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Estimating the Effects of Module Area on Thin-Film Photovoltaic System Costs

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Abstract — **We investigate the potential effects of module area on the cost and performance of photovoltaic systems. Applying a bottom-up methodology, we analyzed the costs associated with thin-film modules and systems as a function of module area. We calculate a potential for savings of up to \$0.10/W and \$0.13/W in module manufacturing costs for CdTe and CIGS respectively, with large area modules. We also find that an additional \$0.04/W savings in balance-of-systems costs may be achieved. Sensitivity of the \$/W cost savings to module efficiency, manufacturing yield, and other parameters is presented. Lifetime energy yield must also be maintained to realize reductions in the levelized cost of energy; the effects of module size on energy yield for monolithic thin-film modules are not yet well understood. Finally, we discuss possible non-cost barriers to adoption of large area modules.**

Index Terms **— cost analysis, large module, photovoltaics, solar economics, thin-film.**

I. Introduction

Area-based economies of scale have been demonstrated in manufacturing of several different technologies, including flat panel displays, coated glass for architectural applications, and wafer-based semiconductor processes. With solar photovoltaic (PV) technology, the vast majority of modules remain relatively small, within the range of 1 to 2 m^2; however, several companies have attempted to leverage area-based economies of scale to reduce PV costs. Perhaps the most-well known and extreme example of such attempts was development of an amorphous silicon (a-Si) SunFab module by Applied Materials. Applied Materials claimed that these modules, which had an area of 5.7 m^2, reduced installed cost of a PV system by more than 20% [1], but then shut down the SunFab line several years later.

It was unclear how much the challenges SunFab faced were attributable to the declining price of incumbent PV, a-Si technology, or the large-area module format. Additionally, despite the fact that very large-area modules have not yet succeeded in the marketplace, interest in the concept has not faded. First Solar, the leading manufacturer of cadmium telluride (CdTe) modules, recently announced plans to move toward much larger area panels, claiming this would reduce capital equipment expenditures (CAPEX) by nearly 40% [2]. REEL Solar Inc. (RSI) has developed a process for electroplating on large-areas to help enable manufacture of large CdTe modules. Siva Power, a start-up in copper indium gallium diselenide (CIGS) module manufacturing, is also developing large area products (2 m^2, which is similar to 72-cell mc-Si modules but larger than other leading thin-film products) [3]. For PV, there are also potential area-based economies for system costs that scale with module count (e.g., installation labor costs). Indeed, this has been observed in comparing labor, electrical, and racking cost per watt for installing 60-cell modules and larger, 72-cell modules [4].

However, the effect of module area on module and system-level costs for larger sizes has not been quantified in the literature. In this paper, we provide an analysis of these costs for the leading commercial thin-film PV technologies: CdTe and CIGS. We focus on the case where rigid glass-glass module architectures are used. Because \$/W costs and the levelized cost of energy (LCOE) are strongly influenced by the performance of modules, we also examine the potential effect of module size on efficiency.

II. Methods

A. Manufacturing Cost Modeling

In this work, we build on NREL's previously developed bottom-up cost models developed for CdTe [5] and CIGS [6] modules of standard size. The CdTe and CIGS models used to generate the results for this paper were last updated in Q4 of 2015 and Q1 2016, respectively. It is important to note that because of this, some costs may have declined. However, there have been no radical technology developments in either of these technologies over the last year, and our cost models are recent enough that they can still be used to illustrate the mechanisms by which module area could drive down cost and estimate the degree of cost reductions that could potentially be achieved.

NREL's bottom-up cost models are based on developing a manufacturing process flow relevant to high volume production and calculating the costs of labor, materials, equipment, facilities, and utilities associated with each step in the process flow. Data is collected from material suppliers, equipment vendors, and PV industry members and is aggregated and anonymized to protect business-sensitive data. NREL is able to obtain high quality data from industry due to existing relationships with members of industry and demonstrated care in handling of sensitive information. Additionally, NREL's analysis center has an established track record of being able to produce cost analyses in-line with publicly available data on costs from PV firms.

In all cases, we assume the large area modules are manufactured at a new manufacturing plant with new equipment, where no subsidies or tax incentives are provided. Large modules can experience increased loading compared to smaller modules, which may cause increased stress. Stress experienced by the cells and module can be controlled through a combination of laminate design, frame design (or frame removal), and mounting. Because very large area modules have not yet been implemented, there is uncertainty around which designs will provide the best performance. For purposes of this analysis, we assume a frameless, glass-glass architecture with the cells located in the neutral axis, which is one possible solution for managing this stress.

