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Environmental effects of China's solar photovoltaic industry during 2011–2016: A life cycle assessment approach

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ABSTRACT

Thanks to many government incentives, China has provided, at relatively low prices, a number of solar PV products to the world and enhanced domestic solar PV power. While China's growing solar PV industry has brought about both domestic and international environmental benefits, the provision of heavy subsidies has motivated the discussion of social and economic benefits and costs of this technology. Using the LCA approach, this paper performs an in-depth analysis on the environmental benefits and costs of this industry for the period of 2011–2016. Differing from existing literature, this paper broadens system boundaries to cover 11 stages of the solar PV industry life cycle, taking module sources and market directions of PV system into consideration, and quantifies the costs of environmental emissions of the industry by shadow pricing. The key finding of this study is that during 2011–2016 the total environment benefit was smaller than the total cost of China's solar PV industry. Meanwhile, coinciding with the rise of the domestic solar PV market, the resulting net environmental benefits have witnessed dramatic yearly growth. Policy implications and conclusions from findings are provided at the end of this paper.

1. Introduction

Along with the increasing concerns of climate change, solar PV power, as a clean energy technology, has seen dramatic growth around the world, particularly in China. Driven by many government incentives, China has provided a number of solar PV products to the world market at more affordable prices and enhanced the rate of domestic installation and deployment of solar PV power. These contributing factors have significantly increased the diffusion of solar PV technology and the mitigation of domestic environmental pressure. While China's solar PV industry has brought about environmental benefits to the world and the country itself, the production of solar PV system has resulted in environmental costs. The purpose of this paper is to perform in-depth analysis on the environment effects of China's solar PV industry during 2011–2016.

Emission rates, especially for GHG (Greenhouse Gas), are one of the key concerns when environmental effects are mentioned. Harder and Gibson (2011) indicated that there is a potential replacement of 24.4 GWh of conventional thermal power production annually with the construction of each 10 MW PV power plant built, saving 10,732 tons of CO_2 in Abu Dhabi, United Arab Emirates. Ramadhan and Naseeb (2011) quantified that the amount of CO_2 emissions will be lowered by approximately 2, 16, 84 and 168 tons per year in the case of PV stations of sizes 1, 10, 50, and 100 MW respectively in the state of Kuwait. Hosenuzzaman et al. (2015) revealed that 69–100 million tons of CO_2 would be reduced by 2030 based on the solar PV capacity predictions of the International Energy Agency (IEA) and Greenpeace. Wang et al. (2014) showed that in 2020 PV power generation could save 17.4 Mtoe fossil energy and 46.5 Tg CO_2 in China, compared with 600 MWe coal-fired supercritical units. However, the existing literature only presents rough estimations and lacks consideration of the details of the solar PV products production process. It is necessary to calculate the resource consumption and environmental impacts of solar PV modules production and generation from a life cycle perspective.

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Life cycle assessment (LCA) is the most popular analysis method to evaluate environmental effects. The key element of LCA is to perform analysis on the life cycle inventory (LCI) and the relevant data. Literature review shows that the environmental effects of solar PV industry vary in different regions: Stoppato (2008) presented the energy payback time (EPBT) and CO_2 emissions results of an LCA of polycrystalline silicon panels in 27 countries including Germany, USA, and Spain. The EPBT ranged from 3.368 years in Spain to 6.522 years in the United Kingdom and CO_2 emissions ranged from 0.002 $kgCO_2/kWh$ in Norway to 0.841 $kgCO_2/kWh$ in Australia. The differences between developed and developing economies are also great: Sumper et al. (2011) evaluated the GHG and EPBT of polycrystalline technology in Catalonia (Spain) based on an LCA analysis; the GHG values for a 200 kWp PV plant were 1.334 $kgCO_2/Wp$ and 0.521 $kgCH_4/Wp$ respectively and EPBT varied from 3.43 year to 4.45 years at different locations in Catalonia. The EPBT and GWP (see section 2.1.2) in Akinyele et al. (2017) of a solar PV system in Nigeria were 0.83–2.83 years and 1.27–3.88 $kgCO_2$-eq/Wp respectively. For a specific country, the data could vary between different years (Stoppato, 2008; Sumper et al., 2011). Thus, data appropriateness should be taken into consideration.

