Energy Payback Time (EPBT) and Energy Return on Energy Invested (EROI) of Perovskite Tandem Photovoltaic Solar Cells

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***Abstract*—Two-terminal tandem perovskite (PK) cells are considered a promising option for future photovoltaic (PV) market due to the rapid improvements in their power conversion efficiencies. However, their large-scale adoption requires a better understanding on the energy performance of these PVs. In this paper, the life-cycle energy consumptions of two-terminal tandem solar cells consisting of lead-based PK top cells prepared on bottom cells of copper indium gallium selenide, copper zinc tin selenide, and monocrystalline silicon are evaluated. The energy payback time (EPBT) and the energy return on invested (EROI) are the two useful metrics for examining the energy generation performance of PV systems. EPBTs of the current state-of-the-art devices range from 7 months to 12 months, while the EROI of the cells is in the reverse order as the EPBT and ranged between 5.2 and 9.2. These two energy indicators of tandem devices are expected to improve as the tandem PV technologies mature, with an EBPT as low as ∼27 day (0.9 month) and the EROI as high as 105 for high-efficiency long-lifetime devices.**

***Index Terms*—Energy payback time, energy returned on investment, perovskite top cell, tandem solar cells.**

I. Introduction

Since 2015, photovoltaics (PVs) have dominated new electricity generation capacity [1], [2], as the capacity of coal-burning power plants being retired is replaced by a combination of renewables, predominantly PV. This dramatic expansion in PV power generation requires the desired combination of cost, reliability, and longevity [3], [4]. The current cost ($/W$_P$) of PV electricity continues to decline due to technological advances in conventional monocrystalline silicon (Si) and thin-film modules [5]. To continue this decrease, module production must become less expensive, or the power conversion efficiency (PCE) of the PV modules must continue to increase [6]. The current champion efficiencies of single-junction Si, CdTe, and copper indium gallium selenide (CIGS) solar cells, i.e., 25%, 22%, and 22%, respectively [7], are approaching the practical PCE limit of ∼27% [8], as thermodynamic and material realities limit the single-junction device efficiency above this value.

Two-terminal tandem solar cell designs can increase the PCE limit by approximately 10% and, therefore, offer an excellent pathway to efficiencies above 25% [9]. To keep electricity costs competitive, the addition of the top cell must increase the PCE without adding significant cost to the new device.

Recently, a promising group of candidates for two-junction tandems has emerged. These tandem devices are comprised of a metal–halide perovskite (PK) top cell produced using low-cost solution-processing techniques and a commercially available bottom cell, such as Si, CIGS, or CZTS [10]–[16].

While the PCE gains are critical performance parameters to reduce the cost of electricity from solar, it is also important to understand the energy performance of the devices. A PV technology that performs poorly in returning the energy invested back to the society would be unlikely to remain in the PV market. Thus, along with the improvements in the PV research, we should also ensure the viability of the technology based on its energy requirement. The energy payback time (EPBT) and the energy return on energy invested (EROI) are the two useful metrics [17]–[21] for examining the energy generation performance of PV devices. EPBT is the time required that a PV system must operate to recover the energy invested for its manufacturing (or the entire lifetime depends on the defined system boundary). EROI, on the other hand, is a dimensionless metric that shows the ratio of the energy produced during the lifetime of the system to the energy needed to manufacture the system. These energy metrics are particularly important from the manufacturers' perspective [18]. Two-terminal tandem devices with a PK top cell are expected to have high PCE and low cost, but the EPBT and EROI of these devices have yet to be considered.

Previously, our work focused on the environmental impacts of two-terminal tandem devices with PK top cell and how those impacts compared to the single-junction devices [19]. Here, we expand upon that work by developing a detailed study of the EPBT and EROI of these devices. In this study, we complete an energy consumption analysis on PK solar cells for two-terminal tandems with CIGS [8], CZTS [20], and Si [21] bottoms by determining the energy consumption of manufacturing, energy content of materials, EPBT, and EROI. Two-terminal tandem