For CIGS, we analyzed a series of module sizes based on standard glass sizes used in the flat panel display industry. These include Gen 6, Gen 7, and Gen 8 glass, which measure 1,500 mm x 1,800 mm, 1,870mm x 2200mm, and 2,160 mm x 2,460 mm, respectively, which are currently used to produce a significant fraction of displays. We additionally analyze the cost of CIGS modules on Gen 10 (2,900 mm x 3,100 mm) Gen 10.5 (2,940 mm x 3,370 mm) glass; Gen 10 and Gen 10.5 fabs for display manufacturing are beginning to be built, but are not widely used today. Possible changes in the CIGS manufacturing process and costs that could result from using larger substrates were based on interviews with members of each industry as well as equipment and material suppliers.

For CdTe, due to the limited number of players in the field, we were not able to obtain sufficient data for a similar bottom-up analysis. Instead, we used publically available information from First Solar about their Series 6 product [2] in combination with NREL's existing CdTe cost models. Information in [2] suggests that the Series 6 module is slightly larger than the Series 5 product, which consists of a panel of three 1.2m x 0.6m modules (for a total area of 1.2m x 1.8m). Because of this, we estimate the area of the Series 6 product to be between 1.2m x 1.8m and 1.5m x 1.8m (Gen 6 size) in our analysis.

B. System Cost Modeling

We evaluated the effect of module area on balance-of-system (BOS) costs for utility- scale systems using NREL's established bottom-up cost model [15–16]. In this model, we benchmarked both (1) soft costs (e.g., installation labor costs and engineering, procurement, and construction/developer overhead) and (2) hardware costs (e.g., structural/electrical BOS and inverter costs). We limit the analysis to the case of 100MW (utility-scale) ground-mount installations. Input data for the models is similarly collected from industry members and component suppliers—typically via interviews—as well as from RSMeans, a standard costing tool used in construction.

A modified system architecture will likely be employed for very large area modules. Several different system architectures for large area modules have been proposed; due to limited field experience, the relative merits of different proposed designs are not well understood. Here, we explore the costs associated with one possible approach, wherein flexible flanges and adhesive material are used in place of traditional fixed clamp connections between modules. This system design was used for our analysis of all large modules (Gen 6 through Gen 10.5). We assume that this configuration allows for the use of one less vertical mounting rail for each module assembly.

Based on our interviews and existing NREL data, we believe that installation of these large modules would require a machine to assist with lifting and placing the modules. In our model, we assume the cost of this machine is equal to that of a standard crane truck used in construction (a truck with a small crane mounted on the bed) plus a 20% premium for the appropriate robots, end effectors, etc. to interface with the module. Our results assume that the machine-assisted module mounting takes approximately the same amount of time as manual module mounting; if this process could be sped up, additional cost savings could be realized. However, as discussed below, the installation labor cost associated with module mounting is a small fraction of the total installation labor costs, so these savings would likely be modest.

Because of the limited experience with large area modules, there is uncertainty around many of the input data for both the manufacturing and installed system cost models. Often, our data sources were making informed estimates about how their costs or processes could be affected by increasing module size. Sensitivity analysis was performed in order to evaluate the potential impact of these uncertainties on our conclusions about the cost of different module areas.

Costs for module shipping are not included, but may be analyzed in greater depth in future work. Preliminary evaluation of the potential of shipping issues associated with very large glass sizes suggests that shipping and handling of glass size Gen 10 or above has been more challenging for the display industry (see [8] for additional discussion).

C. Simulations of Module Efficiency

Rated module efficiency is a key driver of both module and installed system cost per watt. In addition to rated efficiency, LCOE is also strongly influenced by lifetime energy yield. Because of the limited experience with very large area thin-film modules, the effects of module area on these two performance metrics is not well documented. While a comprehensive discussion of these effects requires significantly more research and is well beyond the scope of this paper, we provide simulation of how one of the main causes of non-uniformity in thin-film solar modules—the lognormal distributed shunt [9], which contributes significantly to the cell-to-module efficiency gap [10]—could affect the rated efficiency of CIGS as module area scales. We do this using a physics-based module simulation framework [11-12] and Monte Carlo simulation with different module sizes given a lognormal distribution of shunts. The lognormal distribution of shunts can be inherent in thin-film technologies, which originated from the fact that grain size in poly-crystalline films is lognormal distributed regardless of the choice of materials. Thus, the trends observed in our simulation results may be extensible to other thin-film material systems.

