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/m² 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 \$/m² costs; even lower costs could be achieved if \$/m² 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 (mc-Si) and cadmium telluride (CdTe).

Keywords— CIGS, photovoltaic, co-evaporation, selenization, manufacturing cost analysis, LCOE

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 (mc-Si) and CdTe. Our aim is to provide researchers with context for their work and insights into what is required to reduce 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 μ m)/Mo (250 nm) based on literature review [17]–[21] and interviews with CIGS solar module manufacturers. This device stack is shown in Figure 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 $\text{Ga}/(\text{Ga}+\text{In}) = 0.31$, and $\text{Cu}/(\text{Ga}+\text{In}) = 0.92$ for all calculations. For our base case, the substrate size is $1.6\text{m} \times 0.6\text{m}$ (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 backglass thickness is lower than what was assumed in [16] based on new industry feedback received since that publication.

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.

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 to $2\mu\text{m}$) and compositions also vary, as do module dimensions (the market includes $1.2\text{m} \times 0.6\text{m}$, $1.257\text{m} \times 0.977\text{m}$, and $1.65\text{m} \times 0.65\text{m}$ 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.

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 longterm. 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 mc-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 1GW/year as the production volume for our reference case, rather than 100MW/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 I. 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.

TABLE I
INPUT ASSUMPTIONS FOR LCOE CALCULATIONS

Input Parameter	Assumed Value
Discount rate (nominal)	7%
Inflation rate	2.5%
Analysis period	30 years
Federal income tax rate	35%
Sales tax	5% of total direct cost
Insurance rate (annual)	0.5% of installed cost
Project debt %	0
Inverter replacement cost	\$0.10/W
Inverter replacement frequency	15 years
Module-to-system efficiency loss	6.5%
Federal ITC level	0%
Installation size	100 MW

The methods for computing WACC used in the MSP calculations, as well as the values of the WACC, are the same as in [16]; however, we were not able to provide detailed information on this topic in the prior publication due to space constraints. We provide more detail here, which can be helpful for understanding the new work presented on regional MSPs in Section 4. Equation 1, below, defines the WACC:

$$WACC = E \times R_e + D \times R_d \times (1 - r_t), \quad (\text{Equation 1})$$

where E is the percentage of financing that is equity, D is the percentage of financing from debt, R_e is the cost of equity, R_d is the cost of debt, and r_t is the effective corporate tax rate. Table II shows these input values and computed WACCs for different countries explored here. These are computed using the methodology described in [13], averaging across data for companies in a given country that are public in the U.S. market. Other approaches for computing WACC exist, and this input is somewhat uncertain, especially for countries like the United States where the pool of public PV manufacturers is small and includes companies that have downstream activity in addition to module manufacturing. If a company can achieve a lower cost of capital, their MSP will also be reduced. Germany's WACC and MSP are not included because of the lack of German PV companies that are public in the U.S. market; so an apples-to-apples calculation could not be completed. The effective corporate tax rates shown

TABLE II
WACC VALUES BY COUNTRY (ALL UNITS ARE %)

Country	E	D	R _e	R _D	r _t	WACC
United States	67	33	19.4	6.05	27.7	14.4
Japan	98	2	10.0	0.99	38.8	9.8
Taiwan	94	6	16.7	0.72	14.4	15.7
China	36	64	24.3	11.3	21.5	14.4

are also used to compute tax obligations in the MSP calculation. It should be noted that the number of PV manufacturers public in the U.S. market was not the same for all countries listed in Table II; therefore, the sample size used to compute these WACCs varies and in some cases is very small, leaving uncertainty in the WACC value.

In comparing the LCOE for different technologies, module prices for each technology are set equal to the MSP computed using the same bottom-up methodology discussed here for manufacturing in the United States. The majority of production occurs in China for mc-Si, Japan for CIGS, and Malaysia for CdTe. However, here, we assume the case of U.S. manufacturing for all cases in order to better compare the cost and performance of the core technologies, unobscured by differences in regional manufacturing costs. It is challenging, however, to make a direct comparison of MSP of thin-film modules to that of mc-Si because of the larger number of solar-specific components of the supply chain compared to monolithic thin-film devices, including production of polysilicon, wafers, cells, and modules. Vertical integration across all or part of the supply chain in mc-Si is an option pursued by some companies, but in this analysis we focus on the case where a pure-play module manufacturer purchases complete cells at prices ranging from \$0.30/W to \$0.40/W (\$0.30/W being viewed as a low-margin case that may not be sustainable in the long-term). In the context of today's global PV market, and because of the higher labor costs in the U.S., we might expect that for the case of all U.S. manufacturing, the vertically integrated approach would give a slightly higher MSP. However, this is not necessarily the case for other countries or other scenarios, where vertical integration could be advantageous. This issue will be explored in future work dedicated to mc-Si costs. A comparison based on average selling prices (ASPs) is not possible due to the lack of public companies in the CIGS space and thus dearth of data on CIGS ASPs.

