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An analysis of glass–glass CIGS manufacturing costs

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ABSTRACT

This article examines current cost drivers and potential avenues to reduced cost for monolithic, glass–glass $Cu(In,Ga)(Se,S)_2$ (CIGS) modules by constructing a comprehensive bottom-up cost model. For a reference case where sputtering plus batch sulfurization after selenization (SAS) is employed, we compute a manufacturing cost of $69/m^2 if the modules are made in the United States at a 1 GW/year production volume. At 14% module efficiency, this corresponds to a manufacturing cost of $0.49/W$_{DC}$ and a minimum sustainable price (MSP) of $0.67/W$_{DC}$. We estimate that MSP could vary within ±20% of this value given the range of quoted input prices, and existing variations in module design, manufacturing processes, and manufacturing location. Potential for reduction in manufacturing costs to below $0.40/W$_{DC}$ may be possible if average production module efficiencies can be increased above 17% without increasing $/m^2 costs; even lower costs could be achieved if $/m^2 costs could be reduced, particularly via innovations in the CIGS deposition process or balance-of-module elements. We present the impact on cost of regional factors, CIGS deposition method, device design, and price fluctuations. One metric of competitiveness-levelized cost of energy (LCOE) – is also assessed for several U.S. locations and compared to that of standard multi-crystalline silicon (m(c-Si)) and cadmium telluride (CdTe).

1. Introduction

Since its conception, copper indium gallium diselenide (CIGS) photovoltaic (PV) technology has made significant strides, including improved stability [1], average production efficiencies between 12% and 15% for commercial modules with leading efficiencies of over 16% [2], and a record efficiency in the lab of 22.3% [3]. Solar Frontier, a Japanese company and the world's largest CIGS module producer, has reached a manufacturing capacity in excess of 1 GW/year and shipped over 3 GW of its modules [4]. Stion and AVANCIS currently have capacities between 100 and 200 MW/year. TSMC Solar has also achieved a similar scale, but very recently announced that it would cease its solar manufacturing activities.

Despite progress in efficiency and scaling, challenges remain for CIGS. Degradation rates are typically still higher than other established PV technologies [1], although it is unclear how much of this difference will be eliminated as CIGS matures further and is produced at higher volumes. The absence of public CIGS companies means only limited information is available on costs and prices, although some work analyzing manufacturing costs [5–10] and levelized cost of energy (LCOE) [11–12] has been published in the past. Many of these studies found CIGS costs to be near or within range of competing technologies such as crystalline silicon ((c-Si)) and cadmium telluride (CdTe) at the time of publication, despite the fact that CIGS remains a small fraction of the total solar market, accounting for only 2–4% of global module shipments. A deeper analysis of regional cost drivers, variations in cost with design and deposition process, sensitivity to price fluctuations and module performance, and project financials, all in the context of the larger PV market, is necessary to understand the current landscape and future potential for CIGS. We believe this requires a detailed, bottom-up cost approach. The National Renewable Energy Laboratory (NREL) developed such an analysis methodology and applied it to a wide range of PV technology in the past [13–15]. We have recently leveraged our models to investigate CIGS costs, with initial results presented at the 42nd Photovoltaic Specialist Conference (PVSC) [16]. This paper includes updates to those results and expands further by exploring the costs of the 3-stage co-evaporation processes, analyzing the CIGS supply chain and regional manufacturing costs, and providing in-depth sensitivity and parametric analysis. Additionally, we present new results on the impact of module manufacturing costs and efficiencies on system-level costs, and we compute LCOE for multiple locations within the United States compared to multi-crystalline silicon (m(c-Si)) and CdTe. Our aim is to provide researchers with context for their work and insights into what is required to reduce

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CIGS costs. We also hope this paper can serve as an overview of the current state and future potential of this technology for policy makers, industry members, and the public.

2. Methodology

Our analysis begins with a definition of a reference module. Here, we assume a monolithic module design with AZO (450 nm)/i-ZnO(50 nm)/CdS(50 nm)/CIGS(1.5 μm)/Mo(250 nm) based on literature review [17–21] and interviews with CIGS solar module manufacturers. This device stack is shown in Fig. 1. We assume the AZO, i-ZnO, and Mo are sputtered and that the CdS buffer layer is deposited using chemical bath deposition (CBD). We explore costs associated with different methods of depositing the CIGS layer itself, but take the case of sputtering plus batch sulfurization after selenization (SAS) using H_2Se and H_2S as our reference case, as our interviews indicate that this type of process is currently most prevalent in large-scale manufacturing. All sputtering processes are assumed to use rotary targets; rotary or planar targets can and are used within the industry. We use mass ratios of Ga/(Ga+In)= 0.31, and Cu/(Ga+In)=0.92 for all calculations. For our base case, the substrate size is 1.6 m × 0.6 m (0.96 m^2) with an active area of 0.9018 m^2. We focus on glass–glass modules in this analysis because they constitute the majority of installed MW of CIGS modules. To date, flexible CIGS modules have typically been targeted for use in portable, building-integrated PV, or consumer products; a smaller customer segment.

