Available online at www.sciencedirect.com
ScienceDirect
Solar Energy 105 (2014) 669–678
SOLAR ENERGY
www.elsevier.com/locate/solener

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

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Received 10 May 2013; received in revised form 29 March 2014; accepted 11 April 2014
Available online 21 May 2014

Communicated by: Associate Editor S.C. Bhattacharya

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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http://dx.doi.org/10.1016/j.solener.2014.04.008
0038-092X/

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.

2. Life cycle stages and inventories

Life cycle assessment (LCA) is a well-structured quantitative tool aimed at evaluating the material and energy flows and the associated environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e., cradle-to-grave). Leaving practitioners with a lot of choices without affecting the validity of the LCA results, ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b) provide principles and framework for LCA including: (a) goal and scope definition, (b) inventory analysis, (c) impact assessment, and (d) interpretation. However, the LCA methodology still leaves the individual practitioner with a range of choices for assumptions that can affect the validity of the LCA results. In order to retain consistency, quality and credibility of our findings, we adopt the methodology guidelines reported by IEA (IEA, 2011a, 2011b), which represent a consensus among the authors, PV LCA experts in the United States, Europe, and Asia, for assumptions on PV performance, process input and emissions allocation, methods of analysis, and reporting of the results.

In general, LCA methods can be categorized into three types, namely process-based methods, input–output (I/O) analyses, and hybrid LCA methods. Process-based methods are bottom-up methods and can provide more specific information for the process under study. I/O analyses are a top-down approach, which use public data from I/O tables to evaluate the environmental impacts at the sector-level resolution. Hybrid LCA attempts to integrate I/O analysis with process-based methods to quantify both the direct and indirect impacts (Finnveden et al., 2009). As recommended by the guidelines, we employ the conventional process-based LCA instead of the I/O or hybrid methods, because of the relative maturity of process-based LCA and our interest in detailed product-level LCA. The major stages along the manufacturing of the three Si-PV modules are illustrated in Fig. 1, which is modified from that presented in the work by Fthenakis et al. (2008). As shown in Fig. 1, the three types of Si-PV modules differ in the technology for cell manufacturing, where mono-Si, multi-Si and ribbon-Si technology correspond to the pathway at the top, middle and bottom, respectively. Note that we are not considering the balance of system (BOS) in this work. We employ a "cradle-to-grave" life cycle boundary for the life cycle study. The production of Si-PV modules starts with the mining of quartz sand. The silica in the quartz sand is then reacted in an electric arc furnace using carbon electrodes with wood, charcoal and coal to produce "metallurgical grade" silicon (MG-Si, at least 98% purity). The MG-Si can be further purified into "electronic grade" (EG-Si, 9 N purity) or "solar grade" silicon (SoG-Si, 6 N purity) to meet the more stringent requirement in the electronics and solar industries. This is typically accomplished via either the "Siemens" process or the "modified Siemens" process. In the Siemens process trichlorosilane gas decomposes and deposits additional silicon onto silicon rods at 1100–1200 °C, while in the modified Siemens process silane is used as feedgas instead and the decomposition temperature is kept at about 800 °C (Aulich and Schulze, 2002). Apart from the conventional routes, a number of novel processes are being developed (e.g., Fluidized Bed Reactor process).

The source of SoG-Si usually involves a mixture of EG-Si, off-spec EG-Si and dedicated SoG-Si. Historically, off-spec EG-Si and silicon scraps from the production of EG-Si were the primary sources for the PV industry, but with the large growth in demand from the PV industry, the relative importance of dedicated SoG-Si has been increasing. Manufacturing of mono-Si and multi-Si wafers involves the production of silicon ingots, followed by wafer sawing. On the other hand, ribbon-Si wafers are directly pulled or cast from liquid silicon, thus a much higher material efficiency can be achieved because sawing losses are avoided. The cell manufacturing and subsequent module assembly processes are essentially identical for the three types of Si-PV technologies. Ethylene–vinyl acetate and glass sheets are used to encapsulate the PV modules and provide protection from the physical elements during operation. Aluminum frames are usually employed for additional strength and easy mounting. In our study, we investigate the production of Si-PV modules with 60 solar cells of 156 mm × 156 mm. The nameplate capacity is 224, 210 and 192 W_p for mono-Si, multi-Si and ribbon-Si modules, respectively. The module area is assumed to be 1.60 m^2.

