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Assessing the photovoltaic technology landscape: efficiency and energy return on investment (EROI)†

Z. Zhou * and M. Carbajales-Dale

This study builds on previous meta-analyses of photovoltaic (PV) systems to assess the tradeoff between efficiency and energy inputs (*i.e.* cumulative energy demand, CED) in the energetic performance (as measured by energy return on investment (EROI)) of PV technologies under both high-cost and low-cost balance of system scenarios. This study focuses on three existing technology groups (wafer, thin film, and organic). We find that earlier projections of third-generation (high-efficiency, low-cost), thin-film technologies have not yet emerged, since "third-generation" technologies currently have low-cost but also low-efficiency. However, we also find that the best advances in energetic performance to date come from thin film technology.

Introduction

Solar power is widely promoted as an important means to reduce harmful environmental impacts from electricity generation, particularly avoiding the emission of climate-changing greenhouse gases (GHGs). Governments worldwide support renewable energy by mandating renewable portfolio standards, tax incentives and feed-in tariffs.[1] Due in part to government support and large reductions in module costs, the global installed capacity of solar photovoltaic (PV) systems is increasing rapidly.[2]

The energetic performance of solar cells is dependent on a number of factors: efficiency, lifetime, capacity factor, and energetic cost of cell manufacture. There is a large drive to boost the efficiency of PV cells *via* a number of techniques including improved light trapping;[3] high-efficiency materials, such as gallium arsenide (GaAs);[4] multiple-junction cells to capture more of the sunlight spectrum;[5] multiple excitation generation and quantum dot cells;[6] and plasmonic and hot carrier cells.[7] Previous studies have highlighted both the energetic and climate benefits of PV systems with low embodied energy.[8–10]

This study explores the landscape of energetic performance of a variety of different PV technologies in terms of efficiency, embodied energy (as measured by cumulative energy demand, CED), and energy return on investment (EROI) to identify potential benchmarks for research and technology development.

Background

There has been a large push globally to reduce the financial costs of PV system production. The US Department of Energy (DOE) initiated the SunShot program, targeting a PV system cost of 'one dollar per watt' of installed capacity.[11] Balance of system is usually considered as components and equipment aside from the PV modules themselves that among other functions convert DC energy, which is generated by the solar panel, to the AC energy system.[12] At the outset of the program, the breakdown between financial cost of PV modules *versus* BOS costs was assumed to be around half–half (50 : 44%, the other 6% being power electronics) of the $3.40 per watt system cost. Other researchers have found a similar split (66 : 34) between module and BOS for conventional crystalline silicon (c-Si) PV technology, with an efficiency of 18%.[13]

Many of the costs of PV system production (especially BOS components such as support structures) scale with system area. As efficiency increases, the need to generate the same amount of electricity decreases. As such, system efficiency has become the holy grail of PV technology development. The DOE's National Renewable Energy Laboratory (NREL) tracks developments in the field by maintaining a 'leaderboard' of PV cell efficiency.[14]

A seminal work in the field of PV system analysis represents the tradeoff between efficiency [%] and panel cost [USD per m^2] for three generations of PV: (I) wafer based; (II) thin film; and (III) advanced thin films.[15] In this efficiency–cost space, diagonal lines depict the cost per unit of capacity [USD per W]. The first-generation, wafer-based technology has a higher efficiency than second-generation thin film but at a higher cost per unit area, leading to an overall higher cost per unit capacity. This seminal work projects that third-generation technologies would have dramatically increased efficiency through several approaches (such as multiple energy level, intermediate level cells, and multi carrier excitation), while the cost per unit area would be only slightly higher than traditional thin film.

However, efficiency and financial cost are not the only important metrics by which to judge PV system performance.

