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

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Abstract: Solar photovoltaics (PV) has emerged as one of the world's most promising power-generation technologies, and it is essential to assess its applications from the perspective of a material-energy-water (MEW) nexus. We performed a life cycle assessment of the cradle-to-grave MEW for single-crystalline silicon (s-Si) and CdTe PV technologies by assuming both PV systems are recycled at end of life. We found that the MEW network was dominated by energy flows (>95%), while only minor impacts of materials and water flows were observed. Also, these MEW flows have pyramid-like distributions between the three tiers (i.e., primary, secondary/sub-secondary, and tertiary levels), with greater flows at the primary and lower flows at the tertiary levels. A more detailed analysis of materials' circularity showed that glass layers are the most impactful component of recycling due to their considerable weight in both technologies. Our analysis also emphasized the positive impacts that increased power-conversion efficiency and the use of recycled feedstock have on the PV industry's circularity rates. We found that a 25% increase in power-conversion efficiency and the use of fully recycled materials in PV panel feedstocks resulted in 91% and 86% material circularity for CdTe and s-Si PV systems, respectively.

Keywords: material-energy-water nexus; photovoltaics; PV MEW; CdTe; crystalline silicon PV

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1. Introduction

Solar photovoltaics (PV) are expected to be one of the primary energy technologies for creating a reduced carbon, pollution-free power sector [1,2] due to their competitiveness in generating electricity at low cost [3–6]. Between 2010 and 2020, the cost of electricity from PV modules dropped ~90% from ~$2/watt to $0.21/watt, while installment capacities increased from 39 GW to 760 GW globally [7]. While the adoption of PV will continue to increase, it is crucial to understand the interrelationships of solar PV systems from the perspective of cradle-to-grave materials, energy, and water (MEW) [8–10]. More so, reducing resource extractions and energy demand is essential to sustainable PV technology and promoting a circular economy.

Several methodologies have been adopted to advance our knowledge of PV's MEW consumption and interrelationships. Life cycle assessment (LCA), which includes the emissions, consumption, and waste from process-based operations over a module's life cycle, is the most common approach [11–15]. LCA methodology is a process-based approach that includes the analysis of cradle-to-grave life cycle stages such as raw material extraction, manufacturing, distribution/transportation, use, and disposal/recycling [13]. Commonly, the system boundaries of PV LCA studies consist of life cycle phases from raw material extraction to end of use, i.e., cradle to end of use. This is primarily a result of uncertainty regarding the end-of-life management of PV modules since large volumes of PV waste have not yet been generated [16,17]. In particular, the LCA approach integrates knowledge of the environmental impacts of generating electricity using PV systems, and 1 kWh net electricity generation is a commonly used functional unit in PV LCA studies [18,19]. LCA studies indicate that the energy footprints of PV modules vary by technology [20,21] but are dominated by the processes associated with the extraction and purification of materials [22–24]. As such, PV systems are more water-efficient than other forms of power production, including coal, nuclear, biomass, etc. [25]. A second approach to assessing MEW flows of PV systems is through a network-analysis approach, which captures the interdependencies and connections within various ecological and engineered systems across the life cycle [26,27]. However, interactions of PV systems through the lens of MEW remain rare. Notably, energy and water lost in energy production systems ignore the impacts of a material's end-of-life (EoL) management [28]. To address this, material circularity assessments have been employed to develop circular economy concepts that include PV waste and increase the circularity of PV systems [29,30]. Here, new metrics for effectively circulating material flows from EoL to the manufacturing phase are central to minimizing waste and recovering more valuable materials of secondary PV modules in order to offset cost and reduce associated environmental impacts [30–32].

