Cost analysis of thin film tandem solar cells using real world energy yield modelling

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***Abstract* — Tandem photovoltaic (PV) cells with higher efficiency limits than current market dominated crystalline silicon PV devices are poised to be the next generation of solar cells. In this study we focus on analysis of perovskite/$Cu(In_xGa_{1-x})Se_2$ tandem solar cells in the context of real-world conditions. Using material properties and the most recently updated atmospheric data we simulate the device energy yield for locations with different climate conditions. We use the resultant data in calculating module levelized cost and analyze the conditions under which using different forms of tracking become the cost-effective approach at each location.**

***Index Terms* — Multi-junction photovoltaics.**

I. Introduction

While current high efficiency single junction solar cells are approaching their thermodynamic efficiency limit, tandem solar cells offer an avenue to higher efficiency solar cells. [1] These devices can be fabricated using established technologies with considerable PV market share, such as crystalline silicon (c-Si) and $Cu(In_xGa_{1-x})Se_2$ (CIGS), as bottom cell. These PV cells can be paired with perovskites cells that have demonstrated ideal tandem top cell properties such as cost-effective fabrication, [2], [3] low environmental impact, [4] and facile bandgap and thickness adjustment. [5] These properties will be pivotal for tandem device optimization.

For two-terminal tandems the balance in current generation, where top and bottom subcells produce equal currents and is referred to as current matching, leads to the optimized two-terminal tandem devices. To achieve this condition detailed analysis of the bandgaps and thicknesses of top and bottom cell absorbers is required. For four-terminal devices the current matching limitation does not exist; however, analysis of the bandgap and thickness parameters are required to identify a balance in the efficiency of the top cell and bottom cell in order to have the most efficient four-terminal tandem device. This balance can exist when a wide bandgap top cell can demonstrate high efficiency with high operating voltage while allowing a significant portion of the light to pass to the bottom cell which then produces high photocurrent and, consequently, high power conversion efficiency. [6], [7]

To identify the optimized device parameters for perovskite/CIGS tandems, we analyze the optics of the two- and four-terminal tandems and simulate device efficiency and energy yield (EY) under real world conditions. [7] We use the expected EY values and also the expected cost of production and operation to investigate the economic viability of these tandem PV modules for multiple locations across the US.

II. Methods

We developed a simulation tool that uses real-world conditions to generate device EY for specific locations. This model uses the measured refractive indices of the layers in the device stack and the angle of incidence of the light to produce the external quantum efficiency (QE) as a function of the light wavelength. Using the calculated QE, the reverse saturated (radiatively recombination limited) and photo generated currents are calculated and are implemented in simulating the PV cell current-voltage behavior by diode equation. To calculate the EY's of the devices we use hourly solar irradiance, temperature, angle of the incident light for direct normal irradiance (DNI) and anisotropy of the direct horizontal irradiance (DHI) on hourly basis for multiple locations. [7]

For cost analysis we adopt a bottom up cost model developed for technoeconomic cost analysis of the perovskite and tandem PV modules. [2] The processing cost of the modules are calculated considering a multi-step fabrication process for a reference module. Additionally, operating cost of the modules

TABLE I

ENERGY YIELDS FOR TWO- AND FOUR-TERMINAL TANDEMS FOR OPTIMIZED DEVICES IN MULTIPLE LOCATIONS IN THE US WITH DIFFERENT TRACKING OPTIONS

	Expected Annual Energy Yield ($KWh/m^2.yr$)					
	Two-terminal			Four-terminal		
Location	Standstill module	1-axis tracking	2-axis tracking	Standstill module	1-axis tracking	2-axis tracking
Toledo OH	272.6	356.9	387.1	290.3	367.9	399.3
New Orleans LA	290.5	363.3	409.4	297.6	373.2	421.9
Golden CO	357.6	491.5	559.5	365.4	501.3	570.6
Phoenix AZ	539.5	674.6	754.6	545.8	684.3	767.3

are calculated by considering the annual cost to maintain normal operation.

