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Domestic and overseas manufacturing scenarios of silicon-based photovoltaics: Life cycle energy and environmental comparative analysis

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Abstract

While life cycle assessment (LCA) has been recognized as an invaluable tool to assess the energy and environmental profiles of a photovoltaic (PV) system, current LCA studies are limited to Europe and North America. However, today most PV modules are outsourced to and manufactured in non-OECD countries (e.g., China), which have a substantially different degree of industrialization and environmental restriction. To investigate this issue, we perform a comparative LCA between domestic and overseas manufacturing scenarios illustrated by three kinds of silicon-based PV technologies, namely mono-crystalline silicon, multi-crystalline silicon and ribbon silicon. We take into account geographic diversity by utilizing localized inventory data for processes and materials. The energy payback time, energy return on investment and greenhouse gas (GHG) emissions for both scenarios are calculated and analyzed. Compared to the domestic manufacturing scenario, the energy use efficiency is generally 30% lower and the carbon footprint is almost doubled in the overseas manufacturing scenario. Moreover, based on the LCA results, we propose a break-even carbon tariff model for the international trade of silicon-based PV modules, indicating an appropriate carbon tariff in the range of €105–€129/ton CO_2.

Keywords: Life cycle assessment; Silicon-based photovoltaics; Manufacturing; Renewable energy

1. Introduction

Concerns about climate change, waste pollution, energy security and resource depletion are driving society to search for more sustainable approaches of energy supply. Among the various alternatives (e.g., wind, nuclear), photovoltaics (PV) are considered one of the most promising sustainable energy solutions (Darling et al., 2011). PV systems generate electricity directly from solar radiation, which is so abundantly available that the Earth receives enough solar energy every hour to meet the world's annual energy needs (EPIA, 2011). Furthermore, PV systems produce electricity with no air emissions during operation and have a very low carbon footprint throughout the life cycle stages, thus providing superior environmental performance compared to traditional fossil-fuel-based electricity generation technologies. Silicon-based PV (Si-PV) technologies receive the most attention, both because they were the first to be commercialized and because they have the largest market share (Fraunhofer, 2012; IEA, 2012). Thin-film PV technologies represent a substantially smaller market

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share, and current materials available for thin-film PVs will eventually run up against daunting resource limitation challenges (Feltrin and Freundlich, 2008; Fthenakis et al., 2009b; Keshner and Arya, 2004). Next-generation technologies such as organic PVs are emerging as promising alternatives, but there are still several crucial obstacles to overcome before large-scale implementation can be achieved (Günes et al., 2007; Peet et al., 2009; Yue et al., 2012). Therefore, for the purpose of this study, we only focus on the life cycle energy and environmental analysis of Si-PV technologies.

When measuring the energy and environmental performance of a product system, the life cycle assessment (LCA) methodology is usually employed. LCA takes into account the direct and indirect impacts throughout the entire life cycle of the product, including material sourcing, manufacturing, operation, transportation, disposal, etc. As illustrated by many authors, LCA is recognized as an invaluable tool to assess the energy and environmental profiles of a PV product system (Fthenakis and Kim, 2011). In early life cycle studies, researchers reported a wide range of primary energy consumption and greenhouse gas (GHG) emissions for Si-PV systems. Besides the inherent uncertainty in data collection, the adoption of different assumptions and allocation rules by individual LCA practitioners is considered as the main cause. Alsema (2000) estimated that the total energy requirements for mono-crystalline silicon (mono-Si) and multi-crystalline (multi-Si) frameless modules to be 5700 and 4200 MJ/m^2, respectively. He found the energy payback time (EPBT) to be 2.5–3 years and life cycle GHG emission to be 46–63 g CO_2 eq./kWh for roof-top installations for multi-Si PV. He considered Southern European conditions with an irradiation of 1700 kWh/(m^2 yr) and a performance ratio of 0.75. The module efficiencies were assumed to be 14% for mono-Si and 13% for multi-Si, respectively. Meijer et al. (2003) reported a slightly higher energy demand of 4900 MJ/m^2 for multi-Si modules, which corresponds to an EPBT of 3.5 years. They assumed the conversion efficiency of 14.5% under the irradiation of 1000 kWh/(m^2 yr). Jungbluth (2005) reported an EPBT of 3–6 years and GHG emissions of 39–110 g CO_2 eq./kWh under the Swiss average insolation of 1100 kWh/(m^2 yr), depending on configuration of different PV systems (i.e., façade, slanted-roof, and flat-roof). Their results were based on the assumption that the 300 μm-thick mono-Si and multi-Si PV modules operated with conversion efficiency of 14.8% and 13.2%, respectively.

The PV industry has developed rapidly over the past decade, and therefore material inventory and LCA results have also been updated as new technologies become available. Researchers have (Alsema and De Wild-Scholten, 2006; Fthenakis and Alsema, 2006) reported EPBTs of 1.7–2.7 years and GHG emissions of 30–45 g CO_2 eq./kWh for South-European locations based on the life cycle inventory (LCI) data representative for the technology status in 2004–2005. These studies covered mono-Si, multi-Si as well as ribbon-Si PV technologies for rooftop installations with conversion efficiency of 14%, 13.2% and 11.5%, respectively. Recently, several reports have (De Wild-Scholten, 2009; Fthenakis et al., 2009a) updated these estimates based on the latest technologies involving thinner modules and more efficient processes. Comparing with the 2004–2006 production processes, they reported that the EPBT decreased by 25–40% and the GHG emissions decreased by 30–40% for roof-top installed mono-Si, multi-Si and ribbon-Si PV modules. However, the corresponding LCI data are not yet in the public domain.

Although extensive life cycle studies for Si-PV technologies exist, most of them focus on manufacturing in Europe and North America; the results may not accurately reflect the energy and environmental impact of Si-PV modules made outside these areas. According to the IEA annual report (IEA, 2012), the cumulative installed PV capacity reached 63.6 GW in 2012, of which the greatest proportion (about 60%) was installed in Germany and Italy alone. The United States shared slightly more than 6% of the total capacity worldwide, and China accounted for about 5%. Despite the fact that Europe and the United States are leading the research and development of PV technologies, the majority of the PV modules are manufactured in Asia (about 80%). China alone accounts for 62% of the total production worldwide. European manufacturers produced about 10% of the PV modules, and only 4% of PV modules were made in the United States. These figures indicate that most PV modules are manufactured overseas but installed in Europe and North America, which is driven by factors such as lower labor and material costs and greater vertical integration in China. However, as a non-OECD country, China has a vastly different energy and industry structure with more lenient environmental restrictions. Therefore, the energy and environmental profiles of PV modules made in China can be distinctive from those manufactured in Europe or North America. It is important to conduct a life cycle study that explicitly considers the overseas manufacturing scenario and utilizes country-specific LCI data for processes and materials, which is the focus of this work.

The major novelties of this work are summarized as follows:

- Comparative life cycle study of Si-PV modules considering domestic and overseas manufacturing scenarios.
- Calculations based on country-specific LCI data for processes and materials.
- Break-even carbon tariff model based on LCA results.

Our analysis will be presented as follows. First, we will briefly introduce the LCA methodology and define the domestic and overseas manufacturing scenarios. Then, the life cycle boundary and inventory will be specified, followed by the analysis of energy and environmental profiles using certain indicators. Based on the LCA results, we propose a break-even carbon tariff model as a complementary analysis.