In this work, we combine multiple approaches to deepen our understanding of the circular economy of PV systems and employ accounting approaches at EoL to investigate MEW flow interactions. We selected single-crystalline silicon (s-Si) and CdTe PV technologies for our assessment, as these solar technologies represent ~70% of the global PV market [33]. We constructed a MEW network matrix for these PV systems and performed cradle-to-grave life cycle inventories for the two PV technologies. We adopted a network-analysis approach and assigned each life cycle phase to a trophic level similar to a food web in ecology [34]. We further analyzed MEW flows and, in particular, focused on material flows at the EoL. To identify the material circularity limits of the PV industry, we further investigated the effect of power-conversion efficiency, the amount of recycled/reused feedstock, and their combined effects. We calculated the material circularity scores for CdTe and s-Si industries with the material circularity index to evaluate the strength of the material flows' restorative or linear capacity and to identify potential bottlenecks that hinder its circularity [35]. To our knowledge, this work is the first study that applies both LCA and network analysis approaches combined with material circularity metric calculation in the context of MEW assessment for the PV industry. Particularly, this work addresses the often-overlooked EoL stage essential to minimizing the waste and costs of secondary PV modules.

2. Methods

2.1. Data

We created cradle-to-grave environmental impact assessment models for both s-Si and CdTe PV modules that incorporate the MEW requirements in each life cycle phase. We broadly split the life cycle phases into: (1) cradle to gate, consisting of sourcing, manufacturing, and all associated transportation inventories; (2) gate to use, consisting of the operation of modules and the electricity generated; and (3) EoL, consisting of recovery, recycling, landfill/incineration, and wastewater treatment. We modeled the manufacturing of 1 m^2 PV panels [36] using GaBi software (version 10) [37] and the ecoinvent database (version 3.6) [38].

Six inventories have been included within the three cradle-to-gate, gate-to-use, and EoL phases (Table 1). For the cradle-to-gate phase, we included primary data on PV technologies from the most recent report of the International Energy Agency (IEA) [36], which includes manufacturing inputs and outputs of s-Si and CdTe panels. For the gate-to-use phase, we incorporated the inventories to model the electricity generated during the lifetime of PV systems. For the EoL phase, we modeled the MEW flows, assuming both technologies are recovered and recycled to the quality of manufacturing inputs, which is PV technology dependent. Transportation during EoL is assumed to be consistent between the technologies and is modeled using methods proposed by Latunussa et al. (2016) with transportation distances from Markert et al. (2020) [39,40].

Table 1. Life cycle assessment phases for s-Si and CdTe PV panels, including cradle-to-gate, gate-to-use, EoL, and their corresponding inventories, inputs, and outputs integrated for MEW flows.

Phase	Inventories	Inputs	Outputs
Cradle-to-gate	Solar panel production (manufacturing)	Material components, auxiliary chemicals, electricity, other energy sources, water, fuel	PV panel, manufacturing material waste, manufacturing wastewater, consumed energy, evaporated water
Gate-to-use	Solar industry, electricity grid	PV panels, solar energy	Electricity to the grid
EoL	Recovery	Auxiliary chemicals, PV panels, electricity, water, fuel	Recovered materials, recovered material waste, recovered wastewater, consumed energy
	Recycling	Recovered materials, electricity	Recycled materials, recycling material waste, consumed energy
	Landfill/incineration (hazardous and municipal)	Manufacturing material waste, recovery material waste, recycling material waste, electricity, fuel	Dissipated energy
	Wastewater treatment	Manufacturing wastewater, recovery wastewater, electricity	Clean water, consumed energy, evaporated water

The secondary data for modeling s-Si and CdTe PV technologies were collected from the literature. For s-Si recycling, we followed the pilot-scale full-recovery EoL photovoltaic process [39] and its subsequent metal-refining processes [41]. In this approach, 95% metallurgical-grade silicon is recovered. The glass recovery efficiency is 98%, and the recycling one is 90%, for a combined efficiency of 88% [39,41]. Copper and aluminum are fully recycled and refined with a 97% and 95% efficiency [39,41]. Lead and tin are recovered with 97% and 32% yield efficiency, respectively [39,41]. The glass fiber-reinforced plastic (i.e., junction box) is not recycled, and the ethyl–vinyl acetate is incinerated [39]. Considering the aforementioned materials' mass, 83.73% of the s-Si module is recycled [39,41]. We modeled cradle-to-gate CdTe data based on the work of Frischknecht et al. (2020) [36] and its recycling process based on Sinha et al. (2012) [42]. The recovery efficiency for CdTe's semiconductor is 95%, and the recycling one is 97%, for a combined efficiency of 92.5% [42]. The recovery efficiency of glass and the frame's chromium steel is 90% [42,43]. We assumed copper, aluminum, and reinforced plastic could be 100% recovered and recycled. The discrepancy between reinforced plastic recovery and recyclability is due to different methods being used between the two technologies. Thus, the combined efficiency weighted on a mass basis for CdTe is 86%. The wastewater sent to treatment is modeled by an assumed-treatment efficiency of 90%, and the associated electricity required per treatment of liquid sewage is extracted from the literature [44] (0.61 kWh per m^3). The electricity required for incineration, municipal landfill, and hazardous landfill is assumed to be 1 kWh/kg waste [45].