Along with the expansion of China's solar PV market, available data on solar PV materials and academic papers on the environmental effects of China's solar PV industry are emerging and increasing in scope in recent years (Chen et al., 2015; Fu et al., 2015; Hong et al., 2016; Hou et al., 2016; Huang et al., 2017; Yang et al., 2015; Yao et al., 2014; Yu et al., 2017; Yue et al., 2014). Among these are topics evaluating the environmental effects of monocrystalline silicon solar PV products: Chen et al. (2015) addressed the environmental burden of mono-Si PV cell production in China and key factors such as fossil depletion, climate change, and human toxicity were used to analyze the LCA results; Yue et al. (2014) performed a comparative LCA between China and Europe based on mono-Si, multi-Si and ribbon silicon, EPBT and GHG were calculated and analyzed in this literature. Others such as Fu et al. (2015), Hong et al. (2016), Hou et al. (2016), Huang et al. (2017), Yang et al. (2015), Yao et al. (2014), Yu et al. (2017) and Yue et al. (2014) evaluated the environmental effects of multi-Si solar PV products using the LCA method based on the data from previous literature and typical PV companies in China. Only a few of these papers took international trade of solar PV products and recycling of solar PV systems into consideration. For instance, Yang et al. (2015) introduced the imports of raw materials such as multi-Si and the exports of PV modules in their study, and their results showed these factors influenced the environmental impacts greatly; Huang et al. (2017) compared the environmental effects between recycling treatment (dismantling of multi-Si PV products already used, re-melting of glass, thermal treatment of EVA and chemical treatment for Al and Si) and landfill treatment. Their results showed the former was more environmental friendly. However, the methods used in the existing literature are not truly LCA as they only examined a few stages of the life cycle. Stages like silicon ore mining and transportation have not been taken into consideration. In terms of the measurement of environmental effects, current uniform measurements include CML 2001 (Fu et al., 2015; Yang et al., 2015), IMPACT 2002+ (Hong et al., 2016), and ReCiPe (Chen et al., 2015; Yang et al., 2015; Huang et al., 2017). The shortcoming of these measurements is that their values have not been quantified.

Shadow pricing is a popular measurement tool in the evaluation of environmental effects, for which CO_2 and SO_2 emission levels are the most commonly used. CO_2 emissions from the life cycle of solar PV system may come from the production of all materials used, energy consumption, and the production of PV system itself. Some literature measured the shadow prices of CO_2 in Chinese provinces (Ke et al., 2008; Wang et al., 2011; Wei et al., 2012; Choi et al., 2012; Zhang et al., 2014a,b; Du et al., 2015), where the CO_2 measured is the total CO_2 in the province rather than the CO_2 of each industry in the province. Meanwhile, industrial production, particularly power production, is the major source of SO_2. Thus, SO_2 emissions in power industry are of great concern in China and have been a major research field in shadow pricing (Qian, 2013; Wang, 2016). SO_2 emissions in solar PV power generation largely result from energy consumption.

This paper contributes to the existing literature in three distinct aspects:

(1) Broaden system boundaries. Diverging from existing literature on the environmental effects of China's solar PV industry, which only study a few stages of the industry life cycle, the system boundaries studied in this paper covers all eleven stages of the industry life cycle (see Fig. 1).
(2) Take module sources and the market directions of PV system into consideration. Multi-Si products used in China's production of PV system have two sources-domestically made and imported. Meanwhile, modules produced in China have two market destinations-domestic production of PV systems and exports. While the environmental costs of China's PV module exports should be counted into China's environmental costs, the specific environmental costs of China's imported multi-Si products should be excluded from China's environmental costs since the former costs are incurred in China and the latter costs are incurred in the exporting countries.
(3) Assess environmental effects by shadow pricing. Most of the existing studies on environmental effects using LCA did not numerically evaluate environmental effects. This paper uses shadow prices as a unified measuring standard for environmental benefits and costs, enabling comparisons of emissions.

This paper chooses 2011–2016 as its study period for three reasons: firstly, it was not until 2011 when the nationwide feed-in tariffs were put in place that China's domestic solar PV market grew dramatically (Zhang et al., 2014a,b); secondly, most of the data used in evaluating 1Wp solar PV costs are from recent years; thirdly, the unit environment costs of solar power and thermal power have been constantly changing over the years. Thus, it is not advisable to use these data to evaluate the costs incurred prior to 2011 (though a large amount of PV products were exported resulting in environmental costs in China). The remainder of the paper is organized as follows: Section 2 provides methodology and data source; Sections 3 and 4 evaluate the environmental costs and benefits of China's solar PV industry during 2011–2016 respectively; Section 5 presents overall results; Section 6 puts forward some policy implications; Conclusions are provided in the last section.

2. Methodology and data source

2.1. Methodology

2.1.1. LCA approach

The LCA approach is used as a tool to evaluate the environmental effects of a product, process or activity throughout its life cycle, starting from the use of raw materials to process, transport, and disposal. An inventory of material and energy usage and the emissions to the environment will be made for each stage of the life cycle. An environmental profile will be set up with this inventory, which makes it possible to identify the weak points in the life cycle of the studied system. These weak points are the focal points for