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Analysis of Carbon Footprint Assessment and Accounting System of Photovoltaic Industry under Dual-Carbon Background

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Abstract: With the intensification of global climate change and the growing demand for the Sustainable Development Goals (SDGs), dual-carbon policies are on the rise globally, bringing new challenges and opportunities to the energy industry. Focusing on the photovoltaic (PV) industry, this study carries out a carbon footprint analysis in the context of dual-carbon to gain a comprehensive understanding of the current status of PV modules in terms of carbon emissions and emission reduction measures. This paper firstly summarizes the development of the PV industry, and deeply analyzes the relevant theories and methods of carbon footprint assessment and accounting system. Then, it systematically evaluates the carbon emissions of crystalline silicon PV modules throughout their life cycle, and based on this, it puts forward suggestions on strategies to reduce the carbon footprint. Finally, the opportunities and challenges that the PV industry may encounter in the process of moving towards a low-carbon future are discussed to provide a reference for decision-making and practice in this field.

1. Introduction

Photovoltaic (PV) energy is a clean form of energy based on solar energy that has made significant progress over the past few decades. According to the International Energy Agency (IEA), global installed capacity of PV energy is growing rapidly, increasing nearly tenfold over the past decade to reach the thousands of gigawatts level. As shown in Figure 1, by 2030, Bloomberg New Energy (BNEF) predicts that global PV energy will add 334 GW of installed capacity, with a total of 3,000 GW. This trend suggests that the growth in PV installed capacity is benefiting from declining costs of the technology, improved efficiency, and government incentives, and signals that PV energy will play a more important role in the future energy supply. According to the China Photovoltaic Industry Association (CPIA), China's new PV energy installations have ranked first in the world for ten consecutive years, and cumulative installed capacity is expected to reach 487.60 GW by 2023.

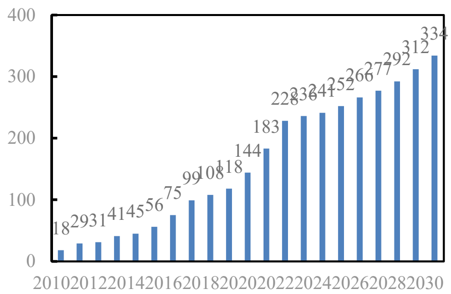

Figure 1 Global PV new installations 2010-2030 (data source from Bloomberg New Energy Finance)

However, the rapid growth of the PV industry has been accompanied by a number of environmental challenges, one of which is the carbon footprint of PV modules. Although PV technology itself is a low-carbon form of energy, a certain amount of carbon emissions are still generated during the production, transportation and maintenance of PV modules. Therefore, when assessing the net carbon footprint of solar panels, it is necessary to consider a number of factors, notably the way in which the materials used to produce the panels are obtained, the manufacturing process, and the expected lifespan.

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2.Current Status Of Domestic And International Research On Pv Carbon Emissions

In terms of carbon emissions, photovoltaic systems are often regarded as clean energy sources with carbon-reducing potential because they produce little pollution during use, but manufacturing, recycling, and other processes can still have a significant impact on the environment [1].Yao et al. (2014) argued that the Chinese photovoltaic industry's disproportionately high carbon emissions over its lifecycle were largely attributed to the inefficiency of China's polysilicon purification process and its highly polluting coal-fired power generation dependence [2]. Xu et al. (2018) extended the system scope of the PV industry to 11 stages and considered the import and export of PV products to study the differences between the Chinese PV industry in terms of domestic and international environmental impacts. They concluded that although the net environmental benefits of the Chinese PV industry have been increasing significantly each year, the total environmental benefits of the industry were still lower than the total environmental costs from 2011 to 2016 [3].