2.2. Network Approach

We followed the ecological network-analysis approach to create a MEW network of PV systems by assigning each life cycle phase to a trophic level, where flows of MEW between and within life cycle phases are modeled after a food web [34] (Figure 1). This framework highlights the dependency that the two PV technologies have on the system's nested industries and the differences between required MEW flows. To compare MEW flows between PV technologies, we normalized data in embedded energy values (i.e., their PED values). Finally, all the PED values of MEW models were normalized for 1 kWh of electricity generation following Equation (1) [46]:

$$PED_{kWh} = \frac{PED_{m^2}}{l \cdot PCE \cdot PR \cdot LT} \tag{1}$$

where l is the solar insolation constant (kWh m^{-2} yr^{-1}), PCE stands for power-conversion efficiency, PR is the performance ratio of actual to the theoretical-energy output of a PV module (%), and LT is the lifetime of the PV panels. Here, we used 1700 kWh m^{-2} yr^{-1} as the value of l, which represents the solar-insolation constant of Southern Europe [23], commonly used as the average global insolation value [47]. The PCE values of s-Si and CdTe are 23.3% and 22.1%, respectively [48]. We assumed a uniform and conservative PR value of 75%, consistent with rooftop installation [49], and a lifetime of 25 years, consistent with First Solar's panel warranty, for both PV technologies [23].

