production, transportation and installation, operation and power transmission and distribution, and decommissioning disposal. The statistical pollutants include 11 types of carbon emissions: SO_2, NO_x, particulate matter, SiO_2, CaF_2, polyethylene glycol, silicon carbide, lactic acid, and citric acid. This paper draws the following conclusions:

(1) Based on the life cycle theory, this paper constructs the life cycle assessment model of a PV power generation system, analyzes and compares the level of pollutant emissions at each stage of the whole life cycle of PV power generation, and presents the experimental results. The production stage has the greatest impact on pollutant emissions, with total emissions accounting for more than 50%.

(2) Sensitivity analysis shows that electricity and aluminum are the main consumables with the greatest impact on the main emission pollutants.

Based on the conclusions obtained in this paper, the following suggestions are made for the future development of the photovoltaic industry:

(1) National-level input requires the state to strengthen its investment in technological innovation and R&D and encourage and support enterprises and research institutes to increase their R&D efforts in PV power generation technology, especially in improving the conversion efficiency of PV panels and reducing production costs, to reduce pollutant emissions at the production stage. Secondly, the construction of smart grids should be strengthened to create conditions for constructing grid-connected PV power plants.

(2) Industry level: The industry should formulate environmental protection industry standards for the PV industry and manage and administer pollutant emissions throughout the life cycle of the PV power generation industry, especially at the production stage, which can be realized by improving processes and using more environmentally friendly materials. Meanwhile, through scientific and technological innovation, it should gradually reduce its reliance on high-consumption goods such as electricity and aluminum and reduce pollutant emissions by improving energy use efficiency and promoting clean energy.

This paper analyzes the emission of pollutants in each stage of the whole life cycle of the photovoltaic power generation industry. It carries out a sensitivity analysis, and the research results reveal the impact of the photovoltaic power generation industry on the environment, which has a promoting role in the sustainable development of the future photovoltaic industry and provides theoretical guidance. However, this study has some limitations. With the change of current power generation modes, PV power generation is mostly coupled with other power generation modes, such as wind-scenery coupling and multiple power generation modes coupling. In future research, the environmental impacts of PV coupled with multiple energy sources should be expanded to study the environmental impacts of the power generation industry.

Data Availability

The data supporting this study's findings are available from the corresponding author upon reasonable request.

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Ethics Approval

This article does not contain any studies with human participants or animals performed by any of the authors.

Competing Interests

The authors declare no competing interests.

Author Contributions

All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Qian Xu, Yongjian Wang, and Yongli Wang. Shudong Wang wrote the first draft of the manuscript, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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