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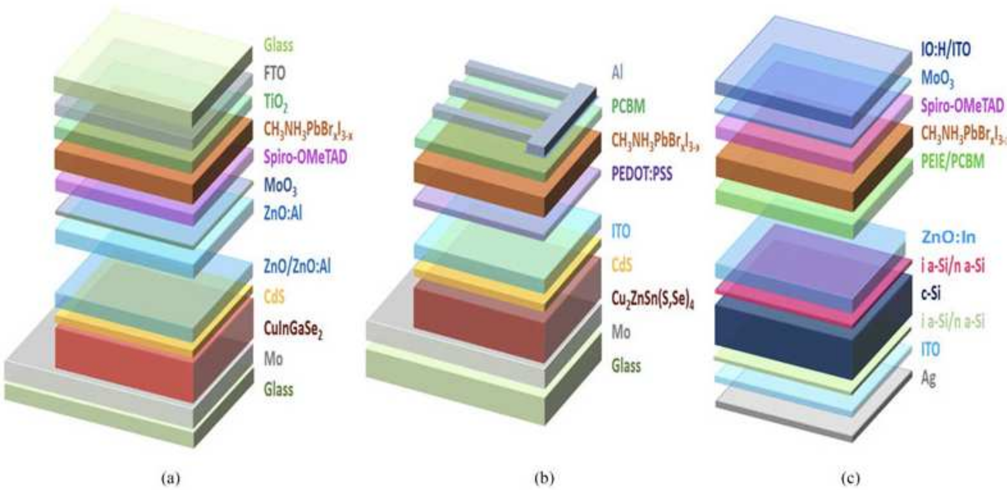

Fig. 1. PK two-terminal tandem solar cell structures. (a) CIGS-PK [8], (b) CZTS-PK [20], and (c) Si-PK [21]. Acronyms used are FTO for SnO_2:F, In_2O_3:SnO_2 for ITO, n a-Si for n-type amorphous Si, and i a-Si for i-type amorphous Si.

cells, undoubtedly, use more materials, and therefore, their manufacturing requires more energy than single-junction cells. The analysis described here was carried out to determine the PCE gains of two-terminal tandem cells required to match the EPBT of single-junction counterparts.

II. Methods

A. Goal and Scope

An "ex-ante" cradle to end-of-use life-cycle assessment (LCA) model was created to compare the potential environmental impacts of laboratory-scale two-terminal tandem solar cells composed of a PK top cell paired with a commercial PV technology, Si, CZTS, and CIGS. The CIGS-PK, CZTS-PK, and Si-PK two-terminal tandem solar cells were modeled by selecting high-efficiency devices presented in the literature, with the reported PCEs of 19.5% [8], 6.0% [20], and 21% [21], respectively. The environmental impacts of the Si-PK, CZTS-PK, and CIGS-PK two-terminal tandem PVs were compared with those of the Si, CZTS, and CIGS commercial single-junction PVs, respectively. These comparisons allow us to determine if the increased PCEs of CIGS-PK, CZTS-PK, and Si-PK two-terminal tandem PV designs compensate for the increased energy and material consumption.

B. Life-Cycle Inventory

The life-cycle inventory was created for manufacturing 1-m^2 CIGS-PK, CZTS-PK, and Si-PK. All the inventories for the layers of the cells were built from the devices reported in the literature [8], [20], [21] and previously reported by the authors [19]. The environmental impact assessment was performed using GaBi 6 [22]. EcoInvent v.3 was used as a database source. The three architectures analyzed are shown in Fig. 1 [23].

C. Calculation of the Energy Payback Time and the Energy Return on Energy Invested

The EPBT is calculated using the following equation:

$$\text{EPBT (year)} = \frac{E_{\text{in}}}{E_{\text{out}}} \tag{1}$$

where E_{in} is the primary energy demand (PED or embedded energy) $(\text{MJ} \cdot \text{m}^{-2})$ of the PV module, and E_{out} is the annual energy generated by the systems $(\text{MJ} \cdot \text{m}^{-2} \cdot \text{year}^{-1})$. The PED involves the energy embedded in the materials of a PV device and the direct processing energy used during the manufacturing of the devices. The PED values are extracted from GaBi once the LCA models of two-terminal tandem cells are created. E_{out} is

$$E_{\text{out}} = I \times \text{PCE} \times \text{PR} \times \varepsilon \tag{2}$$

where I is the solar insolation constant (kWh/m^2·year), PR is the performance ratio of the actual to theoretical energy output of a PV module (%), and ε is the energy-to-electricity conversion efficiency factor.