Different from conventional LCA studies, we are considering two geographically diverse manufacturing scenarios

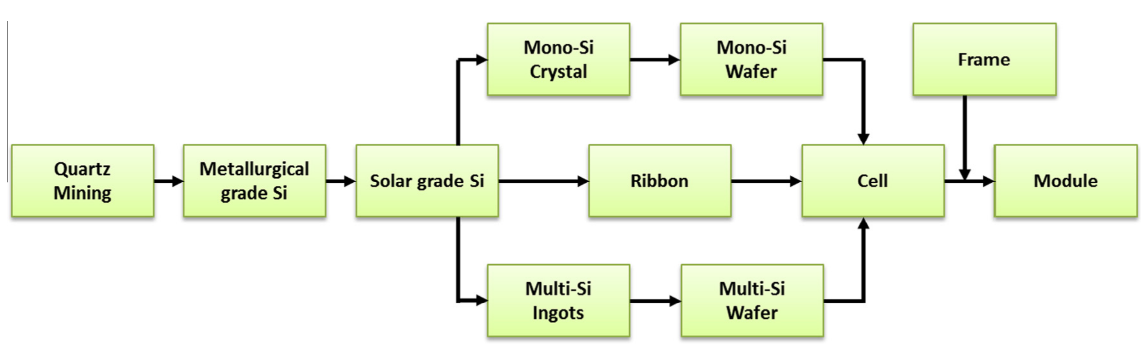

Fig. 1. Flow diagram from raw acquisition to manufacturing stages of Si-PV modules.

in our life cycle energy and environmental comparative analysis. In the domestic manufacturing scenario, we assume that the Si-PV modules are made and installed in Southern Europe. In the overseas manufacturing scenario, we assume that the Si-PV modules are made in China, then exported to and installed in Europe. In both scenarios, we consider installation in Europe, because Europe is the major market for PV modules worldwide, as mentioned in the Introduction. Similarly, we select China as an example of overseas manufacturing, because China has the largest production capacity of PV modules in the world. Note that some European manufacturers also purchase intermediate products (e.g., ingots, wafers and cells) from vendors in places like China. However, we only consider the two most representative scenarios mentioned above for illustration of our comparative life cycle study.

The LCI data of the three kinds of PV modules and corresponding background processes employed for the domestic manufacturing scenario are derived from Ecoinvent database v2.2 (ecoinvent, 2010), which is the most widely used life cycle database in the world. Since China has a different degree of industrialization and environmental restrictions compared to Europe, country-specific LCI data must be used for the overseas manufacturing scenario. In this work, we employ the Chinese Life Cycle Database (CLCD) v0.8 (IKE and SCU-ISCP, 2013), which is available in the software eBalance v4.0 (IKE, 2013). CLCD is a national background life cycle database consisting of about 600 LCI datasets for key materials and chemicals, energy carriers, transport, and waste management, which is based on a consistent core life cycle model and represents the combination of various technologies in the Chinese market. Conveniently, CLCD employs the same data format (Ecospold) as that in Ecoinvent, which facilitates the comparative life cycle study. Since the LCI data for Si-PV modules are not directly available in CLCD v0.8, we build life cycle models in eBalance v4.0 for the overseas manufacturing scenario based on the unit process raw (UPR) data provided in Ecoinvent v2.2, assuming the same manufacturing technologies apply to China. This assumption is valid because the UPR data in Ecoinvent v2.2 represent mixed data including some Asian companies, and many European and American companies have been building production lines in China. Therefore, by employing region-specific data from Ecoinvent and CLCD, we capture the differences in technology level, industrial structure, energy efficiency, electricity mix, etc. in the domestic and overseas manufacturing scenarios.