III. Results

Module manufacturing cost reductions for both CIGS and CdTe result from economies-of-scale in the equipment costs, energy, and labor usage, as well as reductions in the cost per watt of components with a unit cost largely independent of module area (e.g. the junction box or j-box) or increase at a slower rate than module power (e.g. busbar costs). For CIGS, we find that a savings of \$0.13/W in module manufacturing costs may be possible with Gen 10 or Gen 10.5 (approximately 8m^2) glass is used; 71% of this savings is achieved by moving to Gen 6 sizes, with 91% of the realized with Gen 8 modules. J-box savings are significant at \$0.04/W (this assumes the j-box cost per unit is constant, since thin-film j-boxes do not employ bypass diodes like wafer-based designs). Another significant savings is achieved by reduced cost-of-ownership for sputtering processes, which are used for depositing the molybdenum (Mo) back contact layer, the intrinsic and aluminum-doped zinc oxide (i-ZnO/AZO) front contact stack, and the copper (Cu), indium (In), and gallium (Ga) precursors in our modeled process flow. For CdTe, we estimate a potential cost savings of \$0.10/W for increasing to Gen 6 module sizes. The modeled difference in installed cost for a 1.2m x 1.8m versus a 1.5m x 1.8m (Gen 6) module was <\$0.01/W. Given the level of uncertainty in our other inputs, this difference is negligible.

Figure 1(a) shows the sensitivity of the total manufacturing cost savings for CIGS to ±20% changes in key input parameters. As can be observed from the figure, cost savings are most sensitive to variations in the throughput and equipment cost for the batch selenization step. This step is the single most expensive in the CIGS fabrication process. We assumed in our analysis that the same furnace and process is used for selenization with each module size, but that batch sizes decrease proportional to the module area (i.e. as module area increases, fewer, larger modules loaded into the furnace for each run).

For CdTe, a significant portion of the manufacturing cost savings (34%) achieved by going from current module sizes to Gen6 module sizes results from economies-of-scale in capital equipment (CAPEX) costs. As shown in Figure 1(b), manufacturing cost savings for CdTe are also the most sensitive to uncertainties in CAPEX costs. Unfortunately, because insufficient data could be obtained on the CAPEX of each tool for the Gen 6 case, we have little insight into the main drivers of this reduction.

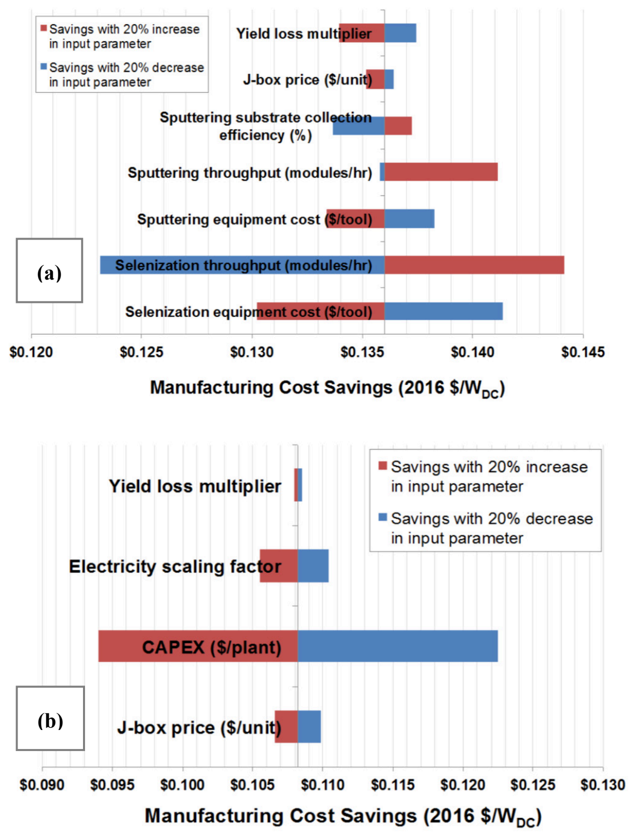

Fig. 1. (a) (top) Sensitivity of CIGS module manufacturing cost savings with Gen 10.5 modules (Gen 10.5 minus reference case cost) to ±20% changes in key input assumptions. (b) (bottom) Sensitivity of CdTe module manufacturing cost savings with Gen 6 modules (Gen 6 minus reference case cost) to ±20% changes in key input assumptions).

