Solar Energy Materials and Solar Cells 174 (2018) 157–162

Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

journal homepage: www.elsevier.com/locate/solmat

A comparative life-cycle assessment of photovoltaic electricity generation in Singapore by multicrystalline silicon technologies

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ARTICLE INFO

Keywords:
Life-cycle assessment
p-type multicrystalline silicon technologies
PERC cell technology
Frameless double-glass PV module
Energy payback time
Greenhouse gas emissions

ABSTRACT

This paper presents a comparative life-cycle assessment of photovoltaic (PV) electricity generation in Singapore by various p-type multicrystalline silicon (multi-Si) PV technologies. We consider the entire value chain of PV from the mining of silica sand to the PV system installation. Energy payback time (EPBT) and greenhouse gas (GHG) emissions are used as indicators for evaluating the environmental impacts of PV electricity generation. Three roof-integrated PV systems using different p-type multi-Si PV technologies (cell or module) are investigated: (1) Al-BSF (aluminum back surface field) solar cells with the conventional module structure (i.e. glass/encapsulant/cell/encapsulant/backsheet); (2) PERC (passivated emitter and rear cell) devices with the conventional module structure; and (3) PERC solar cells with the frameless double-glass module structure (i.e. glass/encapsulant/cell/encapsulant/glass). The EPBTs for (1) to (3) are 1.11, 1.08 and 1.01 years, respectively, while their GHG emissions are 30.2, 29.2 and 20.9 g CO_2-eq/kWh, respectively. Our study shows that shifting from the conventional Al-BSF cell technology to the state-of-the-art PERC cell technology will reduce the EPBT and GHG emissions for PV electricity generation. It also illustrates that mitigating light-induced degradation is critical for the PERC technology to maintain its environmental advantages over the conventional Al-BSF technology. Finally, our study also demonstrates that long-term PV module reliability has great impacts on the environmental performance of PV technologies. The environmental benefits (in terms of EPBT and GHG emissions) of PV electricity generation can be significantly enhanced by using frameless double-glass PV module design.

1. Introduction

Due to the threat of climate change, renewable energies have received enormous interest in recent years. Among the various renewable energy resources, photovoltaic (PV) electricity generation has emerged as a promising and sustainable alternative to the conventional fossil energies. PV technologies, which directly convert sunlight into electricity, have great potential to mitigate greenhouse gas (GHG) emissions and contribute significantly to the global energy mix. Over the past decade, the PV industry has been growing exponentially. In 2015, it achieved global installations of over 50 GW, and the cumulative installed capacity surpassed 228 GW [1,2]. With continuous advancements in PV technologies, the levelised cost of electricity (LCOE) for PV will become increasingly competitive compared with other energy sources, thereby prompting large-scale PV deployment in the near future. It is projected that, by 2050, PV energy generation will reach a cumulative capacity of about 4.7 TW and achieve a 16% share in the global electricity mix [3].

As the PV market continues to grow rapidly, it is important to evaluate the environmental performance of PV technologies from a broader perspective. Although PV is considered to be completely green during its operational life, a considerable amount of energy is consumed to manufacture different components of a PV system [4–10]. Therefore, an in-depth analysis is necessary to understand the environmental performance of various PV technologies. Such analysis not only provides policymakers and energy investors with valuable information, it is also a powerful product optimization tool for PV manufacturers. Life-cycle assessment (LCA) is a useful technique to evaluate environmental impacts of a product or process from the cradle to the grave, which considers material and energy flows at all production

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http://dx.doi.org/10.1016/j.solmat.2017.08.040
Received 25 January 2017; Received in revised form 7 August 2017; Accepted 30 August 2017
Available online 08 September 2017
0927-0248/

stages of a product or process [11]. Many research have investigated the environmental impacts of PV electricity generation using the LCA methodology. However, no previous study has been conducted to compare the impacts of different cell or module structures on the environmental performance of PV electricity generation. In this study, we perform a comparative LCA of PV electricity generation in Singapore by various p-type multicrystalline silicon (multi-Si) PV technologies, which is forecasted to maintain their dominance (~ 50%) in the PV market in the next 10 years [12]. Energy payback time (EBPT) and GHG emissions are used as indicators for evaluating the environmental impacts. While the life-cycle analysis is modelled for Singapore, the comparative results are applicable to other regions.

Firstly, two solar cell architectures are studied and compared: the conventional Al-BSF (aluminum back-surface-field) cell and the state-of-the-art PERC (passivated emitter and rear cell) device. The Al-BSF cell technology has dominated the PV market since the 1980s because of its low cost [12]. However, the PERC cell technology has recently gained huge momentum, driven mainly by major breakthroughs in manufacturing to bring down its cost [12,13]. They provide a superior performance (higher PV efficiency) than the conventional Al-BSF solar cells, largely due to a reduced back surface recombination and increased internal rear surface reflectance [13]. In this paper, a comparison is performed between these two cell technologies using the LCA methodology to illustrate the environmental benefits of shifting from the Al-BSF technology to the PERC technology. The effects of light-induced degradation (LID) on the environmental performance of the PERC technology are also discussed.