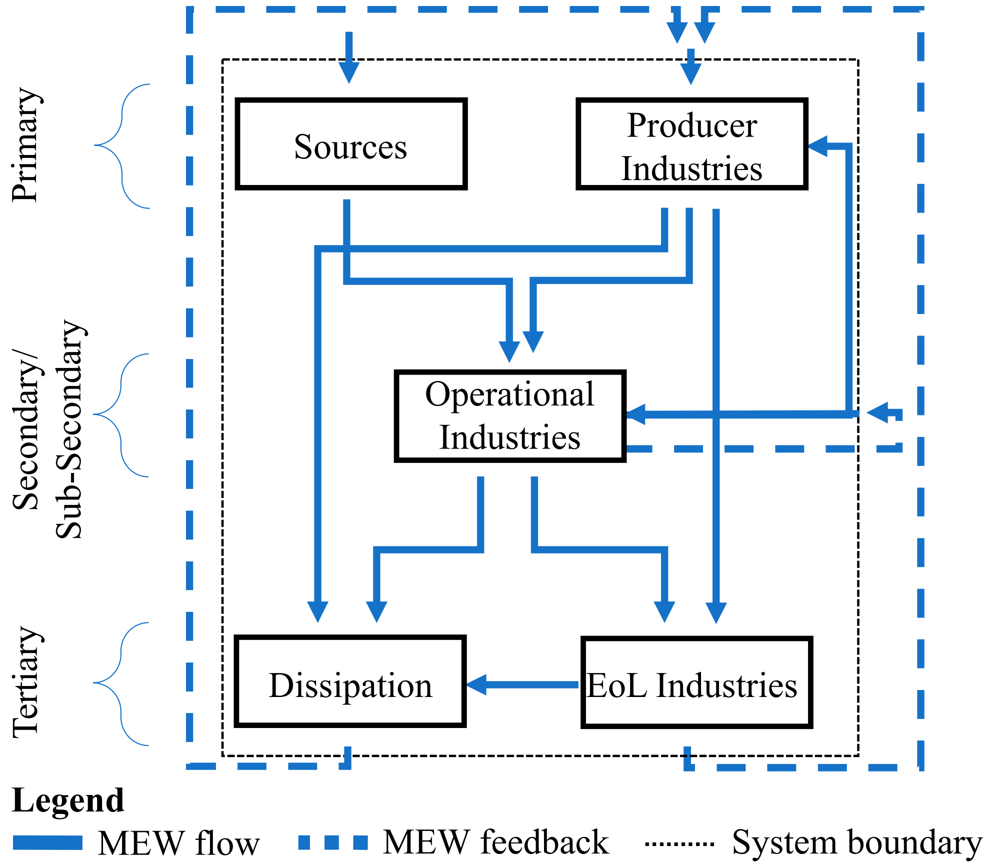

Figure 1. Network approach for the MEW interactions over the lifetime of PV technology. Three tiers in the life cycle include primary, secondary/sub-secondary, and tertiary, representing the ecological network or producers (Sources, Producer Industries), consumers (Operational Industries), and carnivores/detritivores (Dissipation, EoL Industries), respectively. Solid lines indicate MEW throughflow, dashed lines indicate MEW feedback and dotted lines show the life cycle assessment (LCA) of the system boundary.

Figure 1 shows our framework for creating the MEW network of the solar PV industry. Each MEW flow is considered as an input and output to another node. The primary trophic level (i.e., plants and herbivores) contains the sources and producer–industries nodes. The majority of MEW flows are generated from solar radiation and attributed to the source node. The producer-industries node represents the cradle-to-gate phase and is associated with the fuel, water, panel materials, auxiliary chemicals, and solar panel production industries.

Similarly, the secondary/sub-secondary trophic level (i.e., omnivores) containing the gate-to-end-of-use phase is characterized by the operational industries (i.e., the solar industry and the electricity grid), which can expand into multiple levels depending on operational complexity. The solar industry receives MEW inputs from the source node (i.e., solar radiation) and the producer industries (e.g., solar panel production), and it outputs electricity and unused solar (i.e., dissipation). As electricity flows from the solar industry to the grid, the grid is treated as a sub-secondary trophic level. Electricity generated from solar energy can be fed back as an input to the solar industry, measured as MEW feedback efficiency. The amount of dissipated, unused solar energy depends on the module's PCE. We assume the module reaches end of use after 25 years and is sent to the EoL industries (i.e., water and waste treatment industries).

Lastly, the tertiary trophic level includes carnivores and detritivores representing the EoL industry and dissipation. In this trophic level, MEW flows can give feedback to the producer industries to determine the MEW feedback efficiency. The EoL industries node has two major streams: flows for treatment for reuse (i.e., recovery, recycling, and wastewater treatment) and flows for waste management (i.e., landfill/incineration and hazardous landfill). In this study, we assume all used materials (i.e., recovered silicon potential for lithium battery anodes [50]) stay within the system rather than are sold, traded, or used in outside systems, so additional purification is accounted for. The dissipation node is the cumulative dissipation from each trophic level and includes unused solar, evaporated water, and consumed energy.

2.3. Material Circularity Analysis

To fully scrutinize the PV system networks from a material perspective, we further explored the circularity potentials of the PV industry. We calculated the material circularity rates for CdTe and s-Si industries, following the material circularity index (MCI) method. MCI evaluates how restorative or linear the material flows of an industry and identifies potential bottlenecks that hinder its circularity [35]. The MCI analysis considers all materials used as equally relevant, meaning MCI does not distinguish between highly valuable materials (e.g., silver) and less economically significant ones (e.g., cardboard), as done in LCA with economic allocation [35]. The steps of MCI calculations are provided in the Supplementary Materials.

We developed alternative scenarios to better interpret the MCI metric. The scenarios developed (shown in Table 2) represent the stages in the development of technology (e.g., power conversion efficiency—PCE) and circular economy (e.g., the recycled feedstock rates) or their combination. We developed an initial scenario where all panels were collected and sent to recycling. Recycling efficiencies vary by technologies and materials; we drew from the literature for these estimates [39,41]. To better demonstrate the limits of MCI in the solar industry, we assessed the impact of fully closed-loop scenarios [51,52]. We note that a limitation of the MCI analysis is the assumption that PV panels will be recycled in the EoL. This assumption is a result of there being inadequate data regarding the recycling rates of PV panels since large volumes of PV waste have not yet been generated [53].

