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Study on the Carbon Footprint of Photovoltaic Modules Based on the Life Cycle Assessment

Kou Chunxiao*

Power (Beijing) Certification Centre Co.,Ltd. Beijing 100080, China

*Corresponding to: Kou Chunxiao

Abstract: With the global enhancement of environmental protection awareness and adjustments to the energy structure, solar energy, as a clean and renewable form of energy, is increasingly prominent. Photovoltaic (PV) modules, as the core components of solar power generation systems, have garnered significant attention with regard to their carbon footprint during production and usage, which is a key indicator for measuring environmental impact and sustainability. In the context of the global active promotion of climate governance and strengthening carbon regulation, China, as an important exporter of photovoltaic modules in the world, carries out carbon footprint work and deeply taps the carbon reduction potential of products, which has become the only way to promote the high-quality development of the photovoltaic industry. This paper aims to explore the research progress, influencing factors, and strategies for reducing the carbon footprint of PV modules through the study of relevant project cases, providing references for the sustainable development of the photovoltaic industry.

Keywords: Carbon footprint; Photovoltaic (PV) modules; Life Cycle Assessment (LCA); Photovoltaic industry; Sustainable development

1 INTRODUCTION

Since China proposed the "3060" target, President Xi Jinping has repeatedly given important instructions on promoting the transition from dual control of energy consumption to dual control of carbon emissions, requiring the creation of conditions to achieve this transition as soon as possible and to accelerate the formation of incentive and constraint mechanisms for reducing pollution and carbon emissions. Globally, carbon footprint data have become a key indicator for evaluating the international competitiveness of photovoltaic products.

Photovoltaic modules, as the core components of solar power generation systems, refer to the smallest combination of photovoltaic cells that are encapsulated and internally connected, capable of providing direct current electricity and are indivisible. Their manufacturing and usage stages have attracted considerable attention for their environmental impact. Carbon footprint, which is the total amount of greenhouse gases emitted due to the direct or indirect consumption of fossil fuels throughout the product's life cycle, is an important indicator for measuring the environmental impact of photovoltaic modules. This paper will analyze the carbon footprint of photovoltaic modules in detail from the stages of raw material acquisition, production, transportation, use, to disposal, and propose corresponding emission reduction strategies.

2 CARBON FOOTPRINT CALCULATION AND ANALYSIS OF PHOTOVOLTAIC MODULES

2.1 *DEFINITION OF PRODUCT CARBON FOOTPRINT*

The carbon footprint of a product (CFP) refers to the sum of GHG emissions and GHG removals in the product system, expressed in CO2 equivalents, and is based on life cycle assessment for the single environmental impact type of climate change [1].

The calculated carbon footprint is expressed in CO2 equivalents, and the service life of photovoltaic modules is considered to be 25 years.

2.2 *IMPORTANCE OF PHOTOVOLTAIC MODULE*

CARBON FOOTPRINT

As products required for clean energy power generation, photovoltaic modules have significant low-carbon advantages during the power generation stage, but carbon emissions during their manufacturing and installation processes should not be overlooked. Accurate accounting of the carbon footprint of photovoltaic modules helps to comprehensively assess their environmental impact and provides a basis for formulating scientific emission reduction strategies. At the same time, with the continuous improvement of the global carbon trading market, the carbon footprint of photovoltaic modules will also become an important factor affecting their market competitiveness.

2.3 FUNCTION OF EVALUATION

The function of photovoltaic module products is to convert solar energy into electrical energy and provide it to downstream users (feed into the grid or directly transmit to designated users).

2.4 FUNCTIONAL UNIT

A unit photovoltaic module (1 Wp), from cradle to grave, during the defined reference service years, the activities required (≥80% of the labeled output power). The product carbon footprint report should reflect the conversion factor to facilitate the conversion of results related to the functional unit to 1 m2 photovoltaic module.

For example: A unit photovoltaic module (1 Wp) with an output power of 430 Wp, with a reference service year of 25 years, from cradle to grave.