Glass prices can vary significantly depending on the type of glass employed. We assume annealed, 2.2-mm-thick, soda-lime back glass and ultra-clear, tempered 3.2-mm-thick front glass with an anti-reflection coating (ARC). Sodium that diffuses from the soda-lime glass helps to improve the CIGS doping density, open-circuit voltage (V_{oc}), and fill factor (FF), and use of soda-lime glass or another sodium source is required for good CIGS performance. Note that this back glass thickness is lower than what was assumed in [16] based on new industry feedback received since that publication.

The CIGS industry, however, is not standardized, with many variations on this reference design observed. Reported Mo back-contact thicknesses ranged from 240 to 500 nm. CIGS layer thicknesses (typically 1.5–2 μm) and compositions also vary, as do module dimensions (the market includes 1.2 m × 0.6 m, 1.257 m × 0.977 m, and 1.65 m × 0.65 m sizes just for glass–glass designs) and substrate type, as mentioned. Additionally, alternative device designs may be employed. For example, although the sputtered i-ZnO/AZO front contact is common in CIGS manufacturing and the literature, the majority of commercial CIGS modules shipped today (from Solar Frontier) use a metal-organic chemical vapor deposited (MOCVD) ZnO: B front contact and CBD Zn(O,S) layer instead. This could have some advantages in terms of module processing and performance. However, we were unable to obtain required cost information for this layer at this time. The impact of deviations in some of these design parameters is discussed in Section 3.

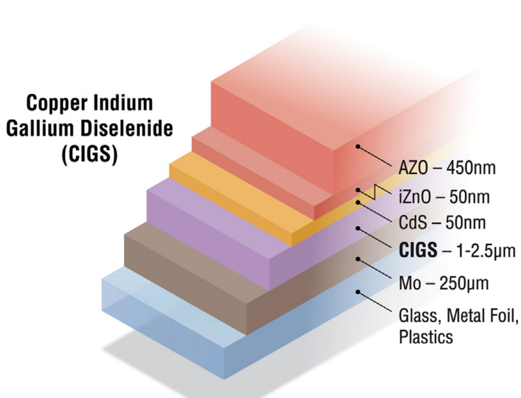

Fig. 1. Schematic of a monolithic CIGS device. For our reference case, we assume a framed, glass–glass module with a 1.5-micron-thick CIGS layer.

Once a reference system is designed, we construct a representative manufacturing process flow and then compute the labor, materials, equipment, building space, and utilities costs associated with performing each step, similar to a cost-of-ownership model. Then, we sum the costs by step and add any additional labor or equipment costs associated with transport between steps. This total is the direct manufacturing cost for the module. We then use that manufacturing cost and other financial input parameters to calculate a minimum sustainable price (MSP). The MSP is defined as the price at which all manufacturing costs and fixed costs (e.g., sales, general, and administrative (SG&A); and research and development (R&D) costs) are covered and the project can generate a return equal to the weighted average cost of capital (WACC), calculated using a *pro forma* capital budgeting discounted cash flow model. We take this as an approximation of a minimum price that would be sustainable in the long term. Of course, this value depends on assumptions about SG&A and R&D costs, as well as financing; and if these fixed costs could be reduced or financing improved, the MSP could be lowered without any change in the direct manufacturing costs. The module MSP is then rolled up into a calculation of the LCOE. The total installed cost of a PV system is comprised of both the module price (taken as the MSP here) and the balance-of-systems (BOS) costs. BOS costs are calculated using NREL's system cost model [22], and they are assumed to be equal per square meter for m(c-Si), CdTe, and CIGS (i.e. any differences in BOS cost between technologies is driven by efficiency alone). This assumption needs to be further explored in future systems cost-modeling work on thin-film devices. We present nominal LCOE values, which include currency inflation effects, and are typically 2–3 cents/kWh higher than real values.

More detailed information on our methods for computing manufacturing costs, MSP, and LCOE is included in [16]. However, several changes to the model have been implemented since this earlier report. First, we use 1 GW/year as the production volume for our reference case, rather than 100 MW/year. We also calculate cumulative manufacturing yield based on yield losses by step, rather than assuming a global effective yield, based on new data received. Total cumulative yield loss of 10% is used in our reference case based on industry feedback. Our interviews indicate that CIGS manufacturing yields currently range from about 85–96%. We have also shifted away from including any overhead labor in manufacturing costs, and we include only direct unskilled and skilled labor requirements. All overhead labor costs are accounted for in the MSP calculation instead. All U.S. wages for direct labor are obtained from the Bureau of Labor Statistics and reflect mean wages for manufacturing production workers (unskilled) and chemical equipment operators and tenders (skilled) in Mississippi. We have neglected warranty and legal costs, to be more consistent with MSP calculations from NREL for other PV technologies. We have similarly modified some of the financial assumptions for the LCOE calculations to be consistent with other work at NREL; the updated input values are shown in Table 1. In this work, we focus on the impact of location and technology on LCOE, rather than the Federal ITC or other incentives, which are not included in any of the LCOE calculations presented here. We also use the newer release (version 2015.6.30) of the System Advisor Model (SAM) for these calculations.

The methods for computing WACC used in the MSP calculations, as well as the values of the WACC, are the same as in [16];