The LCI data derived from CLCD are considered comparable with those from the Ecoinvent database in terms of two aspects. First, the up-to-date Ecoinvent database is integrated in and compatible with CLCD. During the data collection of CLCD, domestic production is distinguished from imported parts. The Ecoinvent database is applied to represent the production outside of China. Production in China is further broken down by process technology and factory scale to collect data and set up models. By weighted average market share in China, the market average technology data are calculated in CLCD. In most unit processes, raw material consumption data are primarily from Chinese industry statistics or technical literature; the main emission data are from the China Pollution Source Census; partial emissions data are derived from chemical equilibrium calculations. Some process data are from cooperative factories, modified as an estimation of industrial average rather than factory-specific data. Second, during the development of CLCD, the data quality assessment method based on the raw data's uncertainty and the data quality control method based on sensitivity analysis are applied according to the methodologies in Ecoinvent for data quality check, evaluation and control. However, we note that Ecoinvent alone is not sufficient for evaluating the overseas manufacturing scenario, because very limited LCI data for China are available in Ecoinvent compared to those in CLCD.

In this study, we define the functional unit as "1 m^2 module area". We note that some life cycle studies use "1 piece of PV module" as the functional unit, of which the LCI data are usually different (IEA, 2011a). In the following sections, we will look into the energy and environmental profiles of Si-PV modules by assessing the relative indicators for both scenarios based on the LCI data.

3. Life cycle energy profile

3.1. Energy payback time

Since PVs are considered as one of the primary alternatives for energy supply, it is of significant importance to understand the energy profile of Si-PV technologies. The most frequently employed metric is the energy payback time (EPBT), which indicates the time needed to compensate for the total primary energy (renewable and nonrenewable) required throughout the life cycle of an energy supply system. Primary energy is defined as the energy embodied in natural resources that has not undergone any anthropogenic conversion and needs to be converted and transported to become usable energy. The total demand, valued as primary energy, during the life cycle of a product is also called the cumulative energy demand (CED), which includes the direct uses as well as the indirect or grey consumption of energy due to the use of construction materials, raw materials, consumables, etc. Based on the LCI data for both the domestic and overseas scenarios, the CED results for the three kinds of Si-PV modules are summarized in Fig. 2. The infrastructure and internal transport to manufacture Si-PV modules are accounted for in the calculation, while international shipping from China to Europe is not included for a fair comparison. However, we note that the stage of international shipping can be easily added to the overseas manufacturing scenario, since it is independent of the other stages or processes. This addition would, of course, add to the EPBT and adverse environmental impact of PV panels manufactured overseas.

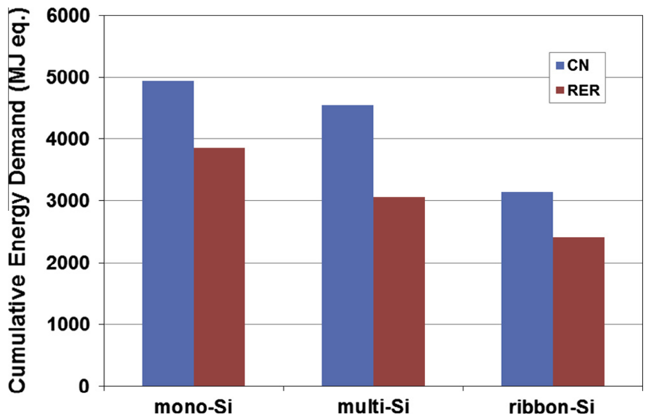

Fig. 2. Cumulative energy demand (CED) results (CN: China, RER: Europe).

As can be seen, in both scenarios, mono-Si technology requires the highest CED and the ribbon-Si technology requires the least. The differences mainly stem from the different processes for ingots and wafer production. For example, ribbon-Si wafers are produced directly from purified liquid silicon, thus avoiding the material as well as energy losses in wafer sawing. Compared to the domestic manufacturing scenario, the overseas manufacturing scenario involves a significantly higher CED, which is 28%, 48% and 30% higher for mono-Si, multi-Si and ribbon-Si modules, respectively. Two of the most important factors underlying these differences are electricity mix and energy efficiency. China generates 80% of its electricity from coal, while renewable energy resources (e.g., hydropower plants) have a larger share in Europe. Moreover, the large share of coal in energy generation also causes the efficiency level in China to stand below the world average (ABB, 2010).