Figure 2 shows how module area affects non-module system costs. For Gen 6 modules, we estimate a potential non-module system cost savings of \$0.03/W. Increasing module area to Gen 10 and Gen 10.5 could enable an additional BOS savings of \$0.005 to \$0.01/W. Several factors drive these cost reductions. Material cost savings are observed by replacing typical clamps for glass-glass modules, which cost approximately \$2.65/module, with flanges and adhesives, which are estimated to cost \$0.80/module. The reduced module count and modified system architecture also result in labor and structural/electrical BOS savings. The reduced module count results in a significant, proportional reduction in module mounting time, but because much of the installation labor is spent on other tasks (e.g. installing the structure, racking, and inverter), the savings as a percent of total installation labor costs are modest. There is also a small additional cost associated with the use of an additional machine to assist with large module placement.

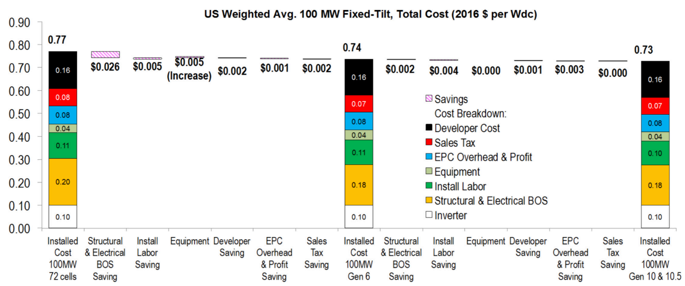

Fig. 2. Modeled impact of module area on non-module installed system costs.

Figure 3 summarizes the total installed cost savings (including both module and non-module savings) for CIGS and CdTe as a function of module area. As can be seen from the figure, CIGS savings begin to asymptote for modules with areas >5m^2 (beyond Gen 8).

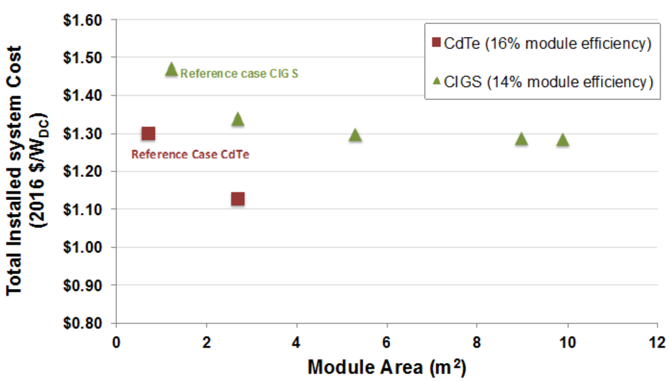

Fig. 3. Effect of module area on U.S.-weighted average total installed system price by technology. Assumes a 100MW utility-scale installation with fixed tilt.

These savings assume that rate module efficiency is constant as area increases. Because large area CdTe or CIGS modules have not yet been publicly demonstrated, this assumption contains significant uncertainty at this point. As discussed above, one key question is how non-uniformities could influence efficiency, and shunts are a primary source of non-uniformities in thin film modules. The results of our efficiency simulations are shown in Figure 4. One observation from the simulation is that modules with a larger size have a narrower distribution of efficiency (i.e., smaller variance). This occurs because the screening effect of poorly shunted cells (at the tail of the log-normal distribution) on the well-performing neighboring cells is reduced as the area of the module increases, which lowers the possibility of producing very inefficient modules. Moreover, as the size of modules expands, it is also less likely to produce a defect-free module with exceptionally high efficiency. Eventually, the efficiency is limited by the mean of shunts for very large modules. Hence, production of monolithic solar modules with greater areas will affect the binning strategy of the manufacturers (i.e., more uniform power rating and pricing). However, it can reduce the market flexibility of selling solar modules to customers with different needs. For example, at the utility-scale, it is not favorable to deploy expensive solar modules with excessively high efficiency, as it does not offset the BOS cost. In contrast, those highly efficient solar modules are more popular at the residential scale. Prior work suggests that, if a reduction in efficiency due to shunts is observed, novel geometry design and post-process scribing could be employed to isolate defects to improve overall module performance [10].