A summary of the key technology-specific LCOE inputs used in our calculations is included in Table III. Rated module efficiency, temperature coefficient, module area, normal cell operating temperature (NOCT), and other electrical specifications (V_{mp} , I_{mp} , V_{oc} , I_{sc}) are taken from the datasheets for Stion's STO-150A (for CIGS), First Solar's FS-4115 (for CdTe), and Trina Solar's TSM-PD05.08 (260W) (for mc-Si). These parameters were input to the "CEC Performance Model with User Entered Specifications" model in SAM in order to perform the LCOE calculations. We assume fixed-tilt, utility-scale systems for all cases, with a ground or rack mounted configuration at an installation height of one building story or lower. The degradation rates used for CIGS, CdTe, and mc-Si are 0.96%/year, 0.40%/year, and 0.64%/year, respectively. These are mean values taken from post-2000 data on module degradation (aggregated from multiple sources of measurement and literature) reported in [1]. However, because of the relative prevalence of c-Si in the market, more data on degradation rates for complete modules are available for mc-Si than for the thin-film technologies, and the degradation rate for CIGS and CdTe contains significant uncertainty at this point in time. We make the simplifying assumption that all the degradation profiles are linear.

TABLE III
TECHNOLOGY SPECIFIC INPUTS TO THE LCOE CALCULATIONS

Input Parameter	CIGS	CdTe	c-Si
Module price (\$/W _{DC})	0.67	0.60	0.64 – 0.76
Total BOS cost (\$/W _{DC})	1.13	1.02	1.02
Rated module efficiency (%)	13.8	15.9	15.9
Degradation rate (%/year)	0.96	0.40	0.64
Temperature coefficient (P_{MPP}) (%/°C)	-0.26	-0.34	-0.41
Nominal cell operating temperature (°C)	45.6	45	44
Module area (m ²)	1.09	0.72	1.64

3. MANUFACTURING COST RESULTS FOR THE UNITED STATES

Figure 2 shows the updated step-by-step module manufacturing costs in $\$/\text{m}^2$ for this reference case. Several interesting points can be observed from this figure. First, we see that material costs dominate, comprising 57% of the total. Of those material costs, 74% is attributable to balance-of-module, only 18% is associated with the materials used to fabricate the CIGS layer, and 8% is attributable to other device materials. After materials, equipment costs are the most significant, comprising 21% of the total, with the batch SAS step being the largest single contributor to both total module cost and equipment costs.

The front and back glass alone accounts for around 17% of the total module costs. Glass prices can vary significantly by supplier and region of the world. Here, we assume a global price for the front glass with an ARC of $\$7/\text{m}^2$ for our reference case. This is aggregated based on data from glass suppliers, CIGS module manufacturers, and reports by consulting firms [23]. This global price includes the impact of tariffs, shipping, taxes, and currency exchange. However, pricing can differ by region; the impact of regional glass pricing on modules costs is illustrated in Section 4. Glass quality (transmittance, durability) can also vary somewhat by supplier and region. For the back glass, we assume a global price of $\$3/\text{m}^2$ and do not explore the impact of regional pricing; however, this may merit further investigation in the future. The sensitivity of module costs to back-glass price is shown in Section 5.

If we account for potential differences in the thickness of the contacts and/or the CIGS layer, CIGS composition, and substrate size between companies, discussed above, we estimate that cost may differ $+\$0.09/\text{W}_{\text{DC}}$ to $-\$0.05/\text{W}_{\text{DC}}$ from what is shown here. This is not including any differences resulting from alternative device stacks or fabrication processes. The frame contributes $\$0.05/\text{W}_{\text{DC}}$, so removing it can reduce module costs significantly. However, this may also lead to changes in BOS costs. We have not yet computed the system costs for frameless thin-film modules, which can be mounted using special clips or using different paneled approaches, using our bottom-up model.

Fig. 2. Step-by-step manufacturing costs for a monolithic CIGS module fabricating using sputtering plus batch SAS. Assumes 1GW/year manufacturing volume and U.S. manufacturing. Total module manufacturing cost is $\$69/\text{m}^2$.