Knowing the CED, we can calculate the EPBT according to the following formula,

$$\mathrm{EPBT} = \frac{\mathrm{CED}}{E_{agen}/n_G} \tag{1}$$

where E_{agen} stands for the annual electricity generation and n_G represents the grid efficiency, which is the average primary energy-to-electricity conversion efficiency at the demand side. We note that, in both scenarios, the Si-PV modules are assumed to be installed in Europe. Thus the denominator in Eq. (1) is the same for both scenarios. In our calculation, we consider the Southern European condition with irradiation of 1700 kWh/(m^2 yr) and a performance ratio of 0.75. The module efficiency for mono-Si, multi-Si and ribbon-Si modules is 14.0%, 13.2% and 12.0%, respectively. The annual electricity production E_{agen} is equal to the product of irradiation, performance ratio, and module efficiency. The average conversion efficiency n_G is assumed as 0.31 for Europe. The EPBT estimates for both scenarios are presented in Fig. 3.

The EPBT of PV modules made in Europe have EPBTs of 1.9, 1.6 and 1.4 years for mono-Si, multi-Si and ribbon-Si technologies, respectively. However, the PV modules made in China have the EPBTs of 2.4, 2.3 and 1.8 years for mono-Si, multi-Si and ribbon-Si technologies, respectively. As can be observed from the stacked column chart, the production of purified silicon is the most energy intensive part in the life cycle of Si-PV modules, which can occupy up to 47% of the EPBT for multi-Si modules. The substantial role of Si feedstock is rooted in the fact that acquisition of SoG-Si feedstock involves a large amount of electricity consumption (e.g., Siemens and modified Siemens processes). As a consequence, the different electricity mix and energy efficiency leads to the increase in EPBT in the overseas manufacturing scenario. Compared to the primary energy consumption associated with electricity use, the differences in other materials are less affected. For example, the differences in primary energy consumption for manufacturing glass and aluminum for module assembly contribute to a relatively insignificant increase in the EPBTs. The results indicate that the largest energy-saving potential lies in the Si feedstock acquisition phase, which can be achieved by development of new technology, higher usage of dedicated SoG-Si instead of EG-Si for Si-PV manufacturing, etc. To narrow the gap of CED and EPBT between the domestic and overseas manufacturing scenarios, a cleaner electricity mix in China is critical, which calls for the employment of more sustainable energy production systems such as Si-PVs themselves. Many countries have adopted policy mechanisms to encourage increased use of renewable energy generation, such as feed-in tariffs and direct subsidies to end users. However, note that the EPBTs presented in Fig. 3 represent the technology status as of 2004–2006, for which detailed LCI data are in the public domain. Current technologies should have lower EPBTs due to the use of novel purification processes for SoG-Si production and thinner wafer thickness. Also, the EPBTs are expected to continue decreasing in the future, though with ever decreasing marginal returns.

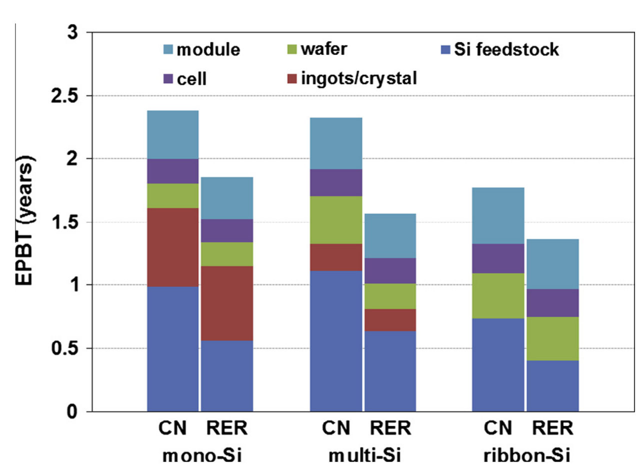

Fig. 3. Energy payback time (EPBT) results (CN: China, RER: Europe).