Here, we used 1700 kWh/m^2·year as the value of I. This value is the solar insolation constant of Southern Europe [24] and is assumed to be an average global insolation value [25]. PCE values for the two-terminal tandem devices were taken from the modeled PV structures (Si-PK (21%) [21], CZTS-PK (6%) [20], and CIGS-PK (19.5%) [8]). We assumed a uniform PR of 75% for these three two-terminal tandem cells [3]. The average energy-to-electricity conversion efficiency was assumed as 31% for the Europe grid [26], which is close to the 29% for the U.S. electricity mix [27], although ε varies depending on the specific grid selected. The electricity inventory for this study was taken from the European Union for the Coordination of the Transmission of Electricity.

The EROI is the ratio of the energy "returned" by an energy system to the energy "invested" to deliver that return [28] and is calculated by

$$\text{EROI} = \frac{\text{Lifetime}}{\text{EPBT}}. \tag{3}$$

III. Results

A. Embedded Energy

The total embedded energies due to direct energy processing and material embedded energies of the three devices are shown in Fig. 2. Note that the direct processing energy corresponds to

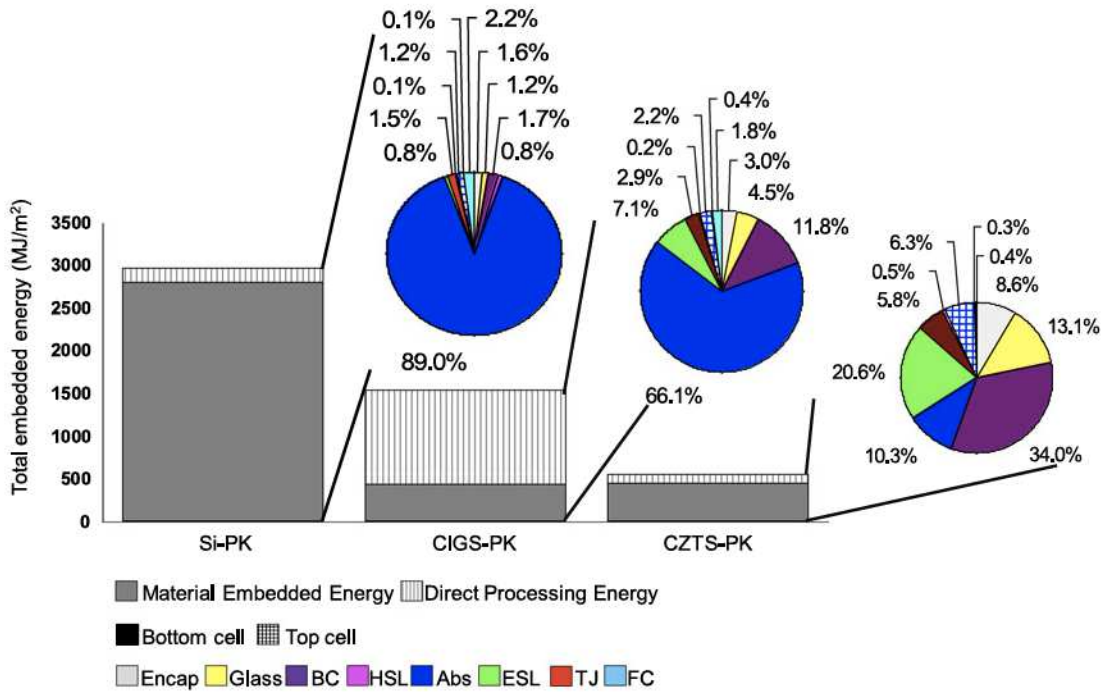

Fig. 2. Embedded energy breakdowns of the two-terminal tandem CIGS-PK (a), CZTS-PK (b), and Si-PK (c) PV cells [19]. FC for front contact, TJ for tunnel junction, ESL for electron-selective layer, Abs for absorber, HSL for hole-selective layer, BC for back contact, and Encap for encapsulation material.

TABLE I
EPBT (MONTHS) OF RECORD SINGLE-JUNCTION AND TWO-TERMINAL TANDEM DEVICES

EPBT	CIGS-PK	CZTS-PK	Si-PK
Bottom cell	5.6	3.4	9.4
Tandem cell	6.4	7.4	11.6

the electricity used during the manufacturing of the PV layers, while material embedded energy includes the energy involved during the material extraction/mining from the environment. Our results show that the total embedded energy of the devices ranges between 549 and 3000 MJ/m^2 [19], with the CZTS-PK cell having the lowest embedded energy content and the Si-PK having the highest energy content.