The formation of the CIGS layer, which in our base case consists of sputtering the CuGa and In precursors and subsequently selenizing the film, constitutes the largest step cost and is typically the topic on which research is most intensely focused. Therefore, we examine the costs of several alternative approaches to depositing this layer. First, we look at sputtering plus selenization via an in-line rapid thermal process (RTP). This technique is being used in production by AVANCIS, but currently

achieves lower efficiencies than batch SAS processing. The details of this process and issues surrounding module performance are outlined in [16]. For both selenization processes, we assume the same parameters for the precursor sputtering step and use updated target prices of \$0.15/g for the CuGa target and \$0.91/g for the In target. Material utilization for all rotary sputtering processes is assumed to be 72% (85% target utilization and 85% substrate collection efficiency). H_2Se price used is \$450/kg and the Se price is \$128/kg.

We also look at the costs for co-evaporation of the CIGS. Many different co-evaporation processes have been proposed and explored, including 1-stage, 2-stage, and 3-stage processes. The 3-stage co-evaporation process holds the record efficiencies for CIGS in the lab. Solibro currently employs a variation on this batch co-evaporation process [24], and Würth Solar, which was acquired by Manz, commercialized a 1-stage in-line process [25]. Global Solar Energy, which currently focuses on flexible CIGS, uses a roll-to-roll, co-evaporation process to produce its modules, although the costs of roll-to-roll deposition are beyond the scope of this work [26]. Pricing of evaporation materials is based upon 99.99% (4N) purity materials (reports varied somewhat as to what purities are required; the type of impurities may be more important). We assume a tool uptime of 90%. These results assume materials utilizations of 40% for the Cu, In, and Ga, and 20% for the Se.

Fig. 3. Comparison of costs for steps required in different processes used for fabricating the CIGS absorber layer.

Figure 3 compares cost of these different deposition processes for the CIGS layer on a $\$/\text{m}^2$ basis. We have separated out the costs of sputtering and SAS in the figure, but sputtering plus one of the SAS steps are required for completed fabrication of the CIGS film. We use the same CIGS layer thickness for each case. There has been some discussion on whether the co-evaporation process will require thicker CIGS layers—around 2 microns [21]—but our interviews indicate that this issue is not yet settled. These $\$/\text{m}^2$ numbers provide good insight into the fundamental cost drivers of each process, and they allow us to present costs independent of efficiency because efficiencies vary by company and product. However, the $\$/\text{W}$ cost, which is also impacted by efficiency, is more important in determining market adoption. TSMC Solar, which used sputtering plus batch SAS, and Manz, which uses in-line co-evaporation, have demonstrated very similar champion efficiencies of 16.5% and 16%, respectively, on commercial lines [2]. It is an open question of which of these processes will have an average production efficiency advantage over the other in the longterm. The efficiencies for the sputtering plus in-line RTP selenization case are typically 0.7%–1.5% lower. 3-stage co-evaporation may be able to achieve up to 2% absolute higher efficiency than the other processes if good performance can be translated in scaled manufacturing with high yields.

In our base case (Figure 3), we assumed a 1.5 minute/module throughput for the batch 3-stage co-evaporation step. The cost of this process is very sensitive to the process throughput due to the high capital cost of the equipment, and throughputs can be influenced by tool design. Because of this—and because this process is still in the very early stages of commercialization—we explore the impact of co-evaporation throughput at different module efficiencies on the total manufacturing costs in Figure 4. This figure illustrates many different combinations of efficiency and throughput improvements that could potentially allow for this 3-stage co-evaporation to achieve reduced costs, more competitive with other processes. It does not capture the additional benefit of efficiency at the system level; this is explored in Section 5. Increasing material utilization for the co-evaporation system could also help significantly reduce the cost of this process.

Fig. 4. Impact of throughput and module efficiency on total module costs for the case where the CIGS layer is deposited via a batch 3-stage co-evaporation process.

4. REGIONAL COST COMPARISON

This section explores the impact of manufacturing location on costs, including differences in wages, benefits, materials, and electricity costs across the globe. We additionally examine the potential effect of regional differences in cost of capital and taxes on the MSP. We focus on comparing five countries: the United States, Japan, Taiwan, and Germany (which are the current locations of major CIGS manufacturing activity) and China (where ground has recently been broken on a large new plant for manufacturing CIGS modules by AVANCIS, which is now Chinese-owned). We explore two cases of urban versus rural China. Most Chinese manufacturing currently occurs in urban areas, such as Shanghai, Shenzhen, and Guangzhou; but prior work has indicated that rural, western regions of China can have substantially lower labor and electricity costs. However, other issues, including severe weather, shortage of skilled labor, and transportation challenges would need to be mitigated to allow for large-scale manufacturing in these regions [13].