3.Research Methodology

The study is based on the Life Cycle Assessment (LCA) methodology, which accounts for the carbon emission data of all resource and energy inputs over the full life cycle of PV modules. The Life Cycle Assessment (LCA) methodology considers the entire life cycle of a product, from raw material extraction to end-of-life, including energy consumption, material production, manufacturing, use and end-of-life disposal. Referring to the methodology of LCA IS0 14040-14044 standard requirements [4,5], the assessment can be divided into four steps: (1) determining the target scope and system boundaries; (2) collecting life cycle inventory data; (3) life cycle impact assessment; and (4) analyzing the results. In this study, the environmental impacts of crystalline silicon photovoltaic (PV) modules under the production, use, and recycling and disposal phases were assessed based on the LCA assessment methodology under the ISO 14040 framework. In this study, Simapro software was used to construct a life cycle model to model the life cycle data inventory of PV module products. The data list is mainly from industry research and literature data, in which the production process data list of high-purity polysilicon, silicon wafers, cells, modules and other products involved in the production stage is mainly from the results of the national environmental protection public welfare industry scientific research special project, "China's new energy industry (solar cells) environmental impact and management research" [6].

4.Calculation Of Life Cycle Carbon Emissions Of Photovoltaic Products

4.1.Functional unit and system boundary

The functional unit of this study is determined as 1 square meters of crystalline silicon photovoltaic module as a functional unit for LCA analysis. Crystalline silicon photovoltaic module "from cradle to gate" assessment of the system boundary including production, use, recycling and disposal stages, as shown in Figure 2. It is assumed that the service life is 25 years, and the global warming trend is based on 100 years [7]. The production phase is mainly composed of energy use, carbon emissions caused by resource utilization, and carbon emissions caused by the treatment of pollutants; the use phase mainly involves carbon emissions caused by resource utilization, and the disposal phase includes carbon emissions caused by energy use, resource utilization, and carbon emissions caused by the treatment of pollutants.

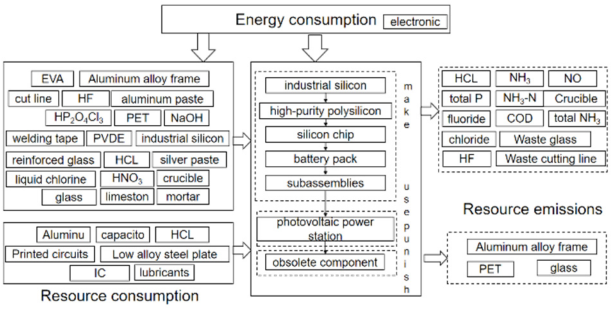

Figure 2 PV Module Full Life Cycle Assessment System Boundary

4.2.Full Life Cycle Inventory Analysis

(1) Production stage

Crystalline silicon photovoltaic modules to high-purity polysilicon as raw materials, and high-purity polysilicon raw materials for industrial silicon, the need to first purify industrial silicon into high-purity polysilicon in the production process, first of all, you need to be through the chemical method or melting method of industrial silicon purification. After purification of high-purity polysilicon can be processed through ingot casting, rod and other ways.

(2) Utilization stage

Considering the availability of data, this study in the use of photovoltaic products in the stage of the main input is the inverter, inverter selected power model for 500kW.

(3) Disposal stage

The technology is based on manual dismantling of the aluminum alloy bezel to separate it from the PV module, and then the high temperature pyrolysis process will be used to sort out the glass and the cell wafers, followed by the recovery of aluminum on the backsheets, silver on the frontsheets, and crystalline silicon wafers through the effective treatment of the chemical method. It is worth mentioning that the quality of the recovered crystalline silicon wafers is comparable to that of brand new wafers and can be used directly in wafer production without depreciation.

5.Analysis And Discussion Of Results

5.1.Analysis of full life cycle environmental impact

In order to systematically evaluate the environmental impacts of crystalline silicon PV modules, this study examined the indicators of abiotic depletion, abiotic depletion (fossil fuels), global warming (GWP100a), ozone layer depletion (ODP), human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification, and eutrophication, and the results are shown in Table 1 and Figure 3.