Moreover, we also compare the environmental impacts of two multi-Si PV module designs. Frameless double-glass PV modules (i.e. glass/encapsulant/cell/encapsulant/glass) have emerged as a viable alternative to the conventional PV modules (i.e. glass/encapsulant/cell/encapsulant/backsheet laminate with an aluminum frame) [12]. On the one hand, a frameless double-glass design offers the potential for achieving a noticeable cost reduction [12]. On the other hand, the rear glass cover is sufficient to compensate for the mechanical stability provided by the metal frame [14]. Moreover, a longer module lifetime and increased long-term reliability can be realized with the double-glass structure [14]. In this study, the life-cycle approach is used to compare the performance of the frameless double-glass and the conventional PV module design from an environmental perspective. The importance of the long-term module reliability of PV technologies is emphasized.

2. PV system description

Roof-integrated PV systems in Singapore using 60-cell silicon PV modules are considered. Three PV systems using different silicon PV technologies (cell or module) are investigated, as summarized in Table 1. The solar cells are made from p-type multi-Si wafers with a size of 156 mm × 156 mm × 180 µm. The module efficiency for scenarios 1 and 2 are extracted from the International Technology Roadmap for Photovoltaic (ITRPV, 7th edition), which represents the average module efficiency from the PV industry [12]. It can be seen from Table 1 that the double-glass modules have a lower efficiency of 16.2% compared to 16.7% for the glass/backsheet modules. The lower double-glass module efficiency can be attributed to its lower optical performance. For a glass/backsheet module, the incident light arriving in the cell-gap regions is reflected by the backsheet, whereby a significant fraction of this reflected light will reach the solar cell (see Fig. 1). However, for a double-glass module, this effect does not occur. The optical loss is in the range of 2–4%, depending on the width of the cell-gap region [15].

More than 15 PV systems in Singapore using p-type multi-Si technologies are surveyed and evaluated. The average performance ratio (PR) of these systems is calculated to be around 78.4%. Therefore, it is reasonable to consider an initial PR (PR_1) of 78.5% for silicon PV systems in Singapore. We have also collected irradiance data from 25 metrological sites in Singapore from 2014 to 2015. An average annual irradiation of about 1580 kWh/m^2/year has been determined to be available to PV systems.

Furthermore, over their entire lifetime of more than 20 years, PV modules experience various degradation processes in the field, such as corrosion, EVA browning and potential-induced degradation [16,17]. As a result, PV module efficiency degrades over time, and with it the PV system's annual energy yield. Hence, the reliability of PV modules has to be taken into account for the calculation of lifetime electricity generation by PV systems. In general, conventional PV modules come with a warranty of 25 years. For frameless double-glass modules, PV manufacturers often offer a longer warranty period of 30 years due to the increased reliability. Based on a three-year study by Ye et al. [18], the PR of conventional multi-Si PV modules was found to degrade at about −1%/year in Singapore. On the other hand, double-glass modules provided excellent protection to the solar cells (monocrystalline silicon), where the yearly PR degradation was only around −0.2%/year [18]. Therefore, a −1%/year degradation to PR and 25-year lifetime is considered for PV systems using the glass/backsheet modules, while a −0.2%/year degradation to PR and 30-year lifetime is used for double-glass modules in this study. The performance of other system components such as the inverter also degrades with time. However, PV system degradation is excluded from the current study for two reasons: (1) the system component degradation is the same for all three investigated systems, so it will not cause a major shift in the comparisons; and (2) PV system degradation is similar to module degradation when modules in a given system degrade similarly [19], which can often be achieved by careful project management and module quality control.

Table 1
Details of the three PV systems using different silicon PV technologies investigated in this study.

	Scenario 1	Scenario 2	Scenario 3
Wafer type	p-multi	p-multi	p-multi
Cell technology	Al-BSF	PERC	PERC
Module construction	Glass/backsheet	Glass/backsheet	Glass/glass
Frame	Yes	Yes	No
Module efficiency	15.9%	16.7%	16.2%

3. Life-cycle evaluation methodology

3.1. LCA scope definition

The entire value chain of PV is considered from the mining of silica sand to the PV system installation (see Fig. 2). For each step, conventional production technologies (i.e. technologies widely used in the industry) are considered. The details of the different production stages are available in numerous sources [20,21] and thus not discussed in this paper. The operation of PV systems is also considered to evaluate the lifetime electricity generation of PV systems. However, system maintenance is excluded from the current study for two reasons: (1) the required maintenance is similar to all three investigated systems, so it will not cause a major shift in the comparisons; and (2) cleaning of PV modules is not as frequent as for modules deployed in deserts due to frequent raining in Singapore's tropical climate. Transportation is not also considered as its contribution is relatively negligible (~ 0.5%), according to Kannan et al. [4]. Furthermore, end-of-life management of PV systems is ignored, since the majority of the PV systems are installed after 2010 and such practice is still under development. The functional unit of LCA is one 60-cell silicon PV module.

3.2. Life-cycle inventory

The entire value chain of PV is divided into five major stages: (1)