In our current model, the contacts and CIGS precursors are deposited by sputtering, as discussed above. Our analysis suggests that the supply chain for Mo, AZO, and CIGS targets (CuGa plus In, or CuInGa, CuIn, or CIGS, depending on the process), and, in particular, rotary targets, is currently fairly limited. To our knowledge, only two companies provide rotary indium targets at significant volumes. Additionally, targets are typically manufactured only at one or maybe two sites, typically in higher-cost regions such as the United States, Europe, or Japan, even if the company has manufacturing locations worldwide. However, some Asian target manufacturers sometimes put downward pressure on target prices from these major manufacturers in Asian markets. In the future, depending on the markets and locations of CIGS manufacturing and suppliers, this could obviously change; but today, the regional differences in pricing for these materials is fairly small and does not have a significant impact on overall module costs. The sensitivity of module price to target prices is discussed in Section 6.

There can be some regional pricing of cadmium sulfate (CdSO_4), thiourea, ammonia, and ammonium acetate solutions used in the CBD of the buffer layer. But the impact of these differences on the total module cost is very small, and some companies either currently do not use a CdS buffer layer (Solar Frontier) or may transfer away from it in the future. The cost of waste management for the CBD CdS buffer layer can, however, vary significantly by region. This depends not only on the regulations of a given country but also on conditions local to the manufacturing facility and company policy. We were unable to obtain sufficient resolution on these cost variations to include differences in the cost of waste management in our model.

Regional pricing of ethylene vinyl acetate (EVA) and busbar materials also exists to some degree; but again, the impact of these differences on overall module cost is minimal. The material input with regional cost variations that most impacts the total module cost is the front glass—with front-glass prices potentially being lower in Asia, higher in Europe, and about the same in North America as the global price. The higher European price is due in part to EU tariffs of up to 36.1% that have been placed on solar PV glass from China. Figure 5 shows regional costs assuming global versus regional front-glass pricing.

As seen in Figure 5, besides potential differences in regional glass prices, labor and electricity costs are the main drivers of regional cost differences. The United States and rural China currently have some of the lowest electricity prices in the world. Our model uses a labor requirement of 700 workers for 1 GW/year production based on public statements by Solar Frontier [4]. If CIGS manufacturing volumes increase further in the future, the theory of learning suggests that labor will become more productive and the required number of workers/plant will decrease. Advances in module efficiencies and automation will also reduce the labor intensity in the future, reducing differences in regional module costs and leaving electricity prices as the primary driver of regional cost differences.

Shipping costs can also play a role, depending on the location of the end markets relative to the manufacturing location. Figure 5 only looks at the costs associated with a given manufacturing location, independent of the end market, so shipping costs are not included. However, we use a model originally developed for c-Si module shipping costs and adapt it to the CIGS case to get an idea of how large of an impact shipping costs could have on global module pricing. This model calculates the cost of shipping from Shanghai, China to Los Angeles, CA in United States and then to Phoenix, AZ in United States. It includes the cost of basic ocean freight shipping, land transportation, a merchandise processing fee, other fees (e.g., handling, document, service), entry bond, and insurance. The insurance depends on the assumed value of the shipment. Here, we assume that the value per watt is equal to the computed MSP for Urban China. We assume 25 modules per pallet and 36 pallets per 40' container, based on information from Solar Frontier's datasheets. Total shipping cost for this case is calculated to be between $\$0.02/W_{DC}$ and $\$0.03/W_{DC}$. One company reports that their global shipping costs are typically near but below these modeled values.

Currently, the majority of CIGS modules are sold by Solar Frontier into the Japanese market, so shipping costs are not hugely significant in influencing most CIGS pricing. However, some companies are shipping significant volumes overseas; for example, TSMC, a Taiwanese company that announced its exit from the solar industry last fall, had its largest markets for its CIGS products in Europe and Africa [2], where shipping costs could play a larger role. Location of the most important end markets for a given company can influence where manufacturing is sited, depending on the degree of regional cost differences.

In addition to influencing manufacturing costs, location can also impact the MSP of a module, as shown in Figure 5. This is driven by differences in effective tax rates and the WACC. The WACC is influenced by the cost of equity, the cost of debt, and the percentage of debt versus equity on a company's books and is not necessarily lower in countries with lower cost of debt and equity. For example, the cost of both debt and equity is higher for Chinese PV companies than for the United States, but Chinese companies currently tend to carry significant amounts of debt on their books compared to other countries, allowing for a lowered cost of capital since the debt is cheaper than equity. Access to capital also varies by country and can significantly impact a company's ability to scale and take advantage of the accompanying cost reductions; treatment of this topic is beyond the scope of this paper.

