Supplementary information
For

Photovoltaic Systems through the Lens of Material-Energy-Water Nexus

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File S1. Material Circularity Index Calculations

The MCI is always greater than 0, given the max function (Equation (S1)), and is penalized when products exhibit short lifetimes and/or poor utility (Equation (S1)). We calculate MCI as [1]:

$$MCI = max\ (0{,}1 - LFI \cdot F(X)) \quad \text{(S1)}$$

$$F(X) = \frac{0.9}{X} \quad \text{(S2)}$$

$$X = \frac{L}{L_{av}} \cdot \frac{U}{U_{av}} \quad \text{(S3)}$$

where a 0.9 is a consequence of the developers of the methodology having chosen fully linear products—i.e., a product made only of virgin materials, and which is not recycled after its use—with average specifications having an MCI of 0.1. As a result, only products with a below-average performance have an 0<MCI<0.1 [1]. In Equation (S3) [1], X is a product advantage/penalty based on the distance to the market average. It consists of two ratios. One is determined by the quotient between the product's longevity (L) and the market average longevity (L_{av}). The other one is the quotient between the number of functional units obtained during the use of the products (U), and the number of functional units obtained from a product that would represent the market average (U_{av}). One of these two ratios is usually considered to be 1. Thus, we assume the product lifetime is equal to the market average (i.e., 25 years). A suitable U to compare PV systems would be the energy generated throughout their lifetimes. Since the PCE is the only parameter affecting the generation of electricity that is different between CdTe and s-Si—Equation (S1) [1]— the ratio of PCEs is equivalent to the ratio of energies generated, all other things being equal. Thus, we selected PCE as U, and used 19.5% as the market average (U_{av}) for PV [2].

The MCI incorporates the linear flow index (LFI), which measures the proportion of materials that flow linearly—i.e., product materials come from virgin materials (V) and end up as unrecoverable waste (W) (Equation (S4)). A product with an LFI=1 is not recycled or reused and does not contain any recycled or reused materials. Products whose LFI=0 would be fully recycled and/or reused, produced exclusively using recycled/reused materials, and generate no waste through their production line [1]. We calculate LFI [1] as:

$$LFI = \frac{V+W}{2M+\frac{W_F-W_C}{2}} \quad \text{(S4)}$$

$$V = M(1 - F_R - F_U) \quad \text{(S5)}$$

where V is the mass of virgin materials needed to produce the PV and its auxiliary materials, which are those used in manufacturing a product that does not end up being part of it (e.g., solvents). M is the mass of the PV and these auxiliaries themselves; W is the total amount of waste, where W_F is the waste generated during the production of recycled feedstock; and W_C is the amount generated during the recycling process [1]. To calculate V, we multiply M by the fraction of recycled feedstock (F_R) and reused sources (F_U) (Equation S6). For s-Si, we assume F_R and F_U are 0, as no recycled or reused material are used in module production. For CdTe we assume F_U is 0 for all materials. F_R is 0 for all materials but the active layer, whose F_R =0.06 [3].

The total amount of waste generated during the production process (W) is estimated as the sum of waste generated from production (W_F), the amount of waste going to landfill and/or incineration (W_O), and waste generated during the recycling process (W_C) [1]. Here, W_F is relevant when including recycled feedstocks, as it is a function of the efficiency of the recycling process (E_F) [1].

$$W = W_F + W_o + W_C \quad \text{(S6)}$$

$$W_F = M\frac{(1-E_F)\cdot F_R}{E_F} \quad \text{(S7)}$$

The waste generated during the recycling process (W_C), is the difference between M and the product of the fraction of used materials recycled (C_R) and the efficiency of the recycling process (E_C) (Equation (S8)) [1]. In this study, E_C=E_F is when the recycled materials can be used as recycled feedstock in the same production line. Finally, W_O is the amount of waste going to landfills and/or incineration, as they are indistinguishable in MCI terms, and C_U is the fraction of material that can be reused. We estimate W_C and W_0 [1] as:

$$W_C = M(1 - E_C)C_R \quad \text{(S8)}$$

$$W_0 = M(1 - C_R - C_U) \quad \text{(S9)}$$

and assume all waste goes to recycling, so therefore C_R=1 and C_U=0.

