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ScienceDirect
Solar Energy 133 (2016) 283–293
SOLAR ENERGY
www.elsevier.com/locate/solener

Life cycle assessment of multicrystalline silicon photovoltaic cell production in China

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Received 12 March 2014; received in revised form 31 March 2016; accepted 10 April 2016
Available online 26 April 2016

Communicated by: Associate Editor D. Yogi Goswami

Abstract

Energy crisis and environmental problems have increased the attention on solar power development and utilization. This study aims to identify the environmental effects associated with photovoltaic (PV) cell made up of multicrystalline silicon (multi-Si) in China by life cycle assessment. Results showed that multi-crystal solar PV technology provided significant contributions to respiratory inorganics, global warming, and non-renewable energy. The emissions generated by aluminum, coal-based electricity, and multi-Si wafer production processes played important roles in the overall environmental burden. To reduce the potential environmental impact of multi-Si PV cell in China, the proportion of renewable energy use for national electricity generation should be increased and the consumption efficiency of energy (i.e., electricity) and raw materials (i.e., silicon and aluminum) should be promoted.

Keywords: Life cycle assessment; Solar electricity; Multicrystalline silicon; Photovoltaic cell

1. Introduction

Solar energy has been explored comprehensively because of the energy crisis and environmental issues caused by fossil fuels (Kelly and Gibson, 2011; Kannan et al., 2006). The photovoltaic (PV) industry has grown dramatically worldwide in recent years, with an average annual growth rate of more than 40% in installed global PV capacity since 2000 (IEA, 2010). Approximately 31.1 GW of PV systems were installed worldwide by the end of 2012 (EPIA, 2013). The rapid growth of global PV capacity is expected to continue in the next few years because of decreasing PV technology costs, increasing clean energy and sustainable development requirements, and high electricity costs (EPIA, 2013). An increase in global PV capacity will increase the demand for multicrystalline silicon (multi-Si), which plays an important role in global PV electricity generation (Stoppato, 2008). China plays a leading role in the global multi-Si market. The multi-Si production capacity of China for 2012 was 71,000 t, which accounts for approximately 30% of the global multi-Si yield (EPIA, 2013). However, the multi-Si industry of China suffers from high environmental pollution, raw material overuse, and low energy efficiency compared with those in European countries. The Chinese government is focused on improving energy efficiency and restoring multi-Si manufacturing plants to save energy and reduce carbon emissions. Multi-Si production plants that consume over 200 kW h/kg of electricity were either shut down, technologically renovated, or structurally readjusted until the end of 2011 (MIIT, 2011).

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http://dx.doi.org/10.1016/j.solener.2016.04.013
0038-092X/

Life cycle assessment (LCA) is an effective and systematic approach for analyzing the environmental improvements associated with a product, process, or activity by identifying, quantifying, and assessing the impact of the utilized energy and materials, as well as the wastes released to the environment. LCA studies are executed according to ISO standards (ISO 14040, 2006; ISO 14044, 2006) and are widely used as bases for process improvement, eco-labeling programs, strategic planning, consumer education, and product design. The environmental impact of multi-Si PV systems has been discussed in Europe and in the United States by using the LCA method (Alsema and De Wild-Scholten, 2005; Stoppato, 2008; Fthenakis and Alsema, 2006; Koroneos et al., 2006a,b; Pacca et al., 2007; Sumper et al., 2011; Kim et al., 2014; Fu et al., 2015). Previous studies indicated that multi-Si PV power generation systems are promising solutions to the global energy crisis and environmental issues. However, most previous studies were conducted by considering only two or three environmental impact categories (i.e., energy, global warming, or external environmental costs), except in the study of Alsema and De Wild-Scholten (2005) and Koroneos et al. (2006b). Alsema and De Wild-Scholten (2005) presented more than three categories (i.e., abiotic depletion potential, global warming potential (GWP), ozone layer depletion potential (ODP), photochemical oxidation potential, acidification potential (AP), and eutrophication potential (EP)) by using the CML 2000 model despite unclear system boundaries. Koroneos et al. (2006b) presented 10 categories and reported that environmental burdens released from the PV-system only during their manufacturing processes. Only a few LCA case studies on PV systems based on the regional data of China have been peer-reviewed and published in English (Ito et al., 2003; Yue et al., 2014; Fu et al., 2015). Diao and Shi (2011) and Fu (2013) conducted LCA studies for PV systems in Chinese. Most inventory and relevant background data for the report of Ito et al. (2003) were collected from Japan (e.g., PV module, aluminum, copper, high density polyethylene, epoxy resin, and polyvinyl chloride). Diao and Shi (2011) and Fu (2013) assessed primary energy demand, energy payback time, and other environmental impact categories (i.e., AP, EP, GWP, human toxicity, ODP, photochemical oxidation potential) by using the CML 2001 model, whereas Yue et al. (2014) assessed two categories only (i.e., energy and carbon emission). However, the upstream inventory data presented in the works of Fu (2013), Fu et al. (2015), and Yue et al. (2014) were mainly collected from the ecoinvent database (2010), which barely represents the situation in China. Electricity generation data, which can show the significant contributions of PV production to the overall environmental burden, were derived from incomplete and low-quantified national statistic data (Zhao et al., 2013; Guan et al., 2012). Most researchers have focused on the environmental benefits of energy and global warming rather than on the impact of coal-based power generation. However, environmental benefits vary widely from one electricity generation technology to another. Moreover, the energy and raw material consumption during the production of multi-Si PV cells causes the transfer of environmental problems. Thus, a reliable evaluation is needed on the environmental impact of multi-Si PV manufacturing in China. In the present study, an LCA of a multi-Si PV cell was performed. The goals of this study are as follows: (a) introduce a Chinese database for multi-Si PV cell production, (b) identify the key factors that contribute to the overall environmental burden, (c) characterize the significant potential to improve raw materials and energy consumption, (d) determine the global standing of China in terms of environmental impact via comparisons with other countries, and (e) verify the existence of environmental problem transfer. Inventory and background data related to solar glass and silicon production, multi-Si wafering, multi-Si PV cell processing, coal-based electricity generation, and aluminum production processes were collected from modern and technically advanced industrial sites in China.

2. Materials and methods

2.1. Functional unit

A functional unit, which provides a quantified reference for all other related inputs and outputs, is a measure of the functional outputs of a studied system (ISO 14040, 2006). In this study, 1 kWp multi-Si PV cell production was selected as the functional unit. All raw materials and energy consumption, infrastructure, direct emissions, transport, and waste disposal levels are based on this functional unit.

2.2. System boundary

System boundary was set by using a cradle-to-gate approach. Hence, multi-Si PV cell consumption and final disposal were excluded. Fig. 1 shows the system boundary and mass flow of the multi-Si PV cell production scenario. The processes of road transport, infrastructure development, direct air emissions (e.g., toluene, fluoride, nitrogen oxides, hydrogen chloride, and chlorine), energy generation, raw materials production, solid waste disposal (i.e., landfills, recycle, and incineration), and onsite wastewater treatment were included. However, the use stage of multi-Si PV cell was excluded because of a lack of information. The main inventory results are presented in Table 1.

2.3. Life cycle impact assessment methodology

Life cycle impact assessment (LCIA) results were calculated at midpoint level by using the IMPACT2002+ method (Jolliet et al., 2003), which is one of the mostly used models in LCA analysis. It considers a broad set of 15 midpoint impact categories including global warming, non-renewable energy, carcinogens, non-carcinogens, ionizing