2.5 SYSTEM BOUNDARY

The system boundary for photovoltaic module accounting should include the following unit processes: (1) Raw and auxiliary material acquisition: the production process of raw and auxiliary materials such as solar cells, glass, frames, films, junction boxes, back sheets, etc., and their transportation to the photovoltaic module manufacturing enterprise; (2) Energy acquisition: the extraction, processing, and production process of energy such as diesel and electricity, and their transportation to the photovoltaic module manufacturing enterprise; (3) Module production: all processes involved in the production of photovoltaic module products, excluding the living facilities and personnel within the factory area. It is advisable to include the following unit processes: (1) Use: processes such as transportation, installation, and operation and maintenance after the product leaves the factory; (2) End of life: processes such as scrapping, recycling, reuse, and final disposal of photovoltaic modules. Overall, it covers the entire process from the extraction of silicon materials, the manufacturing of solar cells, the encapsulation of components, to installation and operation until disposal [3,4].

2.6 LIFE CYCLE ASSESSMENT (LCA)

Life Cycle Assessment is a systematic method for evaluating the environmental impact of a product from "cradle" to "grave" throughout its entire life cycle. The core goal of LCA is to identify and quantify the resource consumption and environmental emissions at each stage of the product's life cycle, thereby providing a scientific basis for decision-making and promoting environmental sustainability [5,6]. For photovoltaic modules, LCA can comprehensively account for carbon emissions from the extraction of raw materials to the disposal of waste. LCA methods are scientific and systematic, and are the mainstream methods for carbon footprint accounting of photovoltaic modules. The unit processes involved in each stage are as follows:

2.6.1 RAW MATERIAL ACQUISITION AND PRODUCTION

Photovoltaic modules: including the production and processing of solar cells, glass, frames, back sheets, films, junction boxes, ribbons, silicone, and other materials (including packaging materials or any related materials related to the production of the final product).

Solar cells: involving the extraction and processing of silicon wafers, chemicals used in the battery manufacturing process, other materials (including packaging materials or any related materials related to the production of the final product), etc. The solar cell is the core of the photovoltaic module, a semiconductor wafer that converts light energy into electrical energy, and determines the power generation capacity of the photovoltaic system. The differences in photovoltaic modules mainly come from the solar cells, which are mainly divided into crystalline silicon, new perovskite, thin-film solar cells, etc.

Silicon wafers: the production and processing of silicon ingots, chemicals used in the silicon wafer manufacturing process, other materials (including packaging materials or any related materials related to the production of the final product).

Silicon ingots: the production and processing of crystalline silicon, recycled silicon ingots, chemicals, other materials (including packaging materials or any related materials related to the production of the final product).

Photovoltaic glass: the production of glass. Its main function is to protect the photovoltaic cells and transmit light. Photovoltaic glass has high transmittance, low iron content, heat resistance, and corrosion resistance, and its quality can directly affect the power generation efficiency and service life of the module.

Frames: the production and processing of aluminum frames or steel frames. The frame is the outermost packaging structure of the module, and the use rate of aluminum frames is much higher than that of steel frames. Aluminum frames have high corrosion resistance, lightness, and strong load-bearing capacity.

Films: the production of films. Utilizing the adhesiveness, durability, and optical properties of films, the solar cells can be bonded with glass and back sheets, thereby protecting the solar cells. The quality of the film can directly determine the packaging quality and service life of the module [7].

Other raw materials' production and processing.

The production of electricity, fossil fuels, and other energy carriers used in upstream processes.

In addition, the transportation of raw materials also increases carbon emissions, especially long-distance transportation and complex logistics processes.

2.6.2 *Module Manufacturing*

The production stage includes the following unit processes:

Further processing of raw and auxiliary materials, such as silicon rods, frames, junction boxes, etc. (if applicable);

Internal transportation within the manufacturing plant;

Final product assembly;

Packaging of finished products (if applicable and related);

Transportation of products from production to external (such as landfill, transportation of outsourced processes, etc.);

Direct emissions generated during production (such as NOx, SOx, heavy metals, particulate matter, VOCs, wastewater emissions);

Fuel, steam, and other energy carriers used in power generation and core production processes.