Fig. 5. Regional manufacturing costs and MSP for CIGS modules (top) assuming global front-glass pricing and (bottom) accounting for potential regional differences in front-glass prices. Assumed 1 GW/year production volumes and 14% efficiency for all locations.

5. COST REDUCTION ROADMAP

Total module manufacturing costs for the case of sputtering plus batch SAS with U.S. manufacturing are estimated at \$69/m². At 14% module efficiency, this corresponds to \$0.49/W_{DC} manufacturing cost and \$0.67/W_{DC} MSP. Now that we have described the breakdown of CIGS costs, we can construct a cost reduction roadmap.

There are many different potential ways to decrease CIGS manufacturing costs. In this roadmap, we highlight process and module design changes currently receiving attention from at least some of the industry, for which more information is available and thus the uncertainty in the potential impact on cost reduced compared to earlier stage innovations. In Figure 6, we have separated out the impact of efficiency and process or design changes, but in some cases these may be coupled, as discussed.

Increasing the throughput of the CIGS process can be done either via changes in the manufacturing process or in reducing the thickness of the device layers. A throughput increase of ~14x-15x corresponds to what might be expected from the rapid, in-line process such as single-stage RTP. Current in-line co-evaporation processes may allow for approximately 6 to 7x, assuming the same CIGS layer thickness. Today, thicknesses are chosen to minimize \$/W, balancing the cost savings from use of thinner layers with decreased efficiency and potentially also decreased yields. These trade-offs for the CIGS absorber layer with current results are presented in Table III. Increasing the throughput of the CIGS deposition process could also reduce the capital equipment expense (CAPEX), because fewer tools would be required to meet a given production level. The reduced CAPEX results not only in a lower manufacturing cost, but also in a lower margin required for the MSP and lower financial barrier to entry, providing multiple benefits. This is discussed in detail in [27].

Efficiency is also a key component of the CIGS roadmap. Our understanding based on interviews and literature review is that 16% module efficiencies may be achievable in production in the near term, and, as previously mentioned, Manz and TSMC have already achieved ≥16% efficiencies for record, commercial-sized modules produced on their lines (although neither of these companies is actively producing modules in volume). Average commercial module efficiencies are not expected to exceed 20%, although it is theoretically possible for higher efficiencies to be achieved. If one assumes that no other module cost-reduction measures are adopted, but that \$/m² costs are not increased, then increasing module efficiency to just over 17% allows for manufacturing costs below \$0.40/W_{DC}. In practice, increasing module efficiency usually requires a trade-off in increased \$/m² costs; but it is foreseeable based on our analysis that cost reductions could be achieved to counterbalance these increases. Realized long-term costs will also depend on price fluctuations for the input materials, notably In, Ga, and Se.

Fig. 6. Roadmap for reducing CIGS module manufacturing costs. U.S. manufacturing and 1GW/year annual production.

The value of any single improvement on this roadmap should be determined by looking at the potential benefit at the *system* level, because total system cost is what ultimately determines the competitiveness of a given technology. LCOE is a suitable way to understand the competitiveness of a PV technology in the larger electricity marketplace. However, LCOE is also very sensitive to financial assumptions unrelated to the core technology. Additionally, potential cost-reduction pathways discussed here do not alter inputs to the LCOE calculation other than system cost. Thus, we chose the total installed system cost as the best metric for

clearly comparing the value of these changes. System costs versus efficiency are calculated using NREL’s system cost model for a utility-scale (100MW) installation in California, where the area of the plant, rather than the rated power, is constrained. This model only has a resolution of 0.5% efficiency steps, and so any impacts on efficiency associated with a roadmap item are rounded to the nearest half percent. We add another dimension by estimating the technology readiness level (TRL). The TRL is a standard metric used to understand the level of development or maturity of given technology or process, and it can act as a proxy for the amount of investment requirement to move a product into commercial production. We use the U.S. Department of Energy (DOE) guidelines to determine the TRL. Table IV lists the estimated TRL versus potential impact on system costs for selected changes to CIGS module design or processes. A negative “savings” is a cost. The changes associated with the largest system cost savings result in increased module efficiencies. Around our reference efficiency of 14%, the slope of the efficiency versus system cost is rather steep, allowing for even small gains in module efficiency to provide significant savings at the system level. This is particularly notable for the case of decreasing the module dead area associated with the module interconnects, which we compute could have a negligible impact on $\$/\text{m}^2$ cost but result in up to a 5% relative (0.7% absolute) increase in module efficiency. This increased efficiency results in a $\$0.02/\text{W}_{\text{DC}}$ savings at the module level and an additional $\$0.03/\text{W}_{\text{DC}}$ at the system level. The most dramatic example of the importance of efficiency in Table IV is for the batch 3-stage co-evaporation process. As discussed in Section 3, this process may have the potential to improve module efficiencies by 2% absolute. Even if we assume the current throughput and higher manufacturing cost computed for this process, significant $\$/\text{W}$ savings could be achieved at the system levels if this process could be adopted to and well controlled in a production environment. The extremely high capital equipment costs associated with this co-evaporation process at its current throughputs may additionally need to be addressed in order for it to be adopted in large volumes, depending on the availability of capital and risk associated with investing such a large sum upfront.