3.2. Energy return on energy investment

Besides the EBPT, it is crucial to measure the energy return on investment (EROI) of an energy production process for the sake of its long-term viability (Raugei et al., 2012). The traditional way of calculating the EROI of PVs is given as follows (Lloyd and Forest, 2010). According to Eq. (2), the value of EROI indicates how much electricity, valued as primary energy, can be returned for the investment of one unit of primary energy. We note that some researchers compute the EROI without prior conversion of the generated electricity into its primary energy equivalent, resulting in a difference by the factor of $1/n_G$.

$$\mathrm{EROI} = \frac{\mathrm{lifetime}}{\mathrm{EPBT}} = \frac{\mathrm{lifetime} \cdot E_{agen}/n_G}{\mathrm{CED}} \tag{2}$$

In this life cycle study, we assume the lifetime of the three kinds of PV modules to be 30 years, in alignment with typical commercial guarantees. Based on the previous results on EPBTs, we present the EROIs for different Si-PV technologies and manufacturing scenarios in Fig. 4.

The calculated EROIs for Si-PV modules manufactured in Europe are 16.1, 19.1 and 22.0 for mono-Si, multi-Si and ribbon-Si technologies, respectively, while the EROIs for Si-PV modules made in China are 12.6, 12.9 and 16.9 for mono-Si, multi-Si and ribbon-Si technologies, respectively. As the EROIs are all greater than 1, the energy production over the Si-PV modules' lifetime is larger than the initial energy investment in the manufacturing process. Therefore, the larger EROI indicates higher net power generation potential. Because the EROI metric has a negative correlation with EPBT, ribbon-Si technology has the highest EROI among the three kinds of Si-PV modules. Comparing the EROI between the domestic and overseas manufacturing scenarios, we can see that the EROIs for Si-PV modules made in China are much lower than those made in Europe. This provides another perspective of the efficiency in energy use. For example, by burning 1 ton of coal in Europe, one can achieve a higher electricity return from PVs than doing the same in China. Therefore, we can conclude that the domestic manufacturing scenario is favored for alleviating the resource depletion crisis.

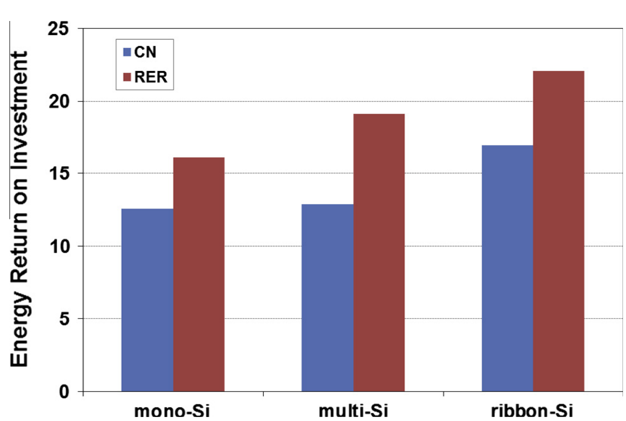

Fig. 4. Results of energy return on energy investment (CN: China, RER: Europe).

4. Life cycle carbon footprint

A central advantage of PV technologies, in the context of increasing attention associated with anthropogenic climate change, is that they have an extraordinarily low carbon footprint with almost no greenhouse gas emissions (GHG) during operation, thus providing significant environmental benefits compared to traditional fossil-fuel or even nuclear technologies. Carbon footprint is usually measured by the amount of greenhouse gas emissions during the life cycle of the PV system, which involves direct emissions from manufacturing processes and various activities, as well as indirect emissions embedded in the materials and infrastructures. In this life cycle study, we estimate the carbon footprint as the equivalent amount of CO_2 that has the same global warming potential (GWP) measured over an integrated time horizon of 100 years, using the most recent global warming potential factors published by IPCC (Forster and Ramaswamy, 2007; IPCC, 2007). The major emissions include CO_2 (GWP = 1), CH_4 (GWP = 25), N_2O (GWP = 298) and chlorofluorocarbons (GWP = 4750–14400), etc. Based on the discussion above, the carbon footprint can be calculated using the following formula,

$$CF = \frac{\sum_{i \in GHG} \lambda_i \cdot CE_i}{E_{agen}} \tag{3}$$

where CF stands for the life cycle carbon footprint of the PV system. Index i represent the species of emissions that belong to the GHG family. λ_i is the GWP factor corresponding to species i. CE_i is the cumulative emissions (direct and indirect) of species i during the life cycle of the system. E_{agen} is the annual generation of electricity, as mentioned before. The total weighted GHG emission is normalized by the annual generation of electricity, because we are interested in establishing the environmental cost, or carbon footprint price, that we pay per kWh electricity generated from the energy production process. Following this approach, we present the carbon footprint results for the three kinds of Si-PV technologies under both scenarios in Fig. 5.

