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Environmental influence assessment of China's multi-crystalline silicon (multi-Si) photovoltaic modules considering recycling process

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The environmental burden of multi-Si PV modules in China has been discussed in existing studies, however, their data are mostly from local enterprises, and none of their environmental assessment involves the decommissioning and recycling process. This study quantitatively assesses the life-cycle environmental impacts of Chinese Multi-crystalline Photovoltaic Systems involving the recycling process. The LCA software GaBi is applied to establish the LCA model and to perform the calculation, and ReCiPe method is chosen to quantify the environmental impacts. LCA of production process reveals that Polysilicon production, Cell processing and Modules assembling have relatively higher environmental impact than processes of Industrial silicon smelting and Ingot casting and Wafer slicing. Among the 14 environmental impact categories evaluated by ReCiPe methodology, the most prominent environment impacts are found as Climate Change and Human Toxicity. LCA including recycling process reveals that although recycling process has environmental impact, the recycling scenario has less environmental impact by comparing with the landfill scenario. Among the five manufacturing processes and recycling process, environmental impacts of polysilicon production, cell processing and modules assembling have relatively higher uncertainty, probably because that the environmental impact of these processes is high, and standard error of parameters such as electricity, aluminum and glass in the three processes are high. Findings of our study indicate that proper measures should be taken in the high pollution processes such as polysilicon production and cell processing. In addition, efforts should also be made to enhance the recovery rate and seek for more environmental friendly materials in the recycling process.

1. Introduction

With increasing awareness of sustainability and the demand for renewable energy sources, the solar industry plays an essential role in providing such a solution. Solar energy presents the opportunity to generate clean electricity, which can lead to a sustainable life style (Brouwer et al., 2011). Solar PV is now, after hydro and wind power, the third most important renewable energy source in terms of globally installed capacity. As an essential renewable energy technology, solar technology is experiencing fast application growing. In 2014, worldwide installed PV capacity has increased to at least 177 giga watts (GW), and is predicted to reach 489 GW in 2020 (Yang, 2015). China is the largest exporter of solar cells in the world, as more than 50% of the global solar cell is produced in China (Qiu et al., 2015). Among the various kinds of solar cell modules produced in China, the amount of silicon cell account for more than 90%, in which mono silicon and multi-Si PV modules are in the majority. Although there was severe the trade barrier from United State and Europe targeting China's photovoltaic products since 2012 (Grau et al., 2012), China enhanced the domestic demand of the solar PV. With the rapid construction of PV power stations, the demand of multi-Si PV modules in China keeps increasing (Chen, 2015a,b).

As a clean technology in the operation process, the manufacturing process of the solar system however has tremendous environmental burdens (Meijer et al., 2003). A number of studies have discussed the environmental impacts of solar PV system. For instance, Frischknecht et al. (2015) summarizes the latest research results of PV LCA in North America, Europe and Asia, and compiling the latest life cycle inventory data. Some other experts focused on the environmental assessment of multi-Si PV modules in specific

