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Pollutant payback time and environmental impact of Chinese multi-crystalline photovoltaic production based on life cycle assessment

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ABSTRACT

A Life Cycle Assessment (LCA), using the end-point damage model (CEDM) of impact assessment, was conducted, to analyse the environmental impacts and pollutant payback times of photovoltaic production, including solar-grade silicon, silicon wafers, silicon solar cells and photovoltaic panels, in China. The inputs and outputs were obtained using site investigation, questionnaires, and field monitoring, and a method of aggregating the data into an industry-level database was established. The production yield of the studied samples accounted for an average 66% of the national yield in 2013. The results showed that the respiratory-inorganics and fossil-fuel categories contributed the most impact, because of the large electricity consumption required. Recent technological advances in raw material reduction and energy savings are the primary pathways to decreasing the environmental impacts. The environmental impact of a photovoltaic system is equivalent to 4.5% of that of the impact of the current coal-based electrical power system in China. The pollutant payback times of chemical oxygen demand, chloride, fluoride, ammonia gas, nitric oxide, sulfur dioxide, hydrogen chloride, hydrogen fluoride and carbon dioxide are 5.11, 1.02, 25.1, 8.01, 0.831, 0.784, 0.716, 1.12 and 0.884 years, respectively, indicating that most of the pollutants could be paid back within the expected lifetime of a photovoltaic system. Therefore, installing photovoltaic systems could reduce not only the consumption of non-renewable energy, but also the emitted pollutants, decreasing the environmental impacts of electricity generation.

1. Introduction

China holds an important share of the world photovoltaic industry. In 2015, the Chinese production yields of solar-grade silicon, silicon wafers, silicon cells, and photovoltaic panels accounted for 47.8%, 79.6%, 85.3%, and 72.1%, respectively, of the total world yields (Wang et al., 2016). Yet, although the Chinese photovoltaic industry has developed rapidly and has excellent prospects, controversy remains about issues such as pollution, and the lack of environmental management and of data supporting the presumed environmental benefits and impacts.

Life cycle assessment (LCA), an environmental management tool that can address the above-mentioned issues, has been developing rapidly over the past several years. An earlier LCA of photovoltaic use focused on its increase since the 1970s and on the consequent reduction in greenhouse gas emissions (Hunt, 1976). In recent years, an increasing number of studies on the life cycle energy and environmental analysis of photovoltaic systems, especially analyses relating to energy payback time and greenhouse gases, have been conducted. Peng et al. (2013) reviewed an LCA of energy payback time and greenhouse gas emissions for solar photovoltaic systems, and reported that the cumulative payback energy requirements for multi-crystalline silicon photovoltaic (PV) systems in the reviewed literature (Alsema, 2000; Ito et al., 2003; Fthenakis and Alsema,

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2006; Pacca et al., 2007; Lu and Yang, 2010; Zhai and Williams, 2010) were estimated to be 2699–5150 MJ/m^2. The energy payback time (EPBT) and greenhouse gas emission rate were 1.7–3.3 years and 12–72 g CO_2-eq/kWh, respectively. In 2016, Leccisi et al. reported energy payback times ranging from 0.9 years for multi-crystalline silicon photovoltaic production at high irradiation (2300 kWh m^{-2} y^{-1}) to 2.8 years for single-crystalline silicon photovoltaic production at low irradiation (1000 kWh m^{-2} y^{-1}) (Leccisi et al., 2016). The main LCA studies of photovoltaic systems in the last five years have shown varying results, such as wide ranges of GHG emissions (from 15.8 to 88.74 g CO_2-eq/kWh) and of energy payback times (0.68–16.9 years). Different studies have used different methods, with different boundary conditions and analytical periods (from 2006 to 2016); relied on different data sources and impact assessment methods (Eco-Indicator 99, IMPACT 2002+, EPS2000, CML2001); considered different solar irradiation values (ranging from 1100 to 2453 kWh m^{-2} y^{-1}) and different power constructions in different locations (European, Spanish, Germany, China, the United States); and modelled different photovoltaic technologies, installation types, module efficiencies, lifetimes, and PV system performance ratios and capacities (Diao and Shi, 2011; Fthenakis and Kim, 2011, 2013; Sumper et al., 2011; Zhong et al., 2011; Desideri et al., 2012; de Wild-Scholten, 2013; Stylos and Koroneos, 2014; Fu et al., 2015; Yang et al., 2015; Lamnatou and Chemisana, 2015; Chen et al., 2016; Hong et al., 2016). All these factors will effect LCA results.

