Optical Materials 112 (2021) 110752

Contents lists available at ScienceDirect

Optical Materials

journal homepage: http://www.elsevier.com/locate/optmat

Short Communication

Comment on “an overview of various configurations of luminescent solar concentrators for photovoltaic applications”

Chenchen Yang [a], Richard R. Lunt [a,b,*]

[a] Department of Chemical Engineering and Materials Science, Michigan State University, East Lansing, MI, 48824, USA
[b] Department of Physics and Astronomy, Michigan State University, East Lansing, MI, 48824, USA

In a recent article, Rafiee et al. [1] overviewed the research progress of luminescent solar concentrators (LSC) from the past decade. Figures of merit to evaluate the photovoltaic (PV) performance of LSCs were outlined, and the configurations, luminophore species, and performance of various LSC reports were described. However, we find that the definitions of several key equations are erroneous and performance metrics acquired from different characterization protocols are incorrectly compared. Here, we help clarify these definitions and reporting.

First, and most important, the wrong area is used in the definition for the power conversion efficiency (*PCE*) in Equation 5 [1]. The *PCE* of any PV or LSC system is calculated from the corresponding current density (*J*) - voltage (*V*) characteristics measured under standard illumination (AM 1.5G). Once a PV cell is edge-mounted onto an LSC waveguide, it is the area of the waveguide front surface (A_{LSC}) that receives the input solar power rather than the edge-mounted PV (A_{Edge}) as shown in Fig. 1A. The scaling of the generated photocurrent (*I*) should always be proportional to the collection area A_{LSC} ($I \propto A_{LSC}$), therefore, all LSC-PV systems should generate the same values of photocurrent density ($J = I/A_{LSC}$) in the ideal case where there is no reabsorption loss as shown in Fig. 1B. In the presence of reabsorption losses, *J* does not increase as quickly with increasing A_{LSC} and decreases slightly with decreasing waveguide thickness. However, if A_{Edge} is applied in calculating the *PCE* as defined in this article, the *G* factor and the calculated *J* (I/A_{Edge}) will increase, approaching infinity as the waveguide thickness decreases with constant A_{LSC}, which will result in drastically overestimated *PCE* above the theoretical limit of a PV device (the single junction Shockley-Queisser (SQ) limit, ~33% under AM 1.5G [2]) as shown in Fig. 1C. Even with the potential concentrating effect of the LSC (under concentrated illumination of ≥1000 AM 1.5G), the maximum *PCE* of a single-junction PV is ~40% [3]. For an LSC system, this concentration improvement will still only result in a *PCE* limit of about ~29% with realistic reflection loss at the waveguide front surface (4%) and trapping losses (25%). Thus the *PCE* of an LSC is necessarily less than the edge-mounted PV. The use of the incorrect collection area is a common mistake in the LSC literature, and thus the tabulated reports in Table 1 of the article combine inconsistent standards. For example, Slooff et al. reported a *PCE* of 7.1% based on A_{LSC} with EQE_{LSC} provided [4]; Li et al. [5] and Ha et al. [6] reported *PCE*s of 8.71% and 6.1%, respectively, based on A_{Edge}. With silicon microcells facing incident to the AM 1.5G (100 mWcm^{-2}) source and the area of the PV applied, Bronstein et al. reported an output power of 77.38 mWcm^{-2}, which is >200% of the SQ limit for single-junction PVs [7]; El-Bashir et al. reported the improvement in *PCE* (not absolute *PCE*) of 53.2% via metal plasmonic enhancement [8], though this is listed as an absolute *PCE* in Table 1. The inconsistent literature review and lack of critical examination could result in incorrect conclusions, potentially misleading the researchers in the LSC community, and creating false baselines of comparison for future reports.

Second, Rafiee et al. defined the optical efficiency (*OE*) as the ratio of the integrated waveguide output energy to integrated input energy. The use of energy fluxes is not meaningful to accurately describe the operating principle of an LSC-PV system. In Fig. 1B (Top) we include two LSC-PV systems as examples to understand this point: LSC-PV1 system with *PL1* and *PL2* and LSC-PV2 system with *PL1*, *PL2*, *PL3*. As the luminophore *PL* spectrum red shifts from *PL1(λ)* to *PL2(λ)* for LSC-PV1 system and from *PL1(λ)* to *PL3(λ)* for LSC-PV2 system, the defined *OE* decreases for both systems due to the decreasing emitted photon energy. However, in practice, as long as the EQE_{PV} cut-off wavelengths encompass the entire *PL* profiles of the luminophore (EQE_{PV1} encompasses *PL1* and *PL2*, and EQE_{PV2} encompasses *PL1* to *PL3*), the same number of emitted photons can reach the waveguide edge and be converted into the same amount of output electrons (assuming the edge-mounted PV *EQE* is constant like with Si), resulting in the same photocurrent and the same *PCE*. The corresponding *J-V* characteristics of these two ideal LSC-PV systems are plotted in Fig. 1D: despite different *PL* positions, all should result in the same short-circuit current density (J_{SC}) due to the same amount of charge carriers generated from the same area receiving the incident solar photon flux. If PVs with different bandgaps are