Other design and production processes may also be included. At least 95% of the manufacturing should be included, including related packaging.

2.6.3 *Transportation And Installation*

The product transportation process includes the following unit processes:

Transporting the product to distribution centers/distribution platforms/retailers/consumers.

The installation process includes the following unit processes:

The manufacture, packaging, and procurement of materials required for installation (excluding the reference product);

Energy, water, and emissions used during the installation process;

All waste generated during installation and the transportation of waste.

2.6.4 *Use Stage*

During the use stage, photovoltaic modules almost do not produce direct greenhouse gas emissions, as the photovoltaic power generation process does not consume fossil fuels. However, to comprehensively assess the carbon footprint of photovoltaic modules, it is also necessary to consider the indirect carbon emissions during equipment maintenance, cleaning, and other processes.

2.6.5 *Disposal And Recycling*

At the end of the life cycle of photovoltaic modules, their disposal and recycling processes will also generate carbon emissions. The design of modern photovoltaic modules has already considered the possibility of recycling. By recycling silicon materials, aluminum frames, and other metal components, the consumption of new materials and the corresponding carbon emissions can be reduced. However, the disposal technology and recycling rate of waste modules still need to be further improved [7].

2.7 *Statistical Period*

In principle, the previous calendar year is used as a statistical period, and the statistical period for individual products is determined according to their specific production cycle. For seasonal and multi-year production, a complete production cycle should be included.

2.8 *Commonly Used LCA Databases For Carbon Footprint Calculation*

The main foreign LCA databases include the Swiss Ecoinvent, the European Life Cycle Document Database (ELCD), the German GaBi extension database (GaBi Databases), the U.S. NREL-USLCI database (U.S. LCI), and the Korean LCI database (Korea LCIdatebase), etc.

Many LCA studies have been conducted domestically, and the application level encourages the use of China's local basic databases, including the China Product Full Life Cycle Greenhouse Gas Emission Coefficient Set (2022) jointly built by the Ministry of Ecology and Environment and 24 research institutions; the China LCA database (CAS RCEES) developed by the Research Center for Eco-Environmental Sciences of the Chinese Academy of Sciences, the inventory database developed by Beijing University of Technology, the China Automobile Alternative Fuel Life Cycle Database developed by Tongji University, and the enterprise product LCA database developed by Baosteel, etc.

3 Technical Paths To Reduce The Carbon Footprint Of Photovoltaic Modules

The main carbon emissions of photovoltaic modules come from the silicon material production link. The manufacturing process of crystalline silicon requires the use of rare metals and materials, and the extraction and refining processes of these materials usually involve energy-intensive activities, resulting in a large amount of carbon dioxide emissions. Therefore, the key to reducing emissions for photovoltaic modules lies in effectively reducing emissions in the silicon material production link of the industry chain. The improvement space of the technical path is mainly concentrated on optimizing the production process of the industry chain, saving energy and reducing consumption, such as reducing the thickness of silicon wafers, increasing the size of silicon wafers, and improving the efficiency of components.

3.1 *Optimize Production Processes*

By adopting advanced production processes and technologies, carbon emissions during the manufacturing process of photovoltaic modules can be reduced. For example, using automated and intelligent production lines to improve production efficiency and energy utilization rates; optimizing silicon wafer cutting and solar cell manufacturing processes to reduce material waste and energy consumption.

3.2 USE CLEAN ENERGY

Using clean energy to replace fossil fuels in the production process of photovoltaic modules is an effective way to reduce carbon emissions. For example, using renewable energy sources such as solar and wind energy to provide electricity for the production process, and using electric forklifts for factory transportation, can significantly reduce carbon emissions.

3.3 PROMOTE LOW-CARBON MATERIALS

Researching and applying low-carbon materials is key to reducing the carbon footprint of photovoltaic modules. Most of the materials that make up photovoltaic modules have recycling value, such as silver, copper, aluminum, etc. Recycling and utilizing these metal materials can not only reduce resource waste and environmental pollution but also improve the sustainability and competitiveness of the photovoltaic industry. In addition, renewable and recyclable materials can be used to replace traditional glass-based solar panels; new efficient conversion materials can be developed to improve the photoelectric conversion efficiency of photovoltaic modules, reducing carbon emissions per unit of electricity generated.

