Applied Energy 185 (2017) 68–81

Contents lists available at ScienceDirect

Applied Energy

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

Life cycle assessment of grid-connected power generation from metallurgical route multi-crystalline silicon photovoltaic system in China

Zhiqiang Yu, Wenhui Ma *, Keqiang Xie, Guoqiang Lv, Zhengjie Chen, Jijun Wu, Jie Yu

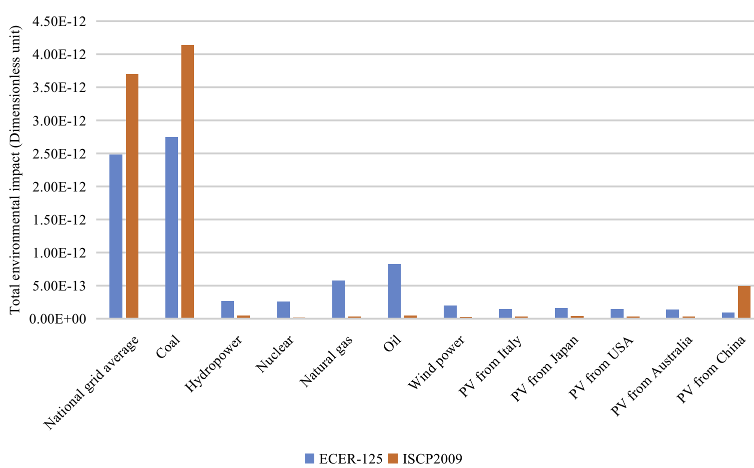
State Key Laboratory of Complex Nonferrous Metal Resources Cleaning Utilization/The National Engineering Laboratory for Vacuum Metallurgy, Kunming University of Science and Technology, Kunming 650093, China
Faculty of Metallurgical and Energy Engineering, Kunming University of Science and Technology, Kunming 650093, China
Key Laboratory of Non-Ferrous Metals Vacuum Metallurgy of Yunnan Province/Engineering Research Center for Silicon Metallurgy and Silicon Materials of Yunnan Provincial Universities, Kunming University of Science and Technology, Kunming 650093, China

HIGHLIGHTS

- The LCA of China's metallurgical route multi-Si PV power generation was performed.
- The contribution analysis and the sensitivity analysis were conducted.
- The metallurgical route has the obvious environmental advantage.
- The environmental impact of photovoltaics is 3.33% of coal-fired power generation.
- The environmental impact of the project is about 56–66% of other nations' PV results.

GRAPHICAL ABSTRACT

Comparison between total environmental impact indexes in the current work and other power generation and other nations' PV results.



ARTICLE INFO

Article history:
Received 19 August 2016
Received in revised form 15 October 2016
Accepted 19 October 2016

Keywords:
Life cycle assessment (LCA)
Photovoltaic (PV) power generation
Metallurgical route

ABSTRACT

A life cycle assessment (LCA) has been performed for the grid-connected electricity generation from a metallurgical route multi-crystalline silicon (multi-Si) photovoltaic (PV) system in China. The energy payback time (EPBT), environmental impacts and total environmental impact indexes were calculated. Based on the contribution analysis, it can find out the most critical stage (or process) and the greatest environmental impact. Meanwhile, the main cause of them were traced respectively. The sensitivity analysis reveals that aluminum consumption makes the most obvious influence. However, PV station retirement affects the result significantly by recycling the important materials. The total environmental impact indexes of solar grade silicon (SoG-Si) production via metallurgical route were compared with purification via modified Siemens process. Results show that the metallurgical route is with obvious advantage. Among the renewable energy, photovoltaics with the minimal environmental impact is only 3.33% of

* Corresponding author at: State Key Laboratory of Complex Nonferrous Metal Resources Cleaning Utilization/The National Engineering Laboratory for Vacuum Metallurgy, Kunming University of Science and Technology, Kunming 650093, China.
E-mail address: mwhsilicon@126.com (W. Ma).

http://dx.doi.org/10.1016/j.apenergy.2016.10.051

Energy payback time (EPBT)
Environmental impacts

coal-fired power generation. The environmental impact of current work is about 56–66% of other nations' PV results. In order to promote the green and sustainable development of the Chinese PV industry, there is usually a brief comment or relevant suggestion for improvement after each analysis and comparison in this research.

1. Introduction

Energy shortage and environmental issues are increasingly becoming the bottleneck restricting social and economic development [1]. The ongoing process of climate change, along with the implications of this phenomena, is one of the most challenging problems the world faces today [2]. The text of the Paris Agreement set a goal of limiting global warming to less than 2 °C compared to pre-industrial levels. The agreement calls for zero net anthropogenic greenhouse gas emissions to be reached during at the second half of the 21st century. The main reason for climate change is the greenhouse gases released from the burning of fossil fuels [2]. Almost 80% of greenhouse gases come from energy production or consumption, 68% of the energy utilized worldwide originates from fossil fuels, with electricity generation being responsible for 40% of global CO_2 emissions [3]. Before 2030, world primary energy demand will demonstrate almost a 1.7% average annual increase, which further increases greenhouse gases [2]. Thus, more and more countries are making great efforts to achieve energy conservation and emissions reduction in electric power sector [4].