The carbon footprint of the modules made in Europe is 37.3, 31.8 and 28.5 g CO_2-eq./kWh for mono-Si, multi-Si and ribbon-Si technology, respectively. However, the carbon footprint of the modules manufactured in China is 72.2, 69.2, and 54.3 g CO_2-eq./kWh for mono-Si, multi-Si and ribbon-Si technology, respectively. These results indicate that the carbon footprint of Si-PV modules in the overseas manufacturing scenario have almost doubled compared to the domestic manufacturing scenario. Since the manufacturing of Si-PV modules is an

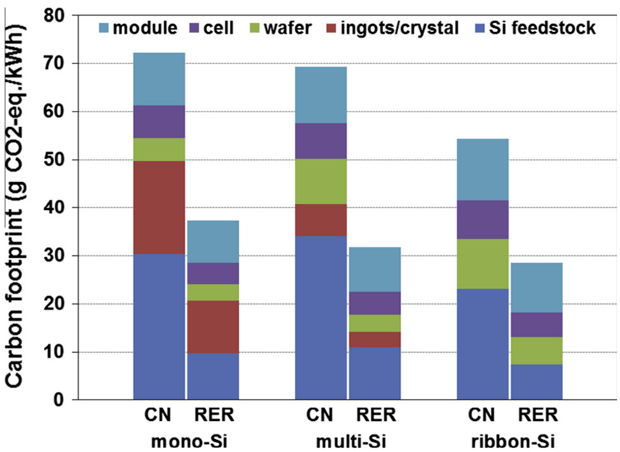

Fig. 5. Results of carbon footprints of Si-PV modules (CN: China, RER: Europe).

electricity-intensive process, most of the carbon footprint can be traced back to the generation of electricity. As mentioned before, China uses a large amount of coal for electricity generation, which is the least climate-friendly fossil fuel because of its high carbon intensity. Therefore, in comparison with Fig. 3, we can observe a similar profile between the EPBT and carbon footprint. Since the current Si-PV capacity in China is relatively small, large-scale installation of Si-PV production systems in China has great potential to restructure the electricity mix, which in return will help to reduce the carbon footprint and increase energy efficiency.

5. Break-even carbon tariff model

We propose a break-even carbon tariff model for Si-PV modules based on the previous calculation. As an essential part of post-Kyoto international climate negotiations, the "carbon tariff", a means of carbon-based border tax adjustments, has been proposed to level the playing field by the United States, European Union and other OECD countries as a policy tool to protect competitive advantages of domestic industries (Bao et al., 2013; Kuik and Hofkes, 2010; van Asselt and Brewer, 2010). Furthermore, according to the Copenhagen accord, several participating countries are launching a carbon tax on their domestic industries to fulfill the pledged emission reduction targets (Meng et al., 2013; Zhang and Baranzini, 2004). However, the legality of carbon tariff policy under the WTO framework is still under discussion, while the carbon tax is currently only accepted in a few countries and localities. Since the focus of this work is on comparative life cycle studies of domestic and overseas manufacturing scenarios for Si-PV modules, we are not performing a comprehensive simulation and analysis for carbon-pricing policies covering all the sectors. The following carbon tariff break-even model is designed to provide insights on the economic impact of Si-PV carbon footprints.

$$(Cost_{CN,raw} + Ctax_{CN} \cdot CF_{CN}) + (Ctar_{CN-RER} \cdot CF_{CN}) = (Cost_{RER,raw} + Ctax_{RER} \cdot CF_{RER}) \quad (4)$$

