Applied Energy xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Life cycle assessment of grid-connected photovoltaic power generation from crystalline silicon solar modules in China

Guofu Hou [a,*,1], Honghang Sun [b,1], Ziying Jiang [c], Ziqiang Pan [c], Yibo Wang [d], Xiaodan Zhang [a], Ying Zhao [a], Qiang Yao [b]

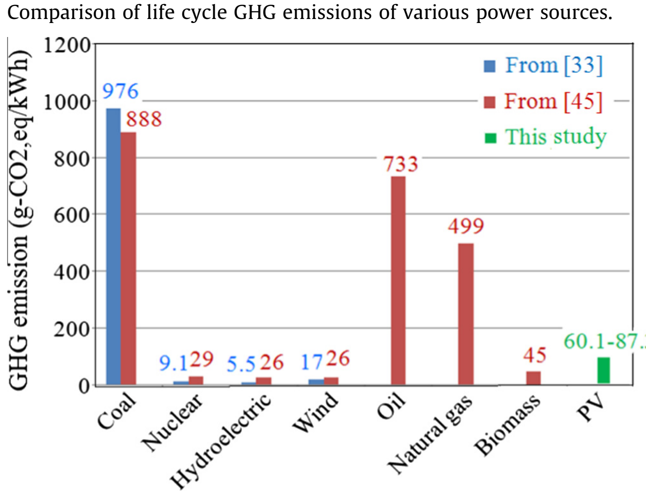
[a] Institute of Photoelectronics, Nankai University, Tianjin 300071, China
[b] Department of Thermal Engineering, Tsinghua University, Beijing 100084, China
[c] China Institute of Atomic Energy, Beijing 102413, China
[d] Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China

HIGHLIGHTS

- The LCA study of grid-connected PV generation with silicon solar modules in China has been performed.
- The energy payback times range from 1.6 to 2.3 years.
- The GHG emissions are in the range of 60.1–87.3 g-CO_2,eq/kW h.
- The PV manufacturing process occupied about 85% or higher of total energy usage and total GHG emission.
- The SoG-Si production process accounted for more than 35% of total energy consumption and GHG emissions.

GRAPHICAL ABSTRACT

Comparison of life cycle GHG emissions of various power sources.



ARTICLE INFO

Article history:
Received 31 August 2015
Received in revised form 27 October 2015
Accepted 9 November 2015
Available online xxxx

Keywords:
Life cycle assessment
Greenhouse gas (GHG) emission
Energy payback time
Grid-connected photovoltaic (PV) power generation
Crystalline silicon (c-Si) solar modules

ABSTRACT

The environmental impacts of grid-connected photovoltaic (PV) power generation from crystalline silicon (c-Si) solar modules in China have been investigated using life cycle assessment (LCA). The life cycle inventory was first analyzed. Then the energy consumption and greenhouse gas (GHG) emission during every process were estimated in detail, and finally the life-cycle value was calculated. The results showed that the energy payback time (T_{EPBT}) of grid-connected PV power with crystalline silicon solar modules ranges from 1.6 to 2.3 years, while the GHG emissions now range from 60.1 to 87.3 g-CO_2,eq/kW h depending on the installation methods. About 84% or even more of the total energy consumption and total GHG emission occupied during the PV manufacturing process. The solar grade silicon (SoG-Si) production is the most energy-consuming and GHG-emitting process, which accounts for more than 35% of the total energy consumption and the total GHG emission. The results presented in this study are expected to provide useful information to enact reasonable policies, development targets, as well as subsidies for PV technology in China.

* Corresponding author.
E-mail address: gfhou@nankai.edu.cn (G. Hou).
[1] These authors contribute equally to this paper.

http://dx.doi.org/10.1016/j.apenergy.2015.11.023
0306-2619/

1. Introduction

Global warming and environmental pollution have become challenging problems in modern times, promoting the rapid development of renewable energy. Photovoltaic (PV) power generation is commonly regarded as one of the most promising renewable energies due to its tremendous capacity and potential to reduce energy consumption and henceforth decrease pollution [1,2]. Since entering the 21st century, both the global PV manufacturing industry and application market have experienced remarkable growth [3,4]. Stimulated by the international market and a series of national policies and regulations, including the Renewable Energy Law and Feed-in Tariff [5], the Chinese PV industry and market have undergone an even much more rapid growth, and occupy one of the most critical sectors in the world [6–9]. For instance, the PV module shipment in China was 27.4 GW_p in 2013, accounting for over 50% of global shipments. The annual installed capacity in 2013 was 12.42 GW_p, one of the largest markets in the world [6–8]. This rapidly growing industry and market have promoted the key technologies related to the PV industry [6–8]. Additionally, solar cell efficiencies are continuously improving. The production energy consumption per kilogram for solar grade silicon (SoG-Si) has decreased dramatically. The PV module and system cost have similarly decreased as well [6–8].