III. RESULTS

To determine the optimized device, we use the described simulation model to explore the various structures in both two-terminal and four-terminal tandem devices under laboratory and real-world conditions. During this process, we identified devices that are amongst the most efficient under laboratory conditions but do not perform as well under real-world conditions. The predicted EY for these devices is not as high as the maximum point, though the efficiencies would suggest otherwise. We investigate climatic conditions in these locations to identify the reasoning behind such disparity between laboratory optimized devices and predictions for the real world. Table 1 shows the annual maximum device EY for two-terminal and four-terminal devices in multiple locations. The results indicate that incorporating 1-axis tracking (solar azimuth) increases the expected EY output by 25 to 37% depending on the location while adding 2-axis tracking (solar azimuth and altitude) increases the EY by 8 to 13% with respect to 1-axis tracking and 37 to 56% increase with respect to no tracking modules. [7]

To investigate the economic viability of tracking applications for these locations we use the results of EY modelling and calculate Levelized cost of energy (LCOE) of modules using

$$LCOE = \frac{\frac{I+\sum_t O_t}{\sum_t (1+r)^t}}{\frac{\sum_t EY_t (1-d)^t}{\sum_t (1+r)^t}} \quad (1)$$

where I is the manufacturing cost, O is the annual operation cost, t is the lifetime, EY is the module annual energy yield, d is the degradation rate and is considered to be 5% for perovskite and 0.5% for CIGS. r is the discount rate and is considered to be is 9%. The processing cost of perovskite and CIGS module and the additional components are included in manufacturing cost. [8], [9] LCOE assumptions are based on utility scale scenario of U.S. Department of Energy SunShot target. [10] We assume the cost of the tracking is a fixed fraction of the module cost. The LCOE for all three tracking conditions were calculated for a range of module lifetime and additional cost due to tracking and compared to each other. The tracking system with the lowest LCOE was selected for each tandem lifetime and fractional cost of the tracking system. The results are shown in Fig. 1(a) and (b) for Phoenix AZ and Toledo OH, respectively for comparison between fixed tilt and 1-axis tracking. Fig. 1 (c) and (d) show the same for comparison between fixed tilt and 2-axis tracking. As these results indicate 1-axis tracking is cost effective when the cost increment is under 20% and 30% for Phoenix AZ and Toledo OH

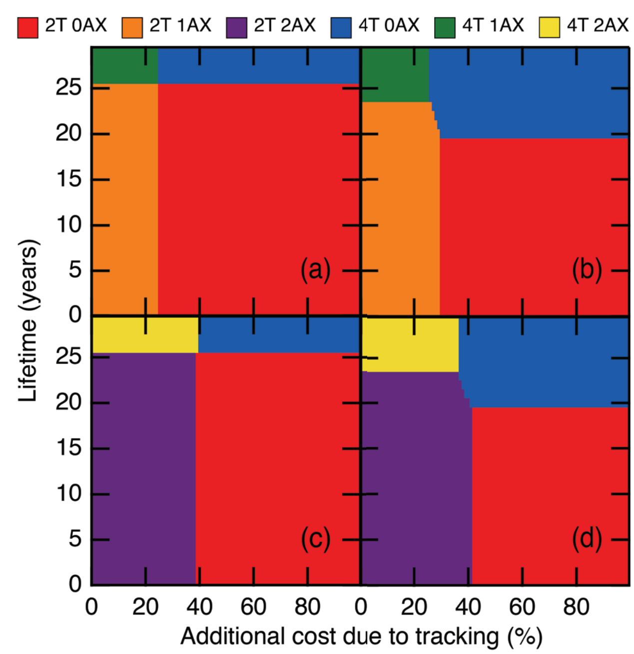

Fig. 1. Lowest LCOE choice for tandem modules as a function of additional cost percentage and lifetime are shown for Phoenix AZ (a) and Toledo OH (b) within fixed tilt and 1-axis tracking options. Panels (c) and (d) show the same for comparison between fixed tilt and 2-axis tracking.

respectively. For the case of Toledo OH, the acceptable price range for 2-axis tracking expands to slightly above 40% additional price. This is similar to the case of Phoenix AZ. For lifetimes above 20 years 4-terminal cases are more cost effective for Toledo OH. For Phoenix AZ same is true in case of module lifetimes above 25 years. 4-terminal modules show low LCOE only in the case of long lifetimes (above 25 years) and low additional cost due to tracking (below 25% for 1-axis and below 40% for 2-axis tracking).