Table 2. Additional scenarios for calculating the material circularity index; PCE is a scenario of power-conversion efficiency increase, and V_{50} and $V_{0\%}$ are feedstock scenarios. These scenarios are also considered for their combinations, including (1) $V_{50\%}$ + PCE and (3) $V_{0\%}$ + PCE.

Scenario	Definition	Comparison with Baseline MCI
PCE	Power conversion efficiency is increased by 25%	The PCE of both modules increased by 25% (29.13% for s-Si and 27.63% for CdTe), while the market average remained at 19.5%
$V_{50\%}$	Material used is 50% virgin material	Increase 50% of feedstock from virgin materials, instead of 0%, while the remaining 50% comes from recycled materials
$V_{0\%}$	Closed loop system, 100% recycled (0% virgin)	Assumes all recovered and recycled waste is reusable as feedstock

3. Results and Discussion

3.1. Material-Energy-Water Flows of PV Network

Figure 2 shows the MEW flows of CdTe and s-Si PV technologies at primary, secondary/sub-secondary, and tertiary levels, which represents cradle-to-gate, gate-to-end-of-use, and EoL phases, respectively. All three levels of the MEW network are dominated >95% by energy flows (e.g., in the form of incoming solar light, electricity generated, or unused sunlight), while the minor impact of materials and water flows are observed in the primary and tertiary levels (e.g., consumed or recycled PV materials and consumed or PV materials' embedded water). Also, the MEW flows have pyramid-like distributions between the three tiers, with higher amounts of flows at the primary level and lower levels of flows at the tertiary level. This structure represents the flow distributions of resilient ecological systems [54].

Our MEW network analysis of the three trophic stages of the systems reveals three outcomes. First, when all ecological and industry-related MEW flows are considered, energy flows due to incoming solar radiation at the primary stage and unused solar energy at the tertiary stage have important impacts on the trophic structure of solar PV technologies. The unused and consequently dissipated solar energy at the tertiary level indicates a significant loss in the systems, which is essentially a result of the thermodynamic PCE limits of solar PV systems [55]. Since sunlight is a renewable resource, the systems' losses do not adversely impact the environment. Similar results were also noted in an ecological network assessment of wind power systems [56]. Second, even though the recycling rates are high in the PV industry, EoL industries treat only ~10% of the total flows while the remaining dissipate (i.e., consumed/unused energy or evaporated water). Regarding tertiary-level EoL industries and recycling rates, 58% and 82% of the CdTe and s-Si MEW flows from the primary to the tertial level, respectively. This indicates that EoL management can be less MEW-intensive than production if we assume all materials and water can be recycled and used again in the production cycle. Third, the MEW feedback ratios within the operational (secondary and sub-secondary), EoL and producer, and dissipation and producer stages showed that the greatest feedback comes from the operational-stage industries, which produce ~36 times their required input (i.e., electricity needed within the system). Accordingly, our results indicate that CdTe is slightly more efficient than s-Si in feeding back MEW flows, e.g., it requires less energy to generate electricity than s-Si PV technologies.

We further analyzed the MEW flows of CdTe and s-Si PV systems by comparing our results with the literature studies. A comparison underlines the following similarities: (1) large amounts of MEW flows are dissipated in the energy-production system [27,57]; (2) the recycling scenario at the EoL of the system has a low MEW-flows impact [56]; and (3) similar to wind power systems, the pyramid MEW-flow network structure indicates the dependence of the systems on flows from the external environment [56]. However, we also noted that the inverted pyramid structures were identified in MEW flows of various systems, including in the literature [26,57–60], power generation, industrial eco-parks, cities, etc. The inverted pyramid MEW flows indicates an imperfect hierarchy where a consumer industry is inefficient in transferring energy from one component to another, which is overrepresented in MEW-flows structures [27].