Some Chinese researchers have also studied photovoltaic systems. Diao and Shi (2011) assessed the life cycle environmental impacts of photovoltaic modules based on mainstream and best technologies in China in 2009, and also analysed energy payback time and global warming potential. Fu et al. (2015) performed a life cycle assessment for a photovoltaic system with multi-crystalline silicon (multi-Si) modules in China, which considered the primary energy demand, EPBT, and environmental impacts. Yang et al. (2015) reported a life cycle environmental assessment of China's multi-crystalline silicon photovoltaic (PV) modules associated with the international trade. Chen et al. (2016) and Hong et al. (2016) conducted an environmental impact assessment of multi-crystalline silicon PV cells in China. Yu et al. (2017) calculated the EPBT and environmental impacts of grid-connected electricity generation from a metallurgical route multi-crystalline silicon photovoltaic system. And Huang et al. (2017) assessed the life cycle environmental impacts of a multi-crystalline silicon photovoltaic system involving the recycling process. However, inventory data for these LCA researches in China were collected from either a single factory or previous literature. These small data samples can hardly represent the actual situation of photovoltaic production in China. And the emissions directly from photovoltaic production processes haven't been reported in these previous studies.

Thus, the purposes of this study were: 1) to establish a method of aggregating data collected from individual factories into industry-level data; 2) to evaluate the actual environmental burdens from photovoltaic production in China, using the end-point damage model and a life cycle assessment approach; and 3) to calculate the pollutant payback time for photovoltaic production for China. The expectation was to provide useful scientific information for Chinese policy makers, so that they could make decisions regarding photovoltaic environmental management, and also to provide helpful information for environmental diplomacy concerning the photovoltaic industry in China.

2. Methodology

This study was conducted according to the recommendations of the International Standards Organization ISO 14044-2006 Environmental Management Life Cycle Assessment Requirements and Guidelines (ISO 14044, 2006) and the more PV-specific guidelines provided by the International Energy Agency (Frischknecht et al., 2015). In order to ensure detailed and accurate results, four types of production and processes were assessed:

- Solar-grade silicon: the silica in the quartz sand was reduced in an arc furnace to metallurgical-grade silicon, which was purified further into solar-grade silicon (>99.9999%), typically through a modified Siemens process.
- Silicon wafers: solar-grade silicon ingots were sliced into wafers less than 0.2 mm thick.
- Silicon solar cells: a p-n junction was formed by dopant diffusion and an electric circuit was created by applying and sintering metallization pastes.
- Photovoltaic panels: cells were connected physically and electronically, and encapsulated by glass and plastics.

Finally, the life cycle environmental impact of photovoltaic production was calculated using the mass balance for each production.

2.1. Functional units and boundaries

The functional units used in this study were: 1 t of solar-grade silicon production, ten thousand pieces of silicon wafers, 1 m^2 of a silicon solar cell, and 1 m^2 of a photovoltaic panel. The inventory of raw materials used in the manufacture of silicon took into account the extraction of silica. The transport of raw materials was not included because silicon wafers, silicon solar cells and photovoltaic panels are always produced in a single factory. The major processes involved all four types of production, and are outlined in Fig. 1.

Table 1 shows the characteristics and specifications of Chinese photovoltaic production in this study.

2.2. Data collection

The data were collected continuously for two years. First, factories in different regions, with different production scales and different levels of processing technology, were chosen, some for direct site investigations and some for questionnaire investigations. For the direct site-investigation factories, we went to each factory and consulted with the manager to determine its current technological status. The data for the raw materials and energy consumption were collected from this consultation and from annual statistics. Emissions were monitored by a qualified environmental monitoring agency approved by the China National Accreditation Service for Conformity Assessment. The methods for sampling, sample preparation and determination of each pollutant followed the national standard of China. For the questionnaire-investigation factories, the data were collected by survey. The samples were intended to represent the situation of photovoltaic production in China with as much accuracy as possible. The description of investigation samples is shown in Table 2.

2.2.1. Data processing

There were too many samples for studying the four types of photovoltaic products, especially for solar cells and panels. Before proceeding, we needed to analyse the accuracy of the data from each input. For this assessment (using basic statistical principles), we relied on relative standard deviation: if the relative standard deviation was less than 0.3, we assumed that the data could be used; otherwise, we needed to check the data source and determine whether the data were reliable. As it turned out, 95% of the