One of the major drawbacks of perovskite PV at the moment is lower stability than the technologies considered here for the bottom cell in tandem configuration. While different approaches in changing the material in the device and encapsulation of the PV cells are proposed to improve the lifetime, the prospect of tandem PV device application could be affected by lower lifetime of one of the subcells. Therefore, we investigated how the lifetime of each subcell in the structure affects choice of tracking system. As the results in table 1 demonstrates EY associated with optimized 4-terminal tandems are in the same range as 2-termnial devices. While 4-terminal production costs are typically higher than that of 2-terminal device, 4-terminal devices do offer a potential advantage when one of the subcell lifetimes is shorter than the other. Because each subcell is controlled independently in four-terminal tandems, failure of one cell will not render the entire tandem useless, as could be the case in two-terminal tandems. To investigate the effect of the lifetimes in the lowest LCOE model we introduce the subcell lifetime separately. For this model, the lifetime of two-terminal tandems is set to the shorter subcell lifetime whereas for four-terminal tandems, the EY of each subcell is calculated for its entire lifetime by considering individual subcell EY. Figure 2 shows the lowest LCOE choice for tandems in Phoenix AZ (a) and Toledo OH (b) within fixed tilt and 1-axis tracking options while (c) and (d) show the same for 2-axis tracking and fixed tilt options. The results show that in the case of shorter lifetime for a subcell compared to the other, 4-terminal tandems demonstrate lower LCOE, while tandems with similar lifetimes in top and bottom subcell leads to two-terminal tandems. For these calculations additional cost due to tracking was assumed to be 40%.

IV. Conclusions

Results showed that climate conditions contribute significantly to EY and consequently to LCOE. Within the SunShot target using the calculated module manufacturing cost, additional cost due to 1-axis tracking is 40%. Results shown here indicate addition of 1-axis tracking is not economically viable for perovskite/CIGS tandems within SunShot target cost estimations. Comparison of LCOE values to those of single junction devices would verify economic viability of perovskite/CIGS tandems.

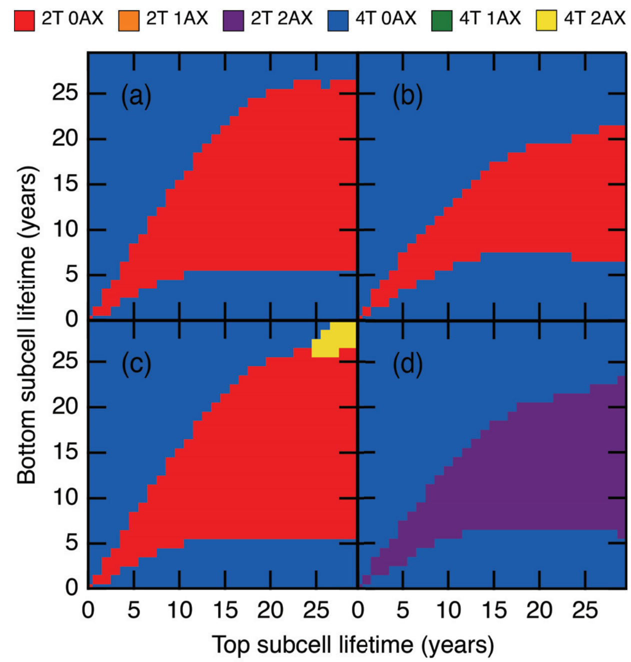

Figure 2. Lowest LCOE choice for tandem modules as a function of top and bottom cell lifetime are shown in Phoenix AZ (a) and Toledo OH (b) within fixed tilt and 1-axis tracking options. Panels (c) and (d) show the same for fixed tilt and 2-axis tracking options.

Acknowledgments

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