Environmental Engineering & Earth Sciences, Clemson University, Clemson, USA. E-mail: zikaiz@clemson.edu

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Net energy performance and environmental impacts (such as GHG emissions or water consumption) may also be important indicators of the benefits and costs of energy delivery technologies.[16,17] Previous meta-analyses have: (i) used GHG emissions,[18,19] water consumption,[20] and CED[10,21] to compare PV technologies; (ii) used cumulative electrical energy demand (CE_eD) [kW h_e/W_p] and electrical energy payback time (E_ePBT) [years] to assess the performance of the global PV industry;[8,22] (iii) understood the impact of deploying energy storage technologies to support PV and wind;[23] and (iv) compared wind, solar PV, and concentrating solar power (CSP) technologies.[24] This paper uses the electrical energy return on investment (E_eROI) as a metric to evaluate and compare the performance of different PV technologies with a specific focus on the impact of panel efficiency and BOS.

Another important financial metric that is increasingly used to assess the financial viability of solar PV technologies is the levelized cost of electricity (LOCE) over the full lifetime of the plant. Estimates range between \$60–560 per MW h,[25] with record-breaking-low bids being made in the United Arab Emirates of \$23 per MW h.[26]

Methodology

Meta-analysis

We build on several previous meta-analyses of the energy inputs to PV systems and update them to find the distribution in CE_eD for different PV technologies. For more discussion of the method, see the ESI,† Section S2, and the spreadsheet of research data taken from previous studies[27–79] is also uploaded as ESI.† The meta-analysis is based mainly upon currently commercialized technologies, unfortunately meaning a lack of studies on perovskite technologies, which show a great deal of promise at the level of research cells.

Capacity factor

PV system electricity generation is dependent on the average power delivery capacity per watt of nameplate capacity, often termed the capacity factor [W_{avg}/W_p]. Previous studies have determined the global average capacity factor for PV systems to be around 12%.[8,16] We have updated this assessment to obtain a value of 15% (for details see Section S2.1, ESI†).

Electrical energy return on investment

E_eROI may be easily defined as

$$E_eROI = \frac{\text{Electrical energy output}}{\text{Electrical energy inputs}} \quad (1)$$

In the context of this study, energy inputs may be defined on a per unit area basis [kW h m^{-2}] by the cumulative electrical energy demand of the PV system CE_eD_{sys}, which may be split into two parts for the module (CE_eD_{mod}) and the BOS (CE_eD_{BOS}). We assume that the energetic costs for operation and maintenance (O&M) as well as disposal are negligible, or that they vary little between different technologies. We may now write the expression for E_eROI as

$$E_eROI = \frac{\kappa L}{C_eED_{sys}} = \frac{\kappa L}{\frac{L}{T}C_eED_{mod} + C_eED_{BOS}} \quad (2)$$

where κ is the capacity factor and L is the standard system lifetime [h], which is $24 \times 365 \times 25 = 219\,000$. T is the module life time [h].

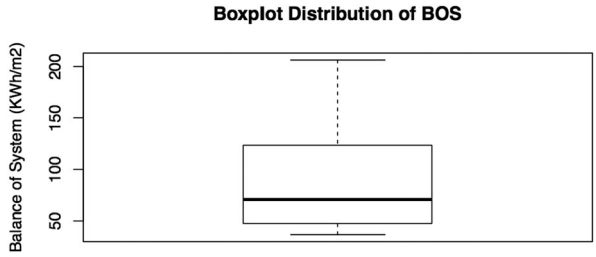

Fig. 1 Distribution in the cumulative electrical energy demand for the balance of system (CE_eD_{BOS}) on a per unit area basis [kW h_e m^{-2}] from our meta-analysis. The 0, 25, 50, 75, and 100 percentile values are, respectively, 36.58, 47.52, 70.59, 123.55, and 206.36 kW h_e m^{-2}.

Balance of system cost

In order to study the impact of module efficiency on energetic performance, we combine the BOS data (see Section S3.5, ESI†) of all technologies together and analyze two scenarios: (a) a high BOS scenario in which we assume that BOS energetic costs take the maximum value 206 kW h_e m^{-2} from the BOS distribution (see Fig. 1); and (b) a low BOS scenario in which BOS energetic costs take the minimum value of 37 kW h_e m^{-2}.