where $Cost_{A,raw}$ stands for the raw price excluding any carbon prices of Si-PVs manufactured in region A. $Ctax_A$ is the carbon tax rate in region A. CF_A represents the carbon footprint of Si-PV modules made in region A. $Ctar_{A\text{-}B}$ is the carbon tariff for Si-PV modules imported by region B from region A. The terms in the first bracket indicate the Si-PV module price in China after a carbon tax. Similarly, the terms in the third bracket indicate the Si-PV module price in Europe after a carbon tax. By inserting the terms in the second bracket, we set the cost of domestic and overseas manufacturing scenarios equal. Therefore, $Ctar_{A\text{-}B}$ is called the break-even carbon tariff. Note that the anti-dumping tariff, which is another means of border tax adjustments to protect domestic industries, is not included in the calculation (ITA, 2012). This model establishes a simple relationship among the local manufacturing cost, carbon tax, carbon footprint, and cross-border carbon tariff. The calculated break-even value can serve as reference for setting future carbon tariffs. Imposing this carbon tariff will drive the overseas Si-PV manufacturers to reduce their carbon footprint and make the domestic Si-PV manufacturers more competitive in the marketplace, thus leading to more sustainable Si-PV manufacturing.

The raw costs of Si-PV modules made in Europe and China are 1.12 and 0.81 €/W_p, respectively. These data are derived from typical spot market prices at the end of 2011 (Wissing, 2012; Xu et al., 2012). Instead of investigating each Si-PV technology individually, we take the average according to their share in global annual PV installation by technology at the end of 2011 (Fraunhofer, 2012), which are 46%, 53% and 1% for mono-Si, multi-Si and ribbon-Si technologies, respectively. This analysis suggests that the average carbon footprint for Si-PV modules is 1.32 and 2.70 kg CO_2 eq./W_p for domestic and overseas manufacturing scenarios, respectively (see Appendix A for detailed calculations). Here, we normalize the carbon footprint in terms of watt-peak (W_p), which is often employed as a measure of the nominal power of a photovoltaic solar energy device.

Knowing the raw prices and carbon footprints of Si-PV modules, we perform a scenarios analysis by varying the values of carbon tax in both domestic and overseas manufacturing scenarios. We assume that the carbon tax in China ranges from 0 to €10/ton CO_2, because China started levying a carbon tax in 2012 at ¥10/ton CO_2, and plans to increase the tax to ¥50/ton CO_2 by 2020 (Xinhua, 2013). We assume that the carbon tax in Europe ranges from 0 to €30/ton CO_2, since different levels of carbon tax programs were launched in European countries (CTC, 2013). The results are presented in Fig. 6.

In Fig. 6, the X-axis is the carbon tax rate imposed in Europe, and the Y-axis is the break-even carbon tariff.

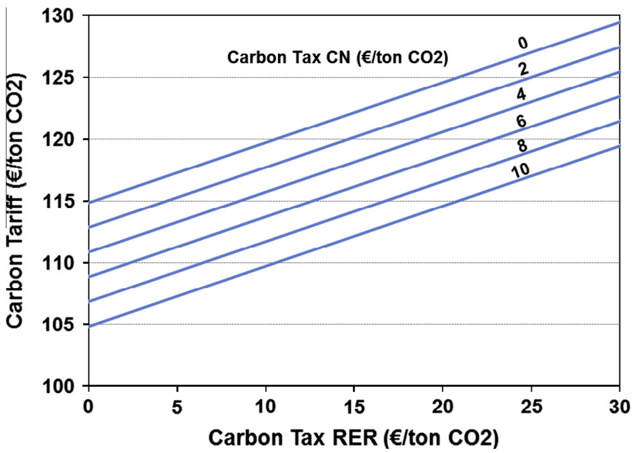

Fig. 6. Break-even carbon tariff.

The series of lines correspond to different levels of carbon tax rate imposed in China ranging from 0 to €10/ton CO_2. A linear relationship between region-specific carbon taxes and break-even carbon tariff can be observed from the figure. The lowest carbon tariff is €105/ton CO_2 if carbon tax is absent in Europe while China has a carbon tax of €10/ton CO_2. The highest carbon tariff is €129/ton CO_2 if carbon tax is absent in China while Europe has a carbon tax of €30/ton CO_2 When carbon tax is absent in both China and Europe, the break-even carbon tariff is about €115/ton CO_2. As an approximation of the current situation, the carbon tax rate in China and Europe is estimated to be €2 and €20/ton CO_2, respectively. This corresponds to a break-even carbon tariff of €123/ton CO_2. Considering the current trend towards stricter environmental restrictions, we expect the carbon tax rate both in China and Europe to increment upward in the future. In year 2020, the break-even carbon tariff may reach €119/ton CO_2, corresponding to the carbon tax rate of €10 and €30/ton CO_2 for China and Europe, respectively.