On the other hand, processes or design changes that result in decreased efficiency face an uphill battle. These require large reductions in $\$/\text{m}^2$ manufacturing costs to compensate for cost increases at both the module and system level due to the lowered efficiency. Because so many steps in the manufacturing process contribute significantly to the total cost, this type of cost reduction is somewhat difficult for efforts focused on only one component of the module. Completely eliminating the cost of the batch selenization step—the single-largest contributor to module cost—would save $\$0.10/\text{W}_{\text{DC}}$ in systems costs. Although this is a huge benefit, it is entirely negated at the system-level if the module efficiency is decreased by 1% absolute.

The ultimate impact on efficiency for lower- or mid-TRL points is often uncertain. Even for some of the higher-TRL changes (i.e., in-line RTP), there is some debate about the potential efficiency gap in the future; this can also depend on specific parameters even within a given process or design (e.g., single vs double RTP), which are not exhaustively explored here. The approach taken in constructing Table IV was to assume efficiencies that have been demonstrated at the current TRL level. For example, because decreasing the CIGS thickness below to 0.5 microns is currently at TRL 3 (lab-level analytical studies, simulations, and proof-of-concept experiments have been completed), with middle values of reported efficiency losses compared to the ~ 1.5 micron case of around 3% absolute [28]–[30]. Some published simulations have indicated that 0.5-micron-thick CIGS layers could be used without efficiency losses with the use of a bandgap grading [31]; but these results have not yet been validated by experiments and so would be associated with a much lower TRL level.

TABLE IV
IMPACT OF DIFFERENT PROPOSED DESIGN AND PROCESS CHANGES ON CIGS COSTS AT THE MODULE AND SYSTEM LEVELS

Change	TRL	Efficiency change (%)	Module savings ($\$/\text{m}^2$)	Module savings ($\$/\text{W}$)	BOS savings ($\$/\text{W}$)
Decrease CIGS thickness to 0.5 micron	3	-3	3.1	-0.11	-0.24
Decrease CIGS thickness to 1 micron	4	-1	1.5	-0.03	-0.07
Sputter Zn(O,S) buffer layer	4	-1.4	1.8	-0.04	-0.10
3-stage co-evaporation	5	2	-8.5	0.01	0.10
RTP SAS	9	-1	6.2	0.01	-0.06
Decrease dead area associated with the interconnects	6	0.7	0.0	0.02	0.04

6. SENSITIVITY ANALYSIS

Uncertainties in these model results arise from the following: a spread in reported pricing for materials and tools; variations in the precision level that quotes from different data sources (suppliers, manufacturers) were provided; differences in wages, even

within states; variations in fabrication processes that give rise to, for example, some differences in material utilization rates; and lack of standardized design, as discussed above. It is difficult to quantify exactly the % error in our results. For example, if there is only one appropriate supplier of a given piece of equipment, getting an accurate quote from that supplier on equipment price likely results in a cost very close to what a manufacturer would expect to encounter, and in that way, the error is low. However, the sample size is very small, and the data taken at a fixed point in time when technology (and markets, which affect prices independently of costs) are constantly evolving. Additionally, companies may have more or less leverage to negotiate prices depending on their relationship with the supplier, size, and the larger market and industry context. However, we can try to understand the impact of uncertainty in input values using sensitivity or range analysis. We use sensitivity analysis rather than range analysis here given the limited number of suppliers for some inputs and the proprietary nature of much of the pricing data. Figure 7 shows the sensitivity of the module cost to a $\pm 10\%$ relative change in the value of the individual input parameters with the largest impact on module cost. It is of note that although the impact of the In and CuGa sputtering target price on overall cost is relatively small, this sensitivity depends on the initial price of these targets. Currently, raw Ga prices are at an all-time low, and In prices are significantly below their highest value over the past 20 years. The impact of these fluctuations is smaller for the case of sputtering CuGa plus In with rotary or high-efficiency planar targets than for co-evaporation because the target price is also heavily influenced by the cost to manufacture it, and the material utilization is currently higher for these sputtering processes than for co-evaporation. Nonetheless, decreasing CIGS layer thickness and/or improving material utilization would be beneficial in that costs would be less sensitive to these price fluctuations for any of the CIGS deposition processes.