Table 1 Full life cycle evaluation results of 1m^2 crystalline silicon photovoltaic modules

Impact category	Numerical value	Unit
Abiotic depletion	0	kg Sb eq
Abiotic depletion (fossil fuels)	5120	MJ
Global warming (GWP100a)	490	kg CO_2 eq
Ozone layer depletion (ODP)	0	kg CFC-11 eq
Human toxicity	1580	kg 1,4-DB eq
Freshwater aquatic ecotoxin	458	kg 1,4-DB eq
Marine aquatic ecotoxicity	959000	kg 1,4-DB eq
Terrestrial ecotoxicity	3	kg 1,4-DB eq
Photochemical oxidization	0	kg C_2H_4 eq
Acidification	2	kg SO_2 eq
Eutrophication	1	kg PO_4 eq

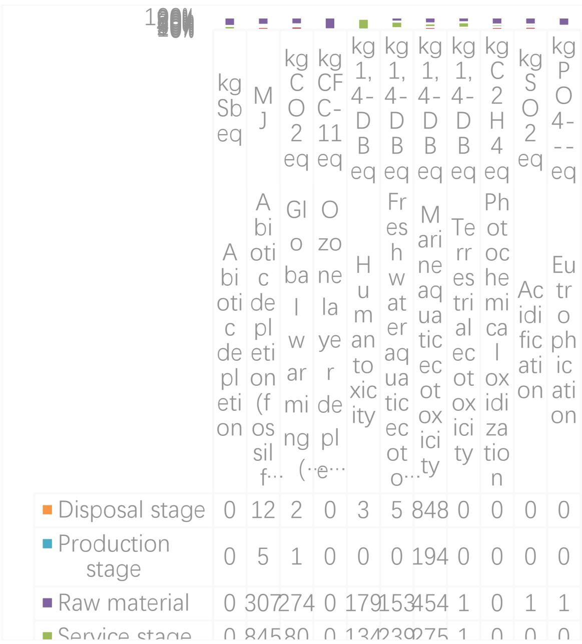

Fig. 3 Percentage of environmental impact of each stage of PV module and raw materials

5.2.Full life cycle carbon emission analysis of crystalline silicon photovoltaic module

From the results, it can be found that the full life cycle carbon footprint of the production of 1 m^2 crystalline silicon PV module is 626.82 kg. The results of the carbon emission quantification of each stage are analyzed, as shown in Figure 4 and Table 2 in detail. The carbon emission in the production phase is 407.14 kg, which contributes the most to the GWP, accounting for about 65 % of the project's full life cycle carbon emission. In addition, the carbon emission from the use phase is 158.72 kg, accounting for about 25 % of the carbon emission from the use phase of the project. Disposal phase carbon emissions are smaller, with carbon emissions of about 60.96 kg, accounting for about 10 % of the project's total life cycle carbon emissions. Thus the total power generation per unit of the PV module is 4,650 kW-h throughout the service life of the PV module. Therefore, the carbon emission per unit of electricity generated by the PV module during its entire service life is about 134.80 g/kW-h.

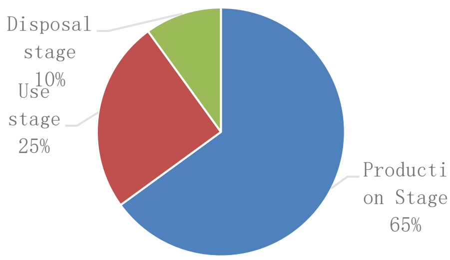

Fig. 4 Carbon emissions of 1m^2 crystalline silicon PV module by stage

Table 2 Full life cycle carbon emissions of 1m2 crystalline silicon photovoltaic modules

Life Cycle Stages	Carbon emission (kg/m^2)
Manufacturing Stage	407.14
Use stage	158.72
Disposal stage	60.96
Total	626.82

Note: Carbon emissions per unit are measured as CO_2 per unit mass in kg/m^2.