* Corresponding author. Department of Chemical Engineering and Materials Science, Michigan State University, East Lansing, MI, 48824 USA.
E-mail address: rlunt@msu.edu (R.R. Lunt).

https://doi.org/10.1016/j.optmat.2020.110752
Received 23 September 2020; Accepted 14 December 2020
Available online 1 January 2021

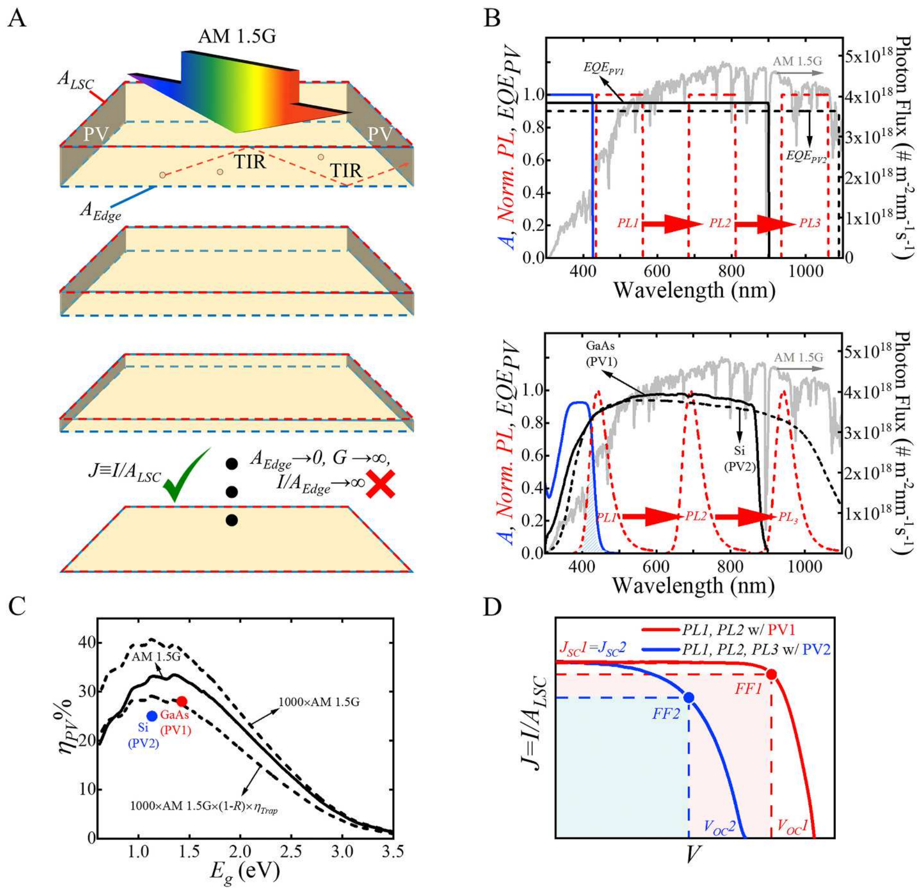

Fig. 1. (A) Schematic of a series of LSC-PV systems with decreasing edge area (A_{Edge}) and the same front surface area (A_{LSC}). A_{LSC} and A_{Edge} are highlighted with red dashed lines and blue dashed lines, respectively. Note: in the absence of reabsorption loss, the photocurrent density (J) is ideally proportional to waveguide front surface area ($I \propto A_{LSC}$) and independent of the waveguide thickness. In the presence of reabsorption losses, J does not increase as quickly with increasing A_{LSC} and decreases slightly with decreasing waveguide thickness. (B) (Top) Idealized absolute absorption ($A(\lambda)$), normalized photoluminescence ($PL(\lambda)$) and position-dependent external quantum efficiency ($EQE_{LSC}(\lambda)$) spectra of two LSC-PV systems with the following conditions: 1) the $A(\lambda)$ is fixed and the $PL(\lambda)$ can shift from *PL1* to *PL3* without changing the shape; 2) there is no overlap between the $A(\lambda)$ and the shifted $PL(\lambda)$ (no reabsorption losses); 3) the $A(\lambda)$ and $PL(\lambda)$ are step functions with sharp cut-offs at the edges; 4) the photoluminescence quantum yield (QY) remains constant as the $PL(\lambda)$ shifts; 5) both of the $EQE_{PV}(\lambda)$ values remain constant (= 1.0) with the cut-off wavelengths encompassing the corresponding shifted *PL* profiles (EQE_{PV1} encompasses *PL1* to *PL2*, and EQE_{PV2} encompasses *PL1* to *PL3*, and both EQE_{PV} profiles are offset slightly from 1.0 for visual clarity); (Bottom) Realistic profiles of $A(\lambda)$, $PL(\lambda)$ and $EQE_{LSC}(\lambda)$ (monocrystalline Si and GaAs PVs) spectra to illustrates the convolution of $EQE_{LSC}(\lambda)$ and $PL(\lambda)$ spectra, and the blue shaded area illustrates the overlap between $A(\lambda)$ and $PL1(\lambda)$. The AM 1.5G photon flux spectrum is also included as the background. (C) Shockley-Queisser (SQ) limits of a single-junction PV/LSC device under AM 1.5G, concentrated illumination (1000 × AM 1.5G) and 1000 × AM 1.5G with reflection and trapping loss. The *PCE* of a practical single-junction LSC is thus always lower than the SQ PV limit [2,3]. (D) The *J-V* characteristics of the ideal LSC-PV1 and LSC-PV2 systems. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