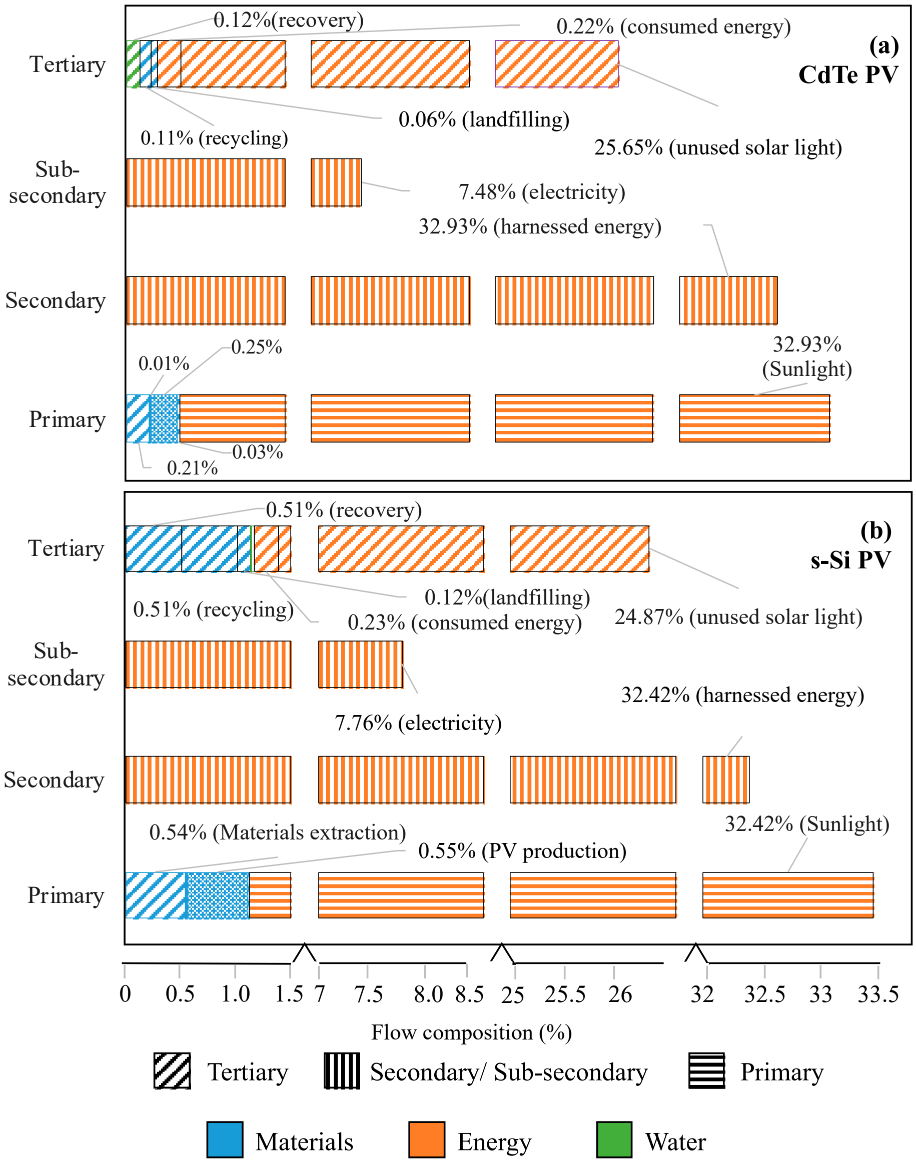

Figure 2. MEW flow of the CdTe (**a**) and s-Si (**b**) PV technology. The trophic characteristics are shown for their percentage of the total inflow in each industry.

3.2. Material Circularity Indicator

Figure 3a shows the MCI values of s-Si and CdTe PV technologies as 0.53 and 0.52, respectively. The MCI values represent the current recycling rates of today's PV market, and they are mostly driven by the recycled glass and Al used in both technologies. The glass represents the largest fraction by mass—82% for CdTe and 64% for s-Si and has a high recycling rate in the two systems (90% for CdTe PVs and 88% for s-Si PVs). Of secondary importance, Al constitutes 11% and 16% of CdTe and s-Si, respectively, and it can be completely recycled at the EoL phase for both technologies. For s-Si PV modules, cells, corrugated board, and reinforced plastic (i.e., junction boxes) have smaller contributions. In the case of CdTe, the contributions of the CdTe cells, steel, lead, and tin are minimal. These results highlight that even with the high recycling rates of the major mass components of the PV systems, high circularity scores cannot be achieved. Therefore, scenarios in addition to PV materials' recycling rates at the EoL need to be examined.