5.3.Analysis of carbon emission in the production stage

As can be seen from Figure 5, in the process of producing 1m^2 crystalline silicon PV module, the total carbon dioxide emission (in terms of CO_2 per unit mass) in the production stage is about 407.14 kg. The carbon emission mainly comes from the input of liquid chlorine materials, and its carbon emission is about 200.62 kg, accounting for 49.27% of the total carbon emission in the production stage. The second is the consumption of electricity, the carbon emission of electricity consumption is about 132.49kg, accounting for 32.54% of the total carbon emission in the production phase of the project.

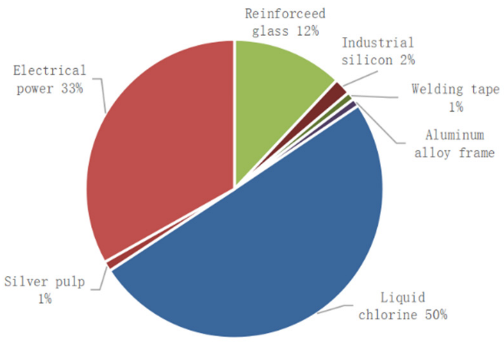

Fig. 5 Carbon emissions of various material inputs during the use stage

5.4. Sensitivity analysis

Based on the research results of the contribution of crystalline silicon photovoltaic modules to the carbon footprint, six input variables such as liquid chlorine, electricity, tempered glass, printed circuits, industrial silicon and silver paste are selected for sensitivity analysis after ranking the environmental impact contribution of the production stage, use stage and disposal stage, and the results of the analysis are shown in Figure 6.

The comprehensive analysis shows that the amount of liquid chlorine input in the production stage has the most significant impact on the carbon emissions of crystalline silicon PV modules. The results of the above sensitivity analyses provide a strong guidance for reducing carbon emissions from crystalline silicon PV modules. As a whole, reducing the amount of liquid chlorine input at the production stage and the utilization stage as well as saving energy in electricity consumption are the most effective strategies to reduce carbon emissions.

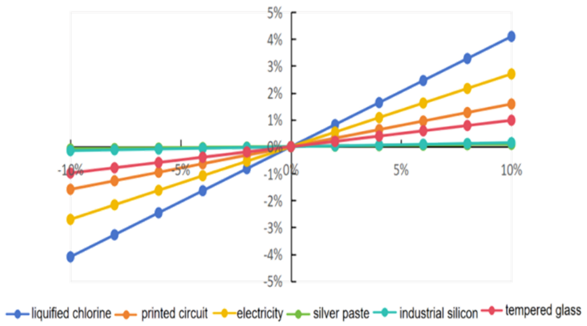

Fig. 6 Sensitivity analysis results of 1m^2 crystalline silicon photovoltaic module

6. Conclusion

Studies have shown that every 1m^2 of crystalline silicon PV module generates about 626.82 kg of carbon emissions during the production phase. Over the entire lifetime, for every kWh of electricity generated, the corresponding carbon emissions are about 134.80 g. The analysis shows that these emissions mainly come from the production stage, especially the use of liquid chlorine which plays an important role in the silicon purification and solar cell manufacturing processes. In addition, electricity consumption is another important source of carbon emissions, especially in the energy-intensive silicon purification and module assembly stages. Therefore, more efficient production processes can be considered to reduce energy consumption, as well as optimizing the use of liquid chlorine and finding environmentally friendly alternative materials and technologies to reduce the amount of liquid chlorine used, improve energy efficiency, and effectively reduce carbon emissions, thereby reducing the overall carbon footprint of PV modules.

Future research should focus on comprehensively considering the complex relationship between solar PV module systems and the environment, greenhouse gas emissions, and other aspects, including the impact of ecosystem services, the evaluation of carbon emission levels, and the improvement of PV module use and production efficiency. These research results will provide a scientific basis for standard setting and related environmental issues in the PV module production industry to ensure that the development of renewable energy is harmonized with environmental protection.

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