replaced on the edge, any potential *PCE* difference of these systems are reflected by differences in the open-circuit voltage (V_{OC}) and the fill factor (*FF*) of the corresponding edge-mounted PVs (neither of which scale linearly with the bandgap). Thus, this definition of the *OE* is not meaningful to understand the actual or relative performance changes of actual devices. Even when defined correctly, the *OE* should only be a secondary metric, not a replacement for directly reporting the *J-V* (scaled properly and corrected for spectral mismatch), *PCE*, and EQE_{LSC} as would be expected for any other PV system [9,10].

In summary, we write this comment to express our concerns over the definitions of the LSC performance metrics and interpretation of literature in the article by Rafiee et al. We hope this will help point the LSC community to utilize standardized and reliable characterization protocols that are harmonized with traditional PV reporting.

Credit author statement

C.Y. and R.R.L wrote the comment.

Declaration of competing interest

R.R.L. is a co-founder, advisor, and a part owner of Ubiquitous Energy, Inc., a company working to commercialize transparent photovoltaic technologies. C.Y. declares no competing financial interest.

Acknowledgements

The authors gratefully acknowledge support from the National Science Foundation under grant CBET-1702591, the James Dyson Foundation Fellowship.

References

[1] M. Rafiee, S. Chandra, H. Ahmed, S.J. McCormack, An overview of various configurations of Luminescent Solar Concentrators for photovoltaic applications, Opt. Mater. 91 (2019) 212–227, https://doi.org/10.1016/j.optmat.2019.01.007.
[2] W. Shockley, H.J. Queisser, Detailed balance limit of efficiency of p-n junction solar cells, Appl. Phys. 32 (1961) 510–519, https://doi.org/10.1063/1.1736034.
[3] C.H. Henry, Limiting efficiencies of ideal single and multiple energy gap terrestrial solar cells, J. Appl. Phys. 51 (1980) 4494–4500, https://doi.org/10.1063/1.328272.
[4] L.H. Slooff, E.E. Bende, a.R. Burgers, T. Budel, M. Pravettoni, R.P. Kenny, E. D. Dunlop, a. Büchtemann, A Luminescent Solar Concentrator with 7.1% power conversion efficiency, Phys. Status Solidi Rapid Res. Lett. 2 (2008) 257–259, https://doi.org/10.1002/pssr.200802186.
[5] C. Li, W. Chen, D. Wu, D. Quan, Z. Zhou, J. Hao, J. Qin, Y. Li, Z. He, K. Wang, Large Stokes shift and high efficiency luminescent solar concentrator incorporated with CuInS2/ZnS quantum dots, Sci. Rep. 5 (2015) 17777, https://doi.org/10.1038/srep17777.
[6] S.-J. Ha, J.-H. Kang, D.H. Choi, S.K. Nam, E. Reichmanis, J.H. Moon, Upconversion-assisted dual-band luminescent solar concentrator coupled for high power conversion efficiency photovoltaic systems, ACS Photonics 5 (2018) 3621–3627, https://doi.org/10.1021/acsphotonics.8b00498.
[7] N.D. Bronstein, Y. Yao, L. Xu, E. O'Brien, A.S. Powers, V.E. Ferry, A.P. Alivisatos, R. G. Nuzzo, Quantum dot luminescent concentrator cavity exhibiting 30-fold

concentration, ACS Photonics 2 (2015) 1576–1583, https://doi.org/10.1021/acsphotonics.5b00334.
[8] S.M. El-Bashir, F.M. Barakat, M.S. AlSalhi, Double layered plasmonic thin-film luminescent solar concentrators based on polycarbonate supports, Renew. Energy 63 (2014) 642–649, https://doi.org/10.1016/j.renene.2013.10.014.
[9] C. Yang, D. Liu, R.R. Lunt, How to accurately report transparent luminescent solar concentrators, Joule 3 (2019) 2871–2876, https://doi.org/10.1016/j.joule.2019.10.009.
[10] M.R. Bergren, N.S. Makarov, K. Ramasamy, A. Jackson, R. Guglielmetti, H. McDaniel, High-performance CuInS2 quantum dot laminated glass luminescent solar concentrators for windows, ACS Energy Lett. 3 (2018) 520–525, https://doi.org/10.1021/acsenergylett.7b01346.