3.4 IMPROVE RECYCLING AND UTILIZATION RATES

Strengthening the waste management and recycling of photovoltaic modules is an important measure to reduce the carbon footprint of the entire life cycle. By improving recycling technology and recycling rates, the consumption of new materials and the corresponding carbon emissions can be reduced. At the same time, a complete recycling system and market mechanism should be established to promote the circular use of photovoltaic modules [2,8].

3.5 IMPROVE THE CONVERSION EFFICIENCY OF PHOTOVOLTAIC MODULES

The conversion efficiency of photovoltaic modules refers to the ratio of the maximum output power of the photovoltaic module to the received light power under standard test conditions (usually 1000 W/m² of light intensity and 25°C ambient temperature). Conversion efficiency is one of the key indicators for measuring the performance of photovoltaic modules and directly affects the power generation and economic benefits of phot ovoltaic power generation systems. It is also affected by many factors such as the material type of the photovoltaic module, light exposure time, light intensity, installation angle, surface cleanliness, and battery degradation. Improving the conversion efficiency of photovoltaic modules is an important way to reduce carbon emissions. Among the currently applied efficient battery technologies, from the traditional PERC to the current TOPCon and HJT, the conversion efficiency has gradually increased, and the carbon footprint per functional unit has also decreased.

4 POLICY MEASURES AND SUGGESTIONS

4.1 ESTABLISH CARBON FOOTPRINT EVALUATION STANDARDS

Establish carbon footprint evaluation standards for photovoltaic products that are in line with international standards and meet high standards to enhance the discourse power of China's photovoltaic industry in international trade. By formulating clear carbon footprint accounting methods and reporting standards, support manufacturers and exporters to meet international trade requirements and sustainability standards.

4.2 PROMOTE CARBON EMISSION FACTOR LIBRARIES

Promote the carbon emission factor library for Chinese photovoltaic products, using high-quality emission factors with time and regional representativeness to improve the accuracy and consistency of carbon footprint accounting. By connecting and recognizing with international databases, promote the competitiveness of Chinese photovoltaic products in the international market.

4.3 ENCOURAGE ENTERPRISES TO APPLY DIGITAL MANAGEMENT PLATFORMS

Encourage enterprises to apply digital management platforms to carry out carbon footprint accounting and green certification work. Through digital platforms, achieve product carbon footprint and supply chain carbon footprint management covering the entire industry chain, improving the transparency and traceability of carbon emission data. At the same time, support enterprises in carrying out green and low-carbon product certification to enhance brand image and market competitiveness.

4.4 INNOVATE AND IMPROVE RESEARCH METHODS

Traditional LCA methods can no longer meet the needs of photovoltaic module carbon footprint research. Therefore, it is possible to explore new research methods and technical means, such as Dynamic Life Cycle Assessment (DLCA), Geographic Information System (GIS), etc. The application of these new methods and technical means provides strong support for the precise calculation and evaluation of the carbon footprint of photovoltaic modules.

4.5 STRENGTHEN INTERNATIONAL COOPERATION AND EXCHANGE

Strengthen cooperation and exchange with international organizations and other countries to jointly promote the green and low-carbon development of the photovoltaic industry. By sharing experience, technology, and policy information, promote the coordinated emission reduction and sustainable development of the global photovoltaic industry.

5 CONCLUSION

As an important part of clean energy technology, the carbon footprint issue of photovoltaic modules should not be ignored. By comprehensively analyzing the carbon emissions of photovoltaic modules throughout their life cycle and exploring technical paths and policy measures to reduce carbon footprints, the green and low-carbon development of the photovoltaic industry can be promoted. In the future, with the continuous progress of technology and the continuous improvement of policies, the carbon footprint of photovoltaic modules is expected to be further reduced, making a greater contribution to addressing climate change and protecting the environment.

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