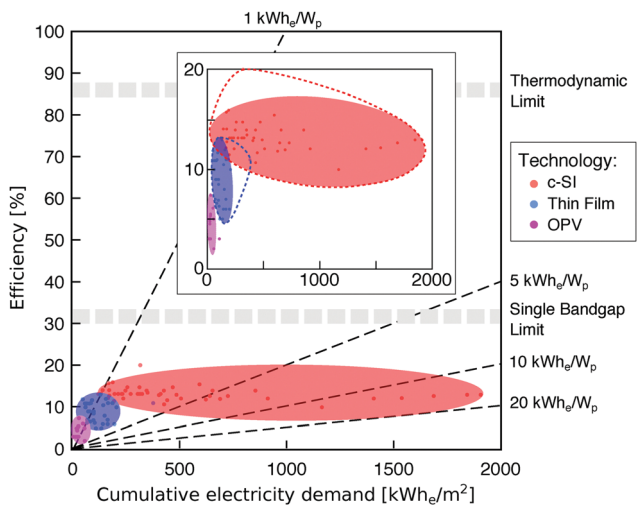

Fig. 2 Energetic performance in terms of efficiency and cumulative electricity demand of three main photovoltaic types: crystalline silicon (c-SI in red), thin film (blue), and organic (OPV, in pink). The inset figure shows the detailed efficiency range between 0 and 20%. The dashed lines show the whole boundaries of each technology.

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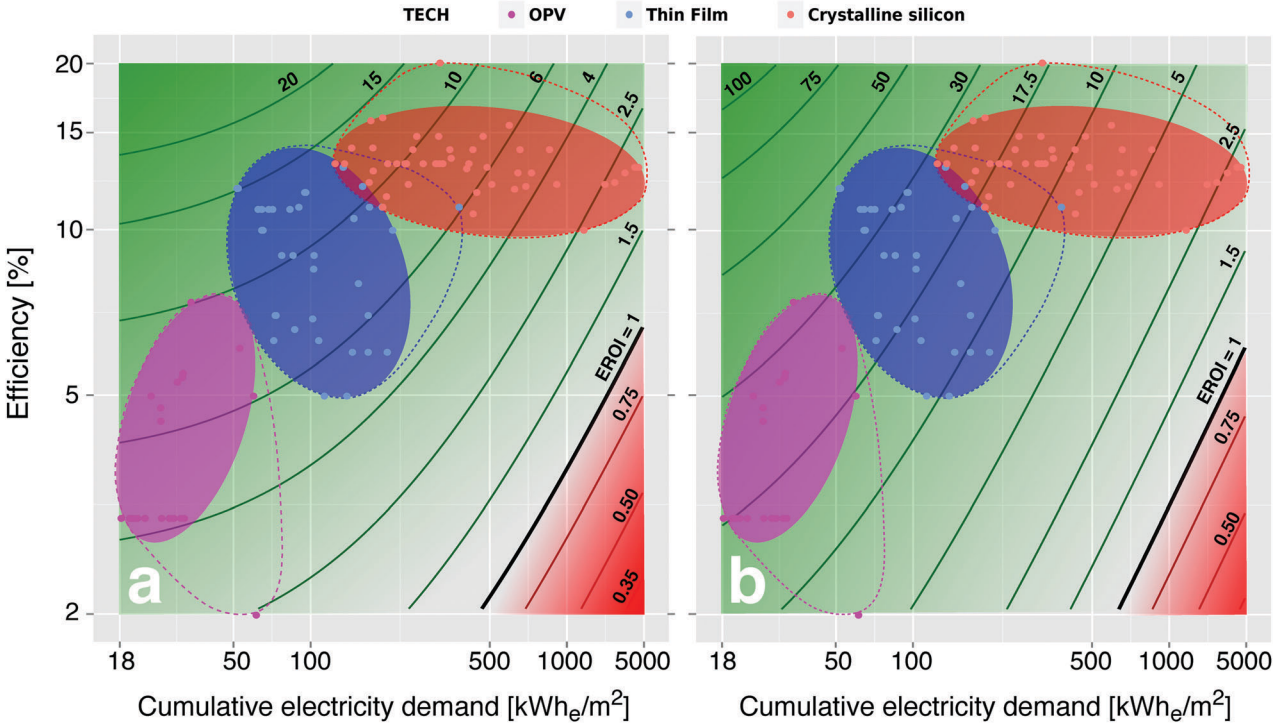