The Si-PK device has the highest energy content mainly due to the material embedded energy (95%) of the silicon absorber of the bottom cell [19], which requires energy-intensive processing to purify standard-metallurgical-grade silicon to solar grade [29]–[32]. The embedded energy of CIGS-PK is approximately half of the embedded energy of Si-PK. Unlike Si-PK, the direct processing energy (66%) for the CIGS deposition, e.g., high-temperature coevaporation, accounts for the dominant energy requirement of the cells. On the other hand, the direct processing energy of the solution-processed CZTS-PK contributes ~20% of the total embedded energy. The dominant energy consumption values are consistent with the literature [33], [34].

To better understand how the specific layers of the PV devices impact the total embedded energies, the breakdown of the total embedded energy of the two-terminal tandem PV devices is also shown in Fig. 2. Many layers are common to the three devices for the same role, such as front contact, electron-selective layer, hole-selective layer, and back contact. In addition, the materials and thicknesses of the substrate and encapsulation layers are the same for the three devices.

The major differences in the embedded energies between the CZTS-PK, CIGS-PK, and Si-PK were observed in absorber material of the bottom cells. The Si and CIGS absorbers used in the bottom cells of Si-PK and CIGS-PK have a large contribution (70–90%) on the total embedded energy of the devices, since these layers require high-energy-intensive methods for the manufacturing. On the other hand, the impact of the CZTS layer on the total embedded energy of the cell layer is much lower. In our model, the CZTS layer was deposited using a spin coating method for 5 min followed by annealing at 540 °C, consistent with the reference work [20]. Note that solution-based methods such as spin coating, dip coating, spray, and printing (inkjet) have lower energy demand compared with vapor-based deposition techniques [35] used to deposit the CIGS absorber or the high-temperature processing required to purify the silicon. As a result of the solution processing, the CZTS absorber accounts for only 15% of the total embedded energy of CZTS-PK. The most impactful layer in the CZTS-PK cell is the Mo back contact, since the Mo back contact is deposited by energy-intensive sputtering methods and is one of the thickest layers in the PV devices.

B. Energy Payback Time

The EPBT is a key parameter for evaluating the performance of energy sources. The EPBT of the two-terminal and single-junction devices is shown in Table I. The EPBT of the two-terminal tandem devices is longer than that of the single-junction cells. This is expected in this case because the PK tandem device field is still developing and the PCEs are currently low. As the technologies improve, the PCEs of the two-junction tandem

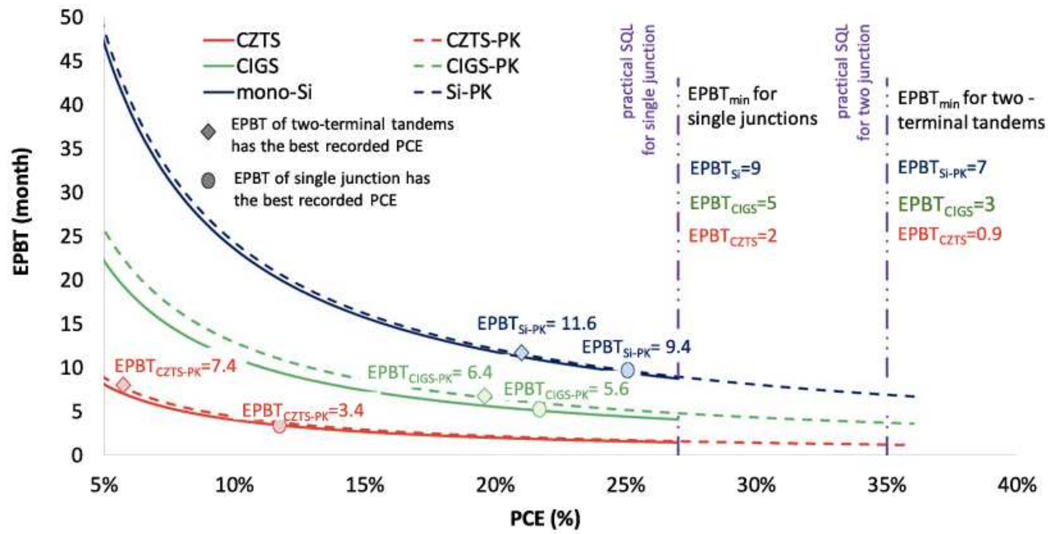

Fig. 3. Illustration of the reciprocal relationship between the EPBT and efficiency. The practical PCE limit for single-junction devices is 27% [8] and 35% for the tandem devices [9]. The EPBT values for devices at these limits are included in the inset tables.

solar cells are expected to approach the theoretical maximums, which will be ∼10% higher than the maximum PCE of the single junction cells [36].