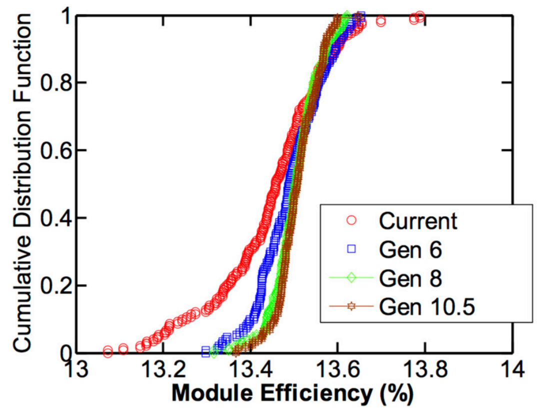

Fig. 4. Effect of module area on the distribution of expected module efficiencies for CIGS modules

Figure 5 shows the sensitivity of the total installed system cost for Gen 10.5 CIGS and Gen 6 CdTe modules to efficiency. We can see from Figure 2 that some cost savings (compared to the reference case size) are still achieved for large area module efficiencies above ~12.5% for CdTe and above ~11% for CIGS, with savings decreasing proportional to the reduction in large module efficiency compared to the reference case. This plot assumes that the module cost in $/m^2 does not vary with efficiency. However, in reality, higher efficiency modules may be associated with cost and/or price premiums, and vice versa. This figure can inform module cost and efficiency targets that must be achieved in order to realize a savings in total installed system cost with large modules.

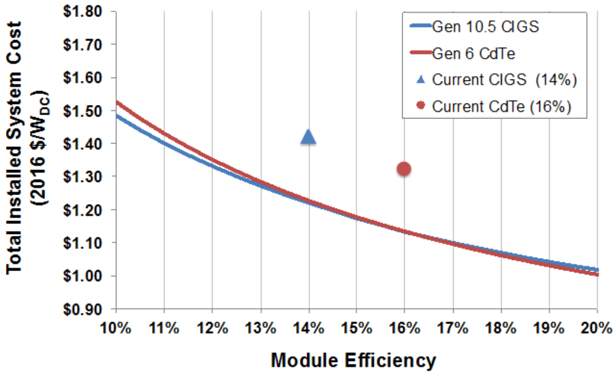

Fig. 5. Effect of module efficiency on realized cost savings with large module sizes for thin-film technologies

IV. Discussion and Conclusion

We explored the potential for increased module area to influence module manufacturing and installed system cost per watt of leading thin-film PV technologies. Our analysis indicates that the use of larger area modules has the potential to drive savings at both the module ($0.13/W for CIGS and $0.10/W for CdTe) and system ($0.04/W) levels We observed diminishing returns to scale for sizes above Gen 8 or Gen 10 for module manufacturing cost for CIGS and for sizes above Gen 6 for BOS and installation costs. We did not model costs for manufacturing CdTe modules at sizes larger than Gen6; if efficiencies can be maintained, further cost reductions could be achieved for larger sizes. While there is still uncertainty in many of our assumptions, our overall conclusions are robust over a wide range of potential input values. Further research is required to better understand how module area effects module efficiency and energy yield in order to better understand the LCOE associated with large area CIGS and CdTe modules.

The exact manufacturing cost savings realized will depend on the specific process steps and factory layout involved, whether large modules are manufactured in a new facility or in an upgraded, existing facility, and what equipment is used. Relative savings achieved with larger module size will also depend on the price of materials at any given point in time. Finally, for Gen 10 and Gen 10.5 glass, challenges around logistics and shipping will need to be addressed in order to achieve low-cost.

There may also be some barriers to very large modules that are unrelated to cost per watt. For example, the upfront cost of equipment required to build up the necessary capacity to manufacture large thin film modules at competitive scale, given the large manufacturing capacity that already exists for mc-Si, is substantial. Downstream suppliers may be slow to adopt large area modules if they require additional investment themselves. Increased module size could also require new investments from equipment manufacturers to develop new tools and processes suitable for large-areas. In some cases, knowledge can be borrowed from other industries, as with sputtering equipment currently used in display manufacturing.

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