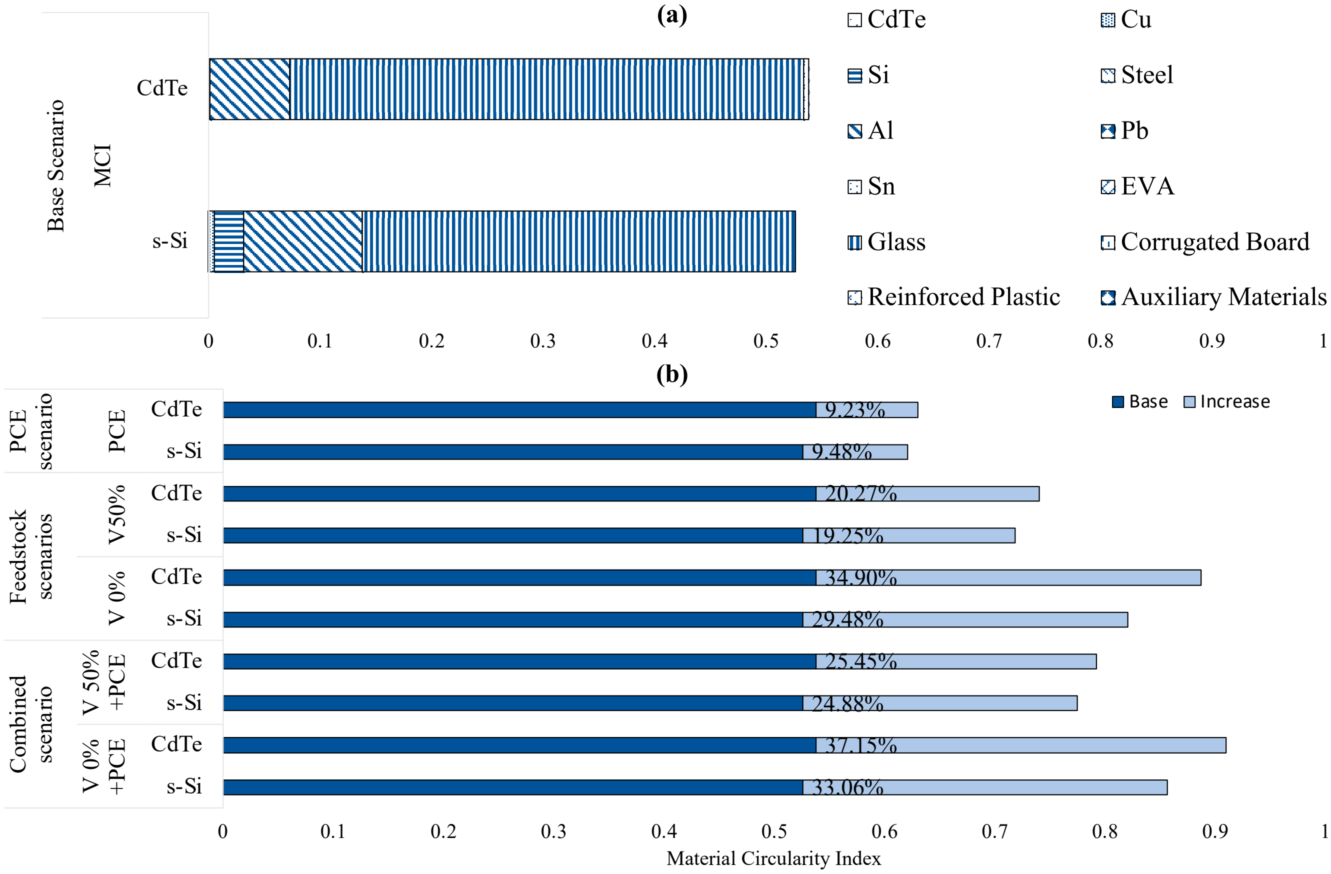

Figure 3. MCIs of CdTe and s-Si solar panels: (**a**) the impact of each PV component to the MCI metric, and (**b**) the impact of alternative scenarios, including the changed in PCE, virgin feedstock rates and their combinations on MCI metric. The increment (%) for each scenario is also shown with transparent bars in (**b**).