The PCEs of the two-terminal tandem devices were varied to determine how much improvement in the PCE is required for the EPBT to be lower for the tandems than the corresponding single-junction devices. The results are shown in Fig. 3. For any given PCE, the EPBTs of two-terminal tandem devices (dashed lines) are slightly higher than the bottom cells (solid lines). This difference is due to the additional embedded energy from top cells. Two-terminal tandem devices, though, can have equal or shorter EPBTs than their bottom cells if they exceed the bottom cell PCE. For example, current champion cell efficiencies for CIGS, CZTS, and Si are 22.3%, 12.3%, and 25%, respectively. The corresponding EPBTs of these devices are given in Table I and identified in Fig. 3 with the diamonds. Two-terminal tandem devices can have EPBT values in the same range once the PCEs of the CIGS-PK, CZTS-PK, and Si-PK reach 23%, 14%, and 26%, respectively.

Since the practical limit of single-junction devices is ∼27% [8], the minimum EPBTs of Si, CIGS, and CZTS are nine, five, and two months, respectively. For the two-terminal tandem devices to reach the same EPBT, their PCEs would need to improve to 28% for Si-PK, 31% for CIGS-PK, and 29% for CZTS-PK. The practical PCE limit of the two-terminal tandem devices is approximately 35% [9]; therefore, the EPBT limit of these devices can be lower with seven months for Si-PK, three months for CIGS-PK, and 0.9 months for CZTS-PK.

C. Energy Return on Energy Invested

The ERIO was determined to evaluate the net energy return to the society during the lifetime of tandems and compared with other commercial PVs and traditional energy sources (see Table II). To be considered a viable option, an EROI of ∼3 is required [24], [37]. The EROI of the tandem devices varied from 5.2 to 9.2, indicating that even at the low PCEs and modeled lifetimes of the current state-of-the-art tandem devices, they generate enough power to be viable.

TABLE II
EROI OF PV TECHNOLOGIES WITH OTHER ENERGY SOURCES

	PCE (%)	Lifetime (year)	EROI
CIGS-PK	19.5	5	9.2
CZTS-PK	6.0	5	8.1
Si-PK	21.0	5	5.2
CZTS	12.3	30	105
Mono-Si	25.0	30	38.3 [23]
Poly-Si	21.3	30	37.9 [23]
CIGS	23.3	30	67.3 [23]
CdTe	22.1	30	76.1 [23]
Oil-fired thermal	–	40	3.7–10.6 [28]
Coal	–	40	12.2–24.6 [28]

As the PK tandem field advances, both the PCE and device lifetimes are expected to improve. Assuming that the tandem device PCE values improve such that the EPBT of the tandem is equal to that of the state-of-the-art single-junction devices (shown in Table I), 25%, 22.3%, and 12.3% for Si-PK, CIGS-PK, and CZTS-PK, respectively, and the lifetimes remain five years, the EROI will be 6.4, 11.2, and 17.6, respectively. When the lifetime is extended to 30 years, the EROI values increase to 38.4, 64.2, and 105.6. Under these assumptions, PK tandem devices would be the best-performing energy systems in terms of their EROI values.

IV. CONCLUSION

This study has offered an analysis of the energy consumed for the manufacturing of and generated by CIGS-PK, CZTS-PK, and Si-PK two-terminal tandem PVs. The results have shown that the embedded energies of the devices range between 549 and 3000 MJ/m^2. The total embedded energies of CZTS-PK and Si-PK were dominated by the material embedded energy, while that of CIGS-PK was dominated by the direct processing energy.

The lowest energy-intensive tandem PK cell is the solution-processed CZTS-PK, while the highest energy-intensive one is the Si-PK. The EPBT values of CIGS-PK, CZTS-PK, and Si-PK ranged between ~7 months and ~12 months, while the EROI of the cells is in the reverse order as the EPBT and ranged between 5.2 and 9.2. These two energy indicators of tandem devices are expected to improve as the tandem PV technologies mature, with an EBPT as low as ~27 day (0.9 month) and the EROI as high as 105 for high-efficiency long-lifetime devices.