Fig. 3 PV system performance landscape (cumulative electricity demand, efficiency, and EROI) for different scenarios for the CE_eD of the balance of system (BOS). (a) A high BOS scenario, value 206 kW h_e m^{-2} and (b) a low BOS scenario, value 37 kW h_e m^{-2}. Outliers of each technology group are captured using a dashed line. As can be seen, the EROI is vastly different in the two scenarios; however, thin-film technologies (CdTe, CIGS, a-Si) perform best in both cases. The higher efficiency of the c-Si technologies (sc-Si, mc-Si) comes at the cost of a higher cumulative electricity demand for the total system.

Lifetime

To compare different technologies on an equal basis, we define a standard lifetime of 25 years. For PV technologies with lower expected lifetimes, *e.g.* organic PV systems, CE_eD_{mod} will be increased to account for the replacement of panels over the 25 year period. For example, if the expected lifetime is 5 years, the CE_eD_{mod} would be increased by a factor of 5 because the panel would need to be replaced 5 times to cover the whole period, whereas we assume that the BOS does not need to be replaced. We do not account for any learning that may have decreased the value of CE_eD_{mod}, *i.e.*, the panels are all paid for 'up front' at the beginning of the 25 period. We assume that organic modules have a lifetime of 5 years[80] (*i.e.*, they require the up-front investment for 5 modules). All other technologies are assumed to last 25 years.

Results and discussion

In Fig. 2, we plot the 'PV energetic performance landscape' for three sets of PV technologies: (1) crystalline silicon (c-SI), which includes single-crystal (sc), multi-crystalline (mc), and ribbon silicon; (2) thin film, which includes amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium (di)selenide (CIGS); and (3) organic polymer (OPV). In the plot, the horizontal axis depicts PV module CE_eD_{mod} on a per unit area basis [kW h_e m^{-2}], the vertical axis depicts PV module efficiency as a percent of incoming sunlight energy converted to DC electricity [%]. As can be seen, the pattern mirrors that of the efficiency *vs.* financial cost plot discussed earlier; wafer-based (first-generation) technologies have higher efficiency and higher energy 'cost' (CE_eD) compared with thin-film and OPV (second-generation) technologies. As yet, no high-efficiency, low-CE_eD (*i.e.* third-generation) panels have been produced.

In Fig. 3, we compare the energetic performance of the PV technologies under a high-BOS (left) and low-BOS (right) scenario now using the efficiency-CE_eD_{sys} 'landscape', *i.e.* including the CE_eD_{BOS} costs. In this case, we are using a log–log plot wherein the E_eROI values are depicted as diagonal contours and vary depending on the (high–low) BOS scenario. Switching between the two scenarios changes the position and slope of the E_eROI contours in the landscape. The slope of the E_eROI contours suggests that low efficiency is more detrimental at high CE_eD_{sys}, since the curve bends upward more steeply on the right side of the plot, especially in the high-BOS scenario.

In both scenarios, thin-film technologies perform best (*i.e.* have the highest and generally higher E_eROI values). Additionally, the best gains in energetic performance of the technologies occur when efficiency gains and reduction in CE_eD_{sys} move the technology through the landscape perpendicularly to the E_eROI contours. As can be seen from the shape and direction of the bounding ovals, OPV technologies are seeing efficiency gains but at the expense of greater CE_eD_{sys}, c-Si is reducing CE_eD_{sys}, but with smaller relative gains in efficiency, whereas thin-film

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is seeing concomitant gains in efficiency and a reduction in CE_eD_{sys}.

Conclusions

This study builds on previous meta-analyses of PV systems to assess the trade-off between efficiency and cumulative energy demand in the energetic performance of PV technologies under both a high-cost and low-cost balance of system scenario. We find that earlier projections of third-generation (high-efficiency, low-cost), thin-film technologies have not yet emerged. We further find that, of the existing technology groups (wafer, thin film, and organic), thin-film has, to date, seen the best advances in energetic performance and is currently performing better.

Conflicts of interest

There are no conflicts to declare.

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