Figure 3b shows the impact of the various scenarios developed in identifying the MCI limits for the solar industry. First, an increase in PCE by 25% will lead to a ~10% increase over the MCI of the base scenario for both technologies. Second, using 50% and fully recycled stock in manufacturing PV panels, the MCI of s-Si and CdTe PV systems increased to ~20% (for 50% recycled) and ~35% (for 50% recycled), respectively. We also noted that increased recycled feedstock resulted in larger benefits for CdTe PV's MCI values. This is a direct consequence of its higher average recycling rate and the fact that CdTe PVs have fewer components that are not recycled. Lastly, we combined scenarios for the increases in PCE and recycled feedstock rates. Our results show that the maximum MCI values that can be achieved for CdTe and s-Si are 91% and 86%, respectively. We note that these results are consistent with the literature. Recently, Zubas et al. analyzed the MCI scores of polycrystalline silicon PV technology. Similar to our study, the MCI score was found to be 0.54 [61], and the researchers emphasized that the closed-loop process (e.g., $V_{0\%}$ scenario) offers the potential to improve the MCI score up to 86%.

It is also worth noting that, unlike some other circularity indicators [62], the MCI method gives not only a measure of the recycling activities involved in the system but also a measure of the increased renewable share in materials and other performance criteria (efficiency, longevity, utility, etc.) of the products. However, it falls short in considering the impact of the monetary value of the recovered materials. Therefore, MCI results do not highlight the impact of valuable materials' recovery, i.e., silver, indium, etc., unlike some assessments in the literature [63]. Thus, the MCI assessment complements the material circularity assessment (i.e., the M in MEW) for PV systems by emphasizing potential opportunities in increased PCE or lifetime values and feedstock values, e.g., the impact of using recycled Al, plastics, and glass in manufacturing solar PV systems. A similar optimization index, the division algorithm adopted from energy management and microgrid literature, may support future work, as it has the potential to estimate cost-effectiveness as well as environmental impacts [64].

4. Conclusions

This work investigates the cradle-to-grave MEW interactions of the s-Si and CdTe PV technologies, assuming both PV systems are recycled at EoL. All three levels of the MEW network are dominated by energy flows (e.g., in the form of incoming solar light, electricity generated, or unused sunlight), while the minor impact of materials and water flows are observed in the primary and tertiary levels (e.g., consumed or recycled PV materials and consumed or PV materials' embedded water). Also, the MEW flows have pyramid-like distributions between the three tiers. Higher amounts of flows occurred at the primary level, while lower amounts occurred at the tertiary level. A more detailed analysis of materials' circularity showed that glass layers are the most impactful component to recycle due to their considerable weight in both technologies. Our analysis also emphasized the positive impacts of increases in power-conversion efficiency and the use of recycled feedstock on the circularity rates of the PV industry. While this work addresses the EoL and MEW circularity within a recycling framework, future directions may consider applying new metrics to evaluate the cost-effectiveness using PV industry case studies to further our understanding of MEW circularity in applied systems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16073174/s1, File S1: Material Circularity Index Calculations; Table S1: Linear Flow Index for the different modules, and data required for its calculation; Table S2: Material circularity index I for the different PV modules and data required for their calculation. References [35,42,65] are cited in the supplementary materials.

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Data Availability Statement: Data is available upon a reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Abbreviation	Description
EoL	End-of-life
LCA	Life cycle assessment
MCI	Material circularity index
MEW	Material, energy, water
PED	Primary energy demand
PCE	Power-conversion efficiency
PV	Photovoltaic
V_{50}	Material used is 50% virgin material.
V_0	Material used is 0% virgin material, fully closed loop system.

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