REFERENCES

[1] M. Munsell, "Solar made up 64% of new electric generating capacity in the US in Q1 2016 | Greentech Media," 2016. [Online]. Available: http://www.greentechmedia.com/articles/read/solar-accounted-for-64-of-new-electric-generating-capacity-in-the-us-in-q1

[2] Z. Shahan, "Renewables = 99% of new electricity capacity in Q1 2016 In USA (Cleantechnica Electricity Reports) | Cleantechnica," 2016. [Online]. Available: https://cleantechnica.com/2016/05/31/renewables-99-new-electricity-capacity-q1-2016-usa/

[3] I. Celik, B. E. Mason, A. B. Phillips, M. J. Heben, and D. S. Apul, "Environmental impacts from photovoltaic solar cells made with single walled carbon nanotubes," *Environ. Sci. Technol.*, vol. 51, no. 8, pp. 4722–4732, Feb. 2017.

[4] P. Nema, R. K. Nema, and S. Rangnekar, "A current and future state of art development of hybrid energy system using wind and PV-solar: A review," *Renew. Sustain. Energy Rev.*, vol. 13, no. 8, pp. 2096–2103, Oct. 2009.

[5] IRENA—International Renewable Energy Agency, "Renewable energy technologies: Cost analysis series," 2012.

[6] Z. Song *et al.*, "A technoeconomic analysis of perovskite solar module manufacturing with low-cost materials and techniques," *Energy Environ. Sci.*, vol. 10, no. 6, pp. 1297–1305, 2017.

[7] J. Jean, P. R. Brown, R. L. Jaffe, T. Buonassisi, and V. Bulovic, "Pathways for solar photovoltaics," *Energy Environ. Sci.*, vol. 8, no. 4, pp. 1200–1219, 2015.

[8] L. Kranz, A. Abate, T. Feurer, and F. Fu, "High-efficiency polycrystalline thin film tandem solar cells," *J. Phys. Chem. Lett.*, vol. 6, no. 14, pp. 2676–2681, 2015.

[9] D. McMeekin, G. Sadoughi, and W. Rehman, "A mixed-cation lead mixed-halide perovskite absorber for tandem solar cells," *Science*, vol. 351, no. 6269, pp. 151–155, 2016.

[10] S. Albrecht *et al.*, "Monolithic perovskite/silicon-heterojunction tandem solar cells processed at low temperature," *Energy Environ. Sci.*, vol. 9, no. 1, pp. 81–88, Jan. 2016.

[11] J. P. Mailoa *et al.*, "A 2-terminal perovskite/silicon multijunction solar cell enabled by a silicon tunnel junction," *Appl. Phys. Lett.*, vol. 106, no. 12, Mar. 2015, Art. no. 121105.

[12] F. Fu *et al.*, "Low-temperature-processed efficient semi-transparent planar perovskite solar cells for bifacial and tandem applications," *Nature Commun.*, vol. 6, Nov. 2015, Art. no. 8932.

[13] C. D. Bailie *et al.*, "Semi-transparent perovskite solar cells for tandems with silicon and CIGS," *Energy Environ. Sci.*, vol. 8, no. 3, pp. 956–963, Mar. 2015.

[14] T. Todorov *et al.*, "Monolithic perovskite-CIGS tandem solar cells via in situ band gap engineering," *Adv. Energy Mater.*, vol. 5, no. 23, Dec. 2015, Art. no. 1500799.

[15] C. D. Bailie and M. D. McGehee, "High-efficiency tandem perovskite solar cells," *MRS Bull.*, vol. 40, no. 8, pp. 681–686, Aug. 2015.

[16] C.-W. Chen *et al.*, "Optical properties of organometal halide perovskite thin films and general device structure design rules for perovskite single and tandem solar cells," *J. Mater. Chem. A*, vol. 3, no. 17, pp. 9152–9159, Apr. 2015.

[17] J. Collier, I. Celik, and D. Apul, "Development of a new online learning module on solar energy sustainability," in *Proc. IEEE 43rd Photovoltaic Spec. Conf.*, 2016, pp. 3296–3299.

[18] F. Meneguzzo, R. Ciriminna, L. Albanese, and M. Pagliaro, "The great solar boom: A global perspective into the far reaching impact of an unexpected energy revolution," *Energy Sci. Eng.*, vol. 3, no. 6, pp. 499–509, 2015.