It could be beneficial to construct a similar bottom-up model of the costs for manufacturing the materials with the largest impact on cost, including the junction box, glass, and indium sputtering target. This would give insights into potential cost reductions that could be achieved for these inputs. However, as we saw in Figure 2, although materials indeed constitute the majority of the CIGS cost, multiple cost inputs would need to be reduced to achieve very large reductions. Paradigm changes in module design or CIGS deposition process, or significant gains in device performance (efficiency) could also be very effective in driving down costs.

Fig. 7. Sensitivity of module manufacturing costs to different input parameters.

7. LEVELIZED COST OF ENERGY

LCOE results as a function of location are shown in Table V. Values are rounded to the closest cent, given the uncertainty inherent in this analysis. These LCOEs, while providing an insightful way to compare technologies, should not be directly compared to market PPA prices since these are simplified cases where we assume long-term sustainable module pricing with U.S. manufacturing and neglect all incentives. Levelized PPA prices are also not always the same as the LCOE, since the PPA escalator may be different than the inflation rate and/or the desired internal rate of return (IRR) may not be the same as the discount rate. However, these results provide a good comparison between the fundamental features of the technologies using a

consistent approach, something that can be muddled if comparing market prices.

With these assumptions of U.S. manufacturing and achievement of a long-term sustainable margin for all technologies, the LCOE for CIGS, multi c-Si, and CdTe would be very similar, with CdTe having the lowest LCOE. The higher LCOE for CIGS compared to CdTe is driven by several factors: the higher system efficiency assumed for CdTe (15.9% compared to 13.8% for CIGS), the higher MSP calculated for the CIGS case, and the higher degradation rate for CIGS reported in [1]. The higher MSP for CIGS results from the lower module efficiency, as well as the higher costs associated with deposition of the active layer, which involves two-steps with high CapEx in our reference case, compared to just a single step required to form the CdTe active layer.

The energy yield of the thin film modules is higher than mc-Si in certain locations. This is partly due to the lower temperature coefficients for these materials resulting from the higher bandgap of CdTe and, to a lesser degree, CIGS, compared to mc-Si. Additionally, these thin film modules exhibit better low-light performance than typical mc-Si modules, which improves the energy yield and could reduce locational variability. This improved low-light performance is in part due to the higher series resistance for these modules, so changes in series resistance may alter low-light performance in the future. For mc-Si modules manufactured in the United States with cells purchased at prices of \$0.33/W or higher, the MSP is higher than the MSP for CIGS with U.S. manufacturing.

It should be noted that these results assume that the degradation rate is the same in all locations (equal to the mean value from many different test sites in [1]); the validity of this assumption can depend on the specific module design and packaging, but detailed analysis on the impact of degradation rate variations is beyond the scope of the study.

TABLE V
COMPUTED NOMINAL LCOES FOR DIFFERENT U.S. LOCATIONS

Location	CIGS LCOE, Module MSP \$0.67/W _{DC} (¢/kWh)	CdTe LCOE, Module MSP \$0.60/W _{DC} (¢/kWh)	mc-Si LCOE (U.S. module manufacturing with cell price of \$0.30 to \$0.40/W), Module MSP of \$0.64/W _{DC} to \$0.76/W _{DC} (¢/kWh)*
Orlando, FL (TMY3)	13	12	11 (12)
Prescott, AZ (TMY2)	11	10	10 (10)
Tucson, AZ (TMY2)	11	9	10 (11)
Bakersfield, CA (TMY2)	12	10	10 (10)
Imperial, CA (TMY3)	10	9	10 (11)
Alamosa, CO (TMY2)	11	10	13 (13)
Kona, HI (TMY3)	12	11	11 (12)
Jacksonville, NC (TMY3)	13	11	12 (13)
Newark, NJ (TMY2)	14	13	14 (14)
Albuquerque, NM (TMY2)	11	9	10 (11)
Las Vegas, NV (TMY2)	11	9	10 (10)
San Antonio, TX (TMY2)	12	11	12 (12)
Simple Average	12	10	11 (12)
Range	4	4	4 (4)