Air pollution is becoming an important environmental concern in some developing countries [5]. As the largest developing country in the world, China has a higher demand for electricity than any other countries [6]. Due to its large population size, rapid economic development, as well as the ongoing process of industrialization and urbanization, China is facing a double pressure concerning to energy and the environment [7]. Constrained by energy resource endowment, energy supply in China has long been dominated by coal [8]. Among China's primary energy consumption in 2014, the usage of coal accounts for about 66% [9]. Among the supply mix of electricity, coal-fired power accounts for approximately 75%. The dramatic increase in coal consumption results in huge greenhouse gases emission as well as severe air pollution problems. Extensive emissions of air pollutants including sulfur dioxide (SO_2), nitrous oxide (NO_x), and particulate matter (PM) during the process of energy consumption results in noxious acid rains and diverse disease [10]. The recent heavy haze enveloping a large swathe of Eastern and Central China is a stark example.

In this context, China has committed to peaking its CO_2 emissions by 2030, increasing the share of non-fossil energy in the total primary energy demand (TPED) to around 20% [11]. The achievement of this dual goal relies heavily on the development of sustainable and renewable energy technologies, which are the solutions to satisfying electricity demands within the whole society while simultaneously reducing the adverse anthropogenic impacts of fossil fuels [12,13]. Chinese government has already instituted an impressive array of green policies and specific policy measures for the purpose of renewable energy development [2]. Among various types of renewable energy sources, solar energy is promising due to its large energy potential and clean nature [14]. The photovoltaic (PV) technology is considered to be one of the greenest and most promising energy-generating technologies as it generates electricity directly from the sun and therefore avoids fossil energy consumption and greenhouse gases (GHG) emissions during system operation [15]. And PV systems offer longer service times with the minimum maintenance costs [16]. The continuing decrease in cost of PV arrays and the increase in their efficiency imply a promising role for PV generating systems in the near future [17].

Since the beginning of the 21st century, the PV industry in China entered its rapid growth stage, with the joint promotion of the international market and domestic policies [18]. In addition, the government is investing heavily into this field for relevant scientific research [19]. China has now become the largest manufacturer of solar PV products in the world [18]. Meanwhile, the Chinese government has the incentive to support the development of PV power generation [19]. China has led the world in newly installed PV capacity for two years [11]. In 2014, the cumulative installed capacity of PV was 30.7 GW [20]. By 2015, it had reached 43.2 GW. China had become the world's largest PV power generation installed capacity country.

Silicon-based PV (Si-PV) technologies receive the most attention, both due to the fact that they were the first to be commercialized and they have the largest market share [21]. Therefore, an increasing number of studies on the life cycle energy and environmental analysis of Si-PV systems, especially greenhouse gases, have been conducted [21–44]. Table 1 shows a compilation of the main results of the last decade. What can be summarized from Table 1 is that life cycle assessment (LCA) results for a number of PV systems indicated different parameters, wide-ranging GHG emissions from 4 to 840 g CO_2 eq/kW h, and the energy payback time (EPBT) range from 0.68 to 16.9 years. Compared with abroad, the range of LCA results for China's Si-PV systems is smaller. Lu and Yang conducted an environmental payback time analysis of a roof-mounted building-integrated PV system in Hong Kong, and found that the EPBT of the PV system was 7.3 years, and the GHG payback time was estimated to be 5.2 years considering fuel mixture composition of local power stations [28]. Hou et al. investigated the environmental impacts of grid-connected PV power generation from crystalline silicon solar modules in China using LCA. The results show that the EPBT ranges from 1.6 to 2.3 years, while the GHG emissions range from 60.1 to 87.3 g CO_2 eq/kW h depending on the installation methods [40]. Fu et al. performed a LCA for a PV system with multi-crystalline silicon (multi-Si) modules. The most important results were the calculation of a primary energy demand (PED) of 12.61 MJ/W_p, and an EPBT of 2.2–6.1 years of multi-Si PV systems produced and installed in China areas [41]. Different studies use different methods, with different boundary conditions and analytical periods, rely on different data sources and inventory methods, consider different solar irradiation and status quos of power mixture at different locations, and model different PV technologies including solar cell types, installation types, module efficiencies, lifetimes, PV system performance ratios and capacities [23]. All these factors will affect LCA results.

PV technology, directly generating electricity from solar energy, seems to be very clear, without environmental pollution. However, taking a sight from its whole life cycle, it can be found that the processes of production, transportation, installation, maintenance, dismantling, as well as recovery and disposal of a PV system actually consume resources, energy, and cause environmental emissions. Especially for the production process of solar grade silicon (SoG-Si), the core material of solar cell, inevitably leads to high energy consumption and serious environmental pollution. Nowadays, the domestic mainstream technology of multi-Si production is