Table S1 Linear Flow Index for the different modules, and data required for its calculation.

	M (kg)	V (kg)	F_R	F_U	E_F	W_F (kg)	C_r	C_u	W_0 (kg)	EC	WC (kg)	W(kg)	LFI
CdTe													
CdTe	0.02	0.02	0	0	0	0	1.00	0	0.00	0.95	0.00	0.00	0.52
Cu	0.00	0.00	0	0	0	0	1.00	0	0.00	1.00	0.00	0.00	0.50
Steel	0.01	0.01	0	0	0	0	1.00	0	0.00	0.90	0.00	0.00	0.56
Al	1.69	1.69	0	0	0	0	1.00	0	0.00	1.00	0.00	0.00	0.50
EVA	0.39	0.39	0	0	0	0	0.00	0	0.39	0.00	0.00	0.39	1.00
Glass	12.59	12.59	0	0	0	0	1.00	0	0.00	0.90	1.26	1.26	0.56
Reinforced plastic	0.11	0.11	0	0	0	0	1.00	0	0.00	1.00	0.00	0.00	0.50
Auxiliary materials	0.47	0.47	0	0	0	0	0.00	0	0.47	0.00	0.00	0.47	1.00
Total	15.30	15.30	0	0	0	0	0.94	0	0.87	0.86	1.26	2.13	0.58
s-Si													
Al	2.13	2.13	0	0	0	0	1.00	0	0.00	0.95	0.11	0.05	0.52
Cu	0.10	0.10	0	0	0	0	1.00	0	0.00	0.97	0.00	0.00	0.52
Si	0.54	0.54	0	0	0	0	1.00	0	0.00	0.95	0.03	0.03	0.53
Pb	0.00	0.00	0	0	0	0	1.00	0	0.00	0.96	0.00	0.00	0.53
Sn	0.01	0.01	0	0	0	0	1.00	0	0.00	0.32	0.01	0.01	1.01
EVA	0.88	0.88	0	0	0	0	0.00	0	0.88	0.00	0.00	0.88	1.00
Glass	8.81	8.81	0	0	0	0	1.00	0	0.00	0.88	1.04	1.04	0.58
Corrugated board	0.76	0.76	0	0	0	0	0.00	0	0.76	1.00	0.00	0.76	1.00
Reinforced plastic	0.30	0.30	0	0	0	0	0.00	0	0.30	0.00	0.00	0.30	1.00
Auxiliary materials	0.06	0.06	0	0	0	0	0.00	0	0.06	0.00	0.00	0.06	1.00
Total	13.59	13.59	0	0	0	0	0.85	0	2.00	0.83	1.19	3.13	0.63

M’, mass of the finished product and its auxiliary materials, V’ mass of virgin materials, FR fraction of feedstock derived from recycled sources, FU fraction of feedstock from reused sources, EF efficiency of the recycling process used to produce the recycled feedstock, W'_F waste generated during the production of recycled feedstock, C_r fraction collected for recycling, C_u the fraction going into component reuse, W'_0 amount of waste going to landfill/energy recovery, EC the efficiency of the recycling process, WC waste generated during the recycling process, W' overall amount of unrecovered waste, LFI' Linear flow Index.

Table S2 Material circularity index I for the different PV modules and data required for their calculation.
LFI' Linear flow index, L lifetime of the product, market average lifetime of the product, number of functional units, market average number of functional units, X utility, F(X) utility factor, MCI'_P Material Circularity Index

	LFI	L	L_{av}	U	U_{av}	X	F(X)	MCI
CdTe	0.58	25	25	22.1	19.5	1.13	0.79	0.54
s-Si	0.63	25	25	23.3	19.5	1.19	0.75	0.53

References

1. Ellen MacArthur Foundation *Circularity Indicators: An Approach to Measuring Circularity: Methodology*; 2015; Vol. 23;.
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