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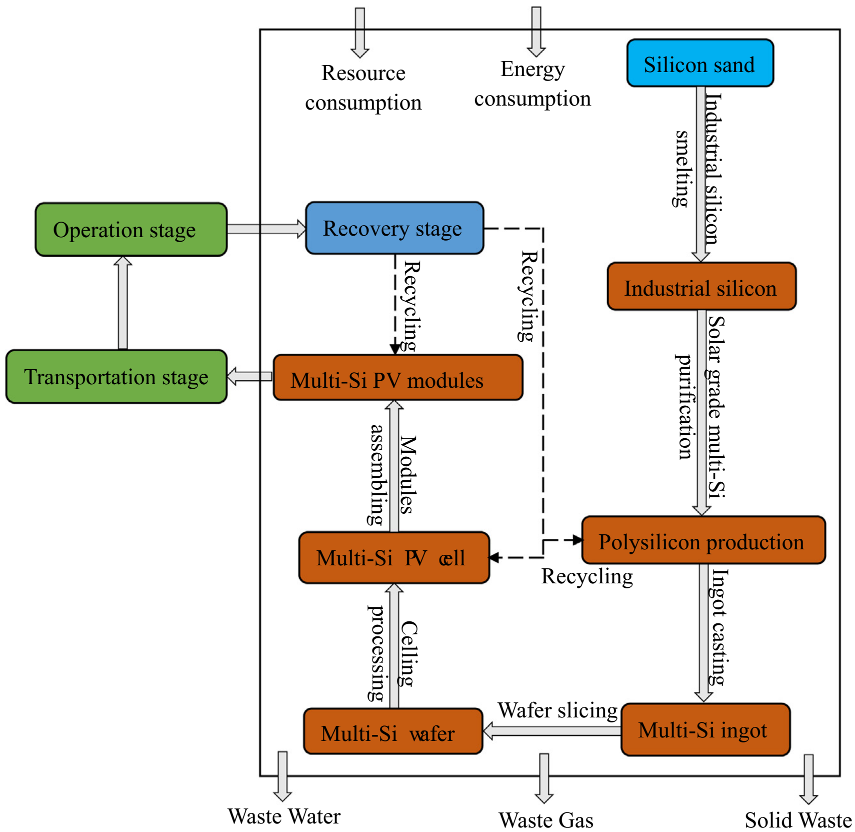

Fig. 1. System boundary of life cycle analysis of multi-Si PV module.

production process (Diao and Shi, 2011; He, 2013; Fu et al., 2015; Frankl et al., 1998; Fthenakis and Kim, 2011; Fthenakis et al., 2015). Few studies (Müller et al., 2005) assessed the environmental contribution from decommissioning and recycling process. The indicators of LCA for solar PV are usually limited to EPBT (energy payback time) and GHG emissions (Alsema and Wild-Scholten, 2005; Jungbluth, 2005; Fthenakis and Alsema, 2006; Wild-Scholten, 2009; Ruther and Krauter, 2004). Regarding the LCA of multi-Si PV modules in China, existing assessment usually focus on local enterprises (Fu et al., 2015; Peng et al., 2013; He, 2013; Diao and Shi, 2011), and none of their environmental assessment involves the decommissioning and recycling process. Considering the life period of a normal multi-Si PV system is around 25 years, China will face with a huge amount of solar PV disposal in the near future (Dale, 2013). Thus, it is essential to give an environmental influence assessment of China's multi-Si Photovoltaic Modules involving decommissioning and recycling process.

2. Methodology

2.1. Assessment procedure

LCIA methods commonly used are EI99, CML[1] (Heijungs et al., 1992), ReCiPe (Cavalett et al., 2013; Hauschild and Potting, 2005; Bekkelund, 2013). In which ReCiPe is the successor of EI99 and CML, having relatively comprehensive and new evaluation index (Goedkoop and Spriensma, 2001; Guinée et al., 2001). Thus ReCiPe method is chosen in our analysis. Results of life cycle impact assessment (LCIA) are calculated at the midpoint level through ReCiPe method.

Table 1
Characteristics of 200 Wp multi-Si PV module.

Item	Description
Module size	1482 × 992 × 35 mm
Mass	16.8 kg
Number of cells per module	54(6 × 9)
Cell area	156 × 156 mm^2
Operation life	25 years
Efficiency of cells	16%
Maximum power at STC[a] (Pmax)	200 Wp

The LCA software GaBi developed by Thinkstep company is applied to establish the LCA model and perform environmental impact calculations. The main steps of conducting LCA in Gabi are as follows: (1) Identify the evaluated processes and establish "plan" in Gabi for each process. (2) Input the inventory data of each process into the material table list. End of life ways such as wastewater treatment and landfill should also be illustrated, as different forms of waste treatment will influence the final environmental impact. (3) Calculate the environmental impact for each process that has input the material inventory. As for ReCiPe method, 16 midpoint environmental impacts will be estimated. It should be noted that environmental impact for each input material will be traced back to the original resources and production actions through the database in Gabi.

2.2. System boundary

Manufacturing technology discussed in this study is Siemens method (Cold hydrogenation), which is the most commonly used

[1] The CML is a problem-oriented LCA method aims to offer best practice for midpoint indicators and operate the ISO 14040 series of standards (Halleux et al., 2006).