*High value is shown in parentheses

These results do not mean the LCOE of CIGS is equal to that of mc-Si technology today in the PV marketplace. As mentioned above, this study aims to compare CIGS, CdTe, and c-Si on a *technology basis*, with uniform assumptions about manufacturing location and standard methodology for computing a long-term sustainable margin. We do not wish to compare current ASPs of the technology as this can be impacted by many other factors (and, as mentioned above, ASPs are not available for CIGS technology since there are few suppliers and all are privately held). For example, today, most CIGS modules are manufactured in Japan, while most c-Si modules are manufactured in China. As discussed in Section 4, Japan has significantly higher manufacturing costs than China for CIGS. In addition, the majority of CIGS products are currently sold into the Japanese market and where they can command higher prices in some cases. The margins for c-Si module companies (and other solar companies) are lower than our estimated long-term sustainable average for pure-play PV companies, and have been quite volatile. Finally, our calculations for all technologies assume new equipment is purchased at full-price; for c-Si, most of the data we have is from American and European equipment vendors. Because some companies may have purchased discounted or used equipment, potentially from lower-cost Chinese suppliers, our manufacturing costs for c-Si in China may somewhat overestimate the actual depreciation expense seen by companies today. Some companies may also be using equipment for production that has been fully

or partially depreciated.

Fig. 8. The independent impact of module price and degradation rate (left) and module efficiency (right) on the LCOE for CIGS solar modules deployed in Phoenix, AZ, United States. Reference case inputs are starred. Note that in the right panel, a constant $\$/W$ module price is assumed, as discussed in the text above.

Figure 8 shows how the LCOE for CIGS solar modules is impacted independently by module price, degradation rate, and efficiency. This provides a guide as to how gains in each of these areas translate to improvements in LCOE. Efficiency drives reductions in LCOE via reduced systems costs. In Figure 8, we compare the impact of efficiency on system price when a constant $\$/W$ versus a constant $\$/m^2$ is assumed for the module price. The assumption of a fixed $\$/W$ for the module as efficiency increases is essentially an assumption that one will have to pay a $\$/m^2$ premium in order to increase module efficiency; for example, if you want better material quality, you may need to use higher purity materials that are more expensive, or if you want greater optical efficiency, you may need to use additional layers or improved ARC that adds expense. However, although high-efficiency cells have often been more expensive on a $\$/m^2$ basis in the past, this may not necessarily be true moving forward. Thus, we illustrate a second case in Figure 8 where module $\$/m^2$ is fixed and so $\$/W$ decreases as efficiency increases. In this case, both the total system cost and the LCOE are more sensitive to efficiency. The true relationship between module cost and efficiency is not this simple, and will reflect cost-performance trade-offs and the influence of innovations, but Figure 8 provides a range of what one might expect.

In addition to module price, degradation rate, and module efficiency, improvements in non-module system costs (in $\$/m^2$), plant operations and maintenance (O&M) costs, module-to-system efficiency losses, and financing can also reduce LCOE, although gains in these areas would likely benefit all three technologies. It has also been demonstrated that using 1-axis tracking can significantly reduce the LCOE for all flat-plate technologies[22].

8. CONCLUSIONS

We have explored the manufacturing cost, MSP, and LCOE associated with monolithic CIGS modules, providing benchmarks for current costs as well as information on how costs could be reduced in the future. We find that, with current technology and manufacturing processes, the LCOE for CIGS would be within the range of mc-Si and slightly higher than CdTe if all modules were manufactured in the United States at a volume of 1GW/year, and sold at a price that allows for a long-term sustainable margin. We compute this long-term minimum sustainable price for our reference case CIGS module to be $\$0.67/W_{DC}$ at a manufacturing cost of $\$0.49/W_{DC}$. We conclude that the main reasons for higher CIGS selling prices sometimes observed today are related to regional manufacturing costs, economies of scale (based on manufacturing volume), and lower margins for many c-Si module manufacturers. Reductions in module cost, increases in efficiency, and lower degradation rates represent opportunities for improving CIGS LCOE in the future. Efficiency has been shown to be a primary cost driver at both the module and system level for CIGS modules, which currently have a relatively low efficiency. Improving the CIGS deposition process by increasing throughput and material utilization as well as reducing balance of module costs, can also allow for significant cost reductions if similar efficiencies are maintained. We find that regional costs are most influenced by differences in labor rates, followed by electricity prices and regional glass pricing.

ACKNOWLEDGMENT

The authorsthank the Solar Energy Technologies Office of the U.S. Department of Energy for funding this work through Contract No. DE-AC36-08GO28308. We thank Lorelle Mansfield, Kannan Ramanathan, Miguel Contreras, Karlynn Cory, and Donald Chung for insightful discussion. Finally, we would like to acknowledge the significant contribution from all our industry collaborators, who provided data and feedback that made this study possible.

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