Since the major parameters of the Si-PV technologies including conversion efficiency, wafer thickness, and material utilization are continuously improving, the above LCA and related calculations may not accurately represent the current or future data, warranting timely updates of these indicators. The comparative analysis reveals a significant difference in the energy and environmental impacts between domestic and overseas manufacturing scenarios. But, as China is adopting stricter energy and environmental policies, energy use efficiency and emission control in China are expected to improve, thus narrowing the difference in EPBT and carbon footprint between the two scenarios.

6. Conclusion

In this work, we conducted a life cycle energy and environmental comparative analysis using region-specific LCI databases, and investigated the domestic and overseas scenarios for manufacturing three types of silicon-based photovoltaic (Si-PV) modules. Since China is the largest PV module producer in the world, while Europe is the largest consumer, we assert that the overseas manufacturing scenario better reflects the current status of the Si-PV supply chain. The results show that the Si-PV modules manufactured in China consume 28–48% more primary energy resources than their counterparts made in Europe, which indicates that the actual energy payback time (EPBT) of the installed PV modules were underestimated. Furthermore, the greenhouse gas (GHG) emissions embedded in Si-PV modules corresponding to the overseas manufacturing scenario were twice as much as those associated with the domestic scenario. This finding suggests that though lower cost of Si-PV modules could be achieved in the overseas manufacturing scenario, the contribution to the risk of global warming is actually doubled. The results of energy return on investment (EROI) also indicate that the relatively higher energy use efficiency in the domestic manufacturing scenario would be beneficial to the relief of the energy depletion crisis. In addition to the conventional energy and environmental analysis, we propose a carbon tariff break-even model, which establishes the correlation between local manufacturing cost, carbon footprint, carbon tax, and cross-border carbon tariff. It can provide reference for setting cross-border carbon tariffs and help to drive toward more sustainable of Si-PV manufacturing. We find that the break-even carbon tariff would be in the range of €105–€129/ton CO_2 as the carbon tax rate in China and Europe ranges from 0 to €10/ton CO_2 and to €30/ton CO_2, respectively.

Acknowledgements

The authors gratefully acknowledge the financial support from the Institute for Sustainability and Energy at Northwestern (ISEN). This work was performed, in part, at the Center for Nanoscale Materials, a U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences User Facility under Contract no. DE-AC02-06CH11357. We are also grateful to IKE Environmental Technology Co. Ltd. for providing part of the life cycle inventory data from the Chinese Life Cycle Database (CLCD) for the life cycle energy and environmental analysis of the overseas manufacturing scenario.

Appendix A. Calculation of average carbon footprint

According to the given nameplate capacity and module area, we can first calculate the capacity per functional unit. Then the average carbon footprint can be calculated according to the given market shares. Detailed calculations are given in the following table; the last two rows show that the average carbon footprint for Si-PV modules made in China and Europe is 2.70 and 1.32 kg CO_2 eq/W_p, respectively.

	Mono-Si	Multi-Si	Ribbon-Si	Unit	Ref. #
Nameplate capacity	224	210	192	W_p	A1
Module area	1.6	1.6	1.6	m^2	A2
Capacity per area	140.00	131.25	120.00	W_p/m^2	A3 = A1/A2
Carbon footprint CN	386.71	349.55	249.25	kg CO_2 eq/m^2	A4
Carbon footprint per capacity CN	2.76	2.66	2.08	kg CO_2 eq/W_p	A5 = A4/A3
Carbon footprint RER	199.75	160.44	130.64	kg CO_2 eq/m^2	A6
Carbon footprint per capacity RER	1.43	1.22	1.09	kg CO_2 eq/W_p	A7 = A6/A3
Market share	46	53	1	%	A8
Average carbon footprint CN	**2.70**			kg CO_2 eq/W_p	A9 = $\sum$A5 × A8
Average carbon footprint RER	**1.32**			kg CO_2 eq/W_p	A10 = $\sum$A7 × A8

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