[19] I. Celik *et al.*, "Environmental analysis of perovskites and other relevant solar cell technologies in a tandem configuration," *Energy Environ. Sci.*, vol. 10, no. 1874–1884, 2017.

[20] T. Todorov, T. Gershon, and O. Gunawan, "Perovskite-kesterite monolithic tandem solar cells with high open-circuit voltage," *Appl. Phys. Lett.*, vol. 105, no. 17, 2014, Art. no. 173902.

[21] J. Werner *et al.*, "Efficient monolithic perovskite/silicon tandem solar cell with cell area >1 cm^2," *J. Phys. Chem. Lett.*, vol. 7, no. 1, pp. 161–166, Jan. 2016.

[22] *GaBi Software*, PE International, Stuttgart, Germany, 2013.

[23] G. Wernet *et al.*, "The ecoinvent databae version 3 (part 1): Overview and methodology," *Int. J. Life Cycle Assessment*, vol. 21, no. 9, pp. 1218–1230, 2016.

[24] R. J. E. Khagendra *et al.*, "Energy payback time (EPBT) and energy return on energy invested (EROI) of solar photovoltaic: A systematic review and meta-analysis," *Renew. Sustain. Energy Rev.*, vol. 47, pp. 133–141, 2015.

[25] G. J. Phylipsen and E. A. Alsema, "Environmental life-cycle assessment of multicrystalline silicon solar cell modules," Rep. 95057, Dept. Sci., Technol. Soc., Univ. Utrecht, Utrecht, The Netherlands, 1995.

[26] D. Yue, F. You, and S. B. Darling, "Domestic and overseas manufacturing scenarios of silicon-based photovoltaics: Life cycle energy and environmental comparative analysis," *Sol. Energy*, vol. 105, pp. 669–678, Jul. 2014.

[27] S. B. Darling and F. You, "The case for organic photovoltaics," *RSC Adv.*, vol. 3, pp. 17633–17648, 2013.

[28] M. Raugei *et al.*, "Energy Return on Energy Invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation: A comprehensive response," *Energy Policy*, vol. 102, pp. 377–384, 2017.

[29] A. Meijer, M. A. J. Huijbregts, J. J. Schermer, and L. Reijnders, "Life-cycle assessment of photovoltaic modules: Comparison of mc-Si, InGaP and InGaP/mc-Si solar modules," *Prog. Photovoltaics, Res. Appl.*, vol. 11, no. 4, pp. 275–287, 2003.

[30] F. Ferroni and R. J. Hopkirk, "Energy return on energy invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation," *Energy Policy*, vol. 94, pp. 336–344, 2016.

[31] E. A. Alsema and M. J. de Wild, "Environmental impacts of crystalline silicon photovoltaic module production," *MRS Proc.*, 895, 0895-G03-05, 2005.

[32] I. Celik, Z. Song, M. J. Heben, Y. Yan, and D. S. Apul, "Life cycle toxicity analysis of emerging PV cells," in *Proc. IEEE 43rd Photovoltaic Spec. Conf.*, 2016, pp. 3598–3601.

[33] H. C. Kim, V. Fthenakis, J. K. Choi, and D. E. Turney, "Life cycle greenhouse Gas emissions of thin-film photovoltaic electricity generation: Systematic review and harmonization," *J. Ind. Ecol.*, vol. 16, pp. 110–121, 2012.

[34] E. Leccisi, M. Raugei, and V. Fthenakis, "The energy and environmental performance of ground-mounted photovoltaic systems—A timely update," *Energies*, vol. 9, no. 8, Aug. 2016, Art. no. 622.

[35] I. Celik *et al.*, "Life cycle assessment (LCA) of perovskite PV cells projected from lab to fab," *Sol. Energy Mater. Sol. Cells*, vol. 156, pp. 157–169, 2016.

[36] T. Ameri, N. Li, and C. J. Brabec, "Highly efficient organic tandem solar cells: A follow up review," *Energy Environ. Sci.*, vol. 6, no. 8, pp. 2390–2413, Jul. 2013.

[37] C. A. S. Hall, S. Balogh, and D. J. R. Murphy, "What is the minimum EROI that a sustainable society must have?" *Energies*, vol. 2, no. 1, pp. 25–47, Jan. 2009.

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