Controversy regarding PV power generation still exists. Some opposition argued that the total energy yield during a PV system's lifetime cannot compensate for the energy consumption during manufacturing. Others insist that PV power is not a clean energy because of its high energy consumption and serious pollutant discharge during system construction, especially for the production of SoG-Si. Realistically, it is difficult to provide reasonable and reliable results if only certain stages are considered, especially as material and energy flows of PV power generation are intermingled and divergent emissions into the environment will occur at different life-cycle stages. PV system operation is nearly maintenance-free and completely "clean" [10]. However, when considering the entire life cycle of PV power generation, from quartz mining to metallurgical silicon production, cell and module production, and the disposal of end-of-life PV systems, the energy consumption and pollution emissions should not be ignored [10]. However, the lifetime of current PV systems is 25 years or more. Although a certain amount of energy is consumed during manufacturing, the value will be much lower when the energy consumption is compared with the total energy output over the system's lifetime. Therefore, it is urgent to quantify the energy consumption and environmental impacts of PV power generation from a life-cycle perspective to determine whether PV technology is an environmentally friendly renewable energy.

To evaluate the energy gains and environmental benefits, life cycle assessment (LCA) was adopted [11–29]. Generally, the life cycle of a product or technology refers to the period from its cradle to grave, including the manufacturing, usage, maintenance, and final disposal [11]. LCA is widely employed to assess production, such as shale gas [12], buildings [13], vehicles [14], and electronic productions [15]. LCA studies for PV technology began nearly forty years – the first research study on PV systems from the life-cycle perspective started in 1976 [16]. The most common indicators used to evaluate sustainability and environmental benefits include energy payback time (T_{EPBT}), energy yield ratio (EYR), and greenhouse gas (GHG) emission [17–19]. LCA tracks not only the direct energy consumption and emissions, but also all indirect energy consumptions and emissions associated with possible fuels [11]. Therefore, LCA can obtain reasonable, reliable and all-inclusive data on PV technology [16–19]. Recently, an increasing number of LCA studies on T_{EPBT} and environmental impacts of PV technologies, especially greenhouse gases, have been conducted [16–29]. The T_{EPBT} and GHG emissions for PV systems are greatly different from each other as a result of different manufacturing, installation location/time [20,21], and installation type, including rooftop and ground-mounted systems [18,22,24]. Sherwani et al. summarized that LCA results for a number of monocrystalline silicon (mono-Si) and multicrystalline silicon (multi-Si) PV systems indicated different efficiencies, solar irradiation and lifetime, wide-ranging GHG emissions from 9.4 to 280 g-CO_2,eq/kW h, and a T_{EPBT} range from 1.5 to 15.5 years [24]. With the rapid development of the Chinese PV industry and market, the environmental impacts of PV technology have received more and more attention [19,25,26]. Guo et al. evaluated mono-Si PV modules produced by Trina Solar, one of the world's leading PV companies, and found that the GHG emissions ranged from 33 to 50 g-CO_2,eq/kW h [25]. Peng et al. performed LCA studies on the building integrated photovoltaic (BIPV) system in Hong Kong. The GHG emission was 53 g-CO_2,eq/kW h for multi-Si PV systems, compared to 61 g-CO_2,eq/kW h for mono-Si systems [19]. Hou's results showed that the life-cycle GHG emission for the c-Si system was 56 g-CO_2,eq/kW h [26].

The literature reviews mentioned above show wide-ranging results for both T_{EPBT} and GHG emission [16–28]. The following reasons could explain this significant variance. First, the energy consumption and GHG intensity of PV generation depends on a wide variety of factors including the solar cell type, local solar irradiation, installation type, efficiency of BOS components, system capacity, lifetime, module efficiency, status quo local power mixture, etc., [20–23]. Any changes in these factors will inevitably result in GHG emission and/or T_{EPBT} variation. Secondly, different boundary conditions are applied. Some reports only present the results of PV modules [16,27,28], while other reports consider the whole life cycle, from raw material extraction until PV system integration. However, there are still few results considering energy loss during power transmission from PV stations to terminal consumers. To clarify the published life-cycle results of solar PV, scientists from National Renewable Energy Laboratory (NREL) reviewed hundreds of published scientific literatures and then harmonized key performance characteristics to produce more comparable and consistently derived results [23].

Although some direct and/or indirect results were obtained [19,25,26], Chinese studies offer little detailed analysis or calculation. It is necessary to perform reasonable and reliable LCA studies, and update state-of-the-art results to match the rapid growth of the PV industry and market in China. Because of its dominant role in the global and Chinese PV market, only crystalline silicon (including mono-Si and multi-Si) PV systems were considered. Though more than 90% of Chinese PV modules depend on international markets [6–8], only those PV systems produced and installed in China were considered. Different from the previous LCA studies on PV based on operating data of actual PV stations or literature reviews, we collect and balance the average data of Chinese PV technology to obtain the latest and most accurate LCA results in this study.

2. State-of-the-art Chinese c-Si PV technology

In order to obtain the latest and most accurate LCA results, the average data of Chinese PV technology were collected and applied by combining and balancing data from published literatures [1,5–10,25,26], field visits of key PV enterprises, expert and professional engineer interviews and questionnaire surveys. Key technical parameters of Chinese PV technology in 2013 are summarized and listed in Table 1.

According to current Chinese PV industry levels, 2.0 kg quartz is used to produce 1.0 kg UMG-Si. 1.35 kg UMG-Si is needed to produce 1.0 kg SoG-Si. 1.1 kg SoG-Si is used to produce 1.0 kg