Open and closed-loop recycling of End-of-Life PV: An analysis from a circular economy perspective

Emily Ruth Suyanto, Massoud Sofi, Elisa Lumantarna, Lu Aye*

Renewable Energy and Energy Efficiency Group, Department of Infrastructure Engineering, Faculty of Engineering and Information Technology, The University of Melbourne, Victoria 3010, Australia

Introduction

End-of-life (EoL) solar photovoltaic panel (PVP) recycling has undergone significant technological development in recent decades. Initially, recycling of EoL PVP prioritised mass-based bulk material recovery. Later, focus has been shifted to high-purity value-based recovery by more elaborate recycling technologies to reclaim secondary constituents such as silicon and silver. Recycling of EoL PVP has been an open loop, which follows the conventional linear economy model (Contreras-Lisperguer et al., 2020). In this model, material flow is linear from extraction, manufacturing, to waste disposal in a landfill and it is named cradle-to-grave (McDonough & Braungart, 2002). Large scale closed-loop recycling of EoL PVP is not yet technically and financially viable. It is mainly due to low purity of secondary materials recovered, lack of scalability and profitability of the existing processes, and unreliability of waste feedstock availability because of the longevity of the product (Deng et al., 2019; Tao et al., 2020). The aim of this work is to analyse three simplified life cycle impact-derived parameters on material circularity indicator (MCI). And to use the result to compare open and closed-loop recycling of EoL crystalline silicon-based PVP.

Methods

Three recycling technology scenarios are compared for open-loop and closed-loop recycling. Simple recycling is a purely mechanical separation combined with incineration and landfill which recovers 86% of overall waste by mass (Latunussa C et al., 2016a). Full Recovery End-of-Life Photovoltaics (FRELP) is a combination of mechanical, thermal, and chemical process which can recover silver and other trace constituents (SASIL Srl, 2014). It recovers 90% of recoverable materials. Modified FRELP, which focuses on high purity silicon rather than silver, recovers close to 89% overall waste. The analysis focuses on some key recoverable materials, as stated in Table 1.

A comprehensive (material-by-material) approach to Material Circularity Indicator (MCI) (Eq. 1-3) (Ellen MacArthur Foundation, 2019) is deployed for functional unit (FU) of 1000 kg of recycled crystalline-silicon based EoL PVP. Input data for PVP composition are taken from Latunussa C et al. (2016a). Financial and energy data and technical details of recycling technologies analysed may be found in Suyanto et al. (2023).

$MCI\ =\ 1 - LFI \times F(X)$ where ($Fully\ restorative\ MCI = 1,\ fully\ linear\ MCI = 0$) Eq. (1)

$Linear\ Flow\ Index\ LFI = \frac{V+W}{2M+\frac{Wf-Wc}{2}}$; $Utility\ Factor\ F(X) = \frac{0.9}{\frac{L\quad U}{LavUav}}$ Eq. (2) and (3)

$V = mass\ of\ virgin\ material;\ W =\ total\ waste;\ M = mass\ of\ product;\ Wf = waste\ from\ processing\ recycled\ content\ ; Wc = waste\ from\ recycling;\ L = lifetime;\ Lav = industry\ average\ lifetime; U = use; Uav = industry\ average\ use;\ F_R = fraction\ of\ recycled\ content;\ E_c = efficiency\ of\ recycling;\ E_f = efficiency\ of\ recycled\ material\ processing.$

In this work, recycling is the only circular economy strategy considered. EoL PVPs are collected for recycling and no landfill (i.e. $C_r = 1$). In open-loop recycling, PVP uses 100% virgin material input. In closed-loop recycling, everything recovered through recycling is used to replace virgin materials in new PVP production (i.e. $E_C = E_F$).

Literature suggests that up to 90% of recovered materials from state-of-the-art recycling technology such as FRELP can be re-injected into new PVPs (Fthenakis, 2000; Latunussa et al., 2016b; Maceno et al., 2022). Hence, closed-loop recycled content for all materials is assumed to

---

*Corresponding author. Email address: lua@unimelb.edu.au (Lu Aye).

be $F_R = 0.9E_C$. Lifetime is assumed to remain the same as the industry average despite recycled content, i.e. $X = \frac{L}{L_{av}} = 1$.

The original MCI does not consider that different material composition has lower economic value and embodied energy. MCI guideline allows further refinement to the original equations. Three allocation factors are selected to account for the original MCI's bias towards mass-based recovery. They weigh each material's contribution to circular economy performance based on mass, financial, and energy proportion in the recycling of 1000 kg PVP.

Mass-based allocation acts as the base case.

$$\alpha_x = \frac{Quantity\ of\ material\ x\ in\ FU\ (kg)}{Total\ \ material\ recovery\ quantity\ in\ FU\ (kg)} \qquad \text{Eq. (4)}$$

Economic allocation factor β_x represents the actual revenue from secondary material x resale in each recycling scenario compared to total possible resale revenue.

$$\beta_x = \frac{Quantity\ of\ material\ x\ in\ FU\ (kg) \times material\ x\ unit\ resale\ price\ (\$)}{Total\ material\ resale\ revenue\ in\ FU\ (\$)} \qquad \text{Eq. (5)}$$

Energy recovery-based allocation γ represents the avoided energy burden from raw material extraction and production owing to material recovery. It is compared to total possible avoided energy in 1000 kg of waste.

$$\gamma_x = \frac{Quantity\ of\ material\ x\ in\ FU\ (kg) \times Embodied\ energy\ (MJ/kg)}{Total\ material\ embodied\ energy\ in\ FU\ (MJ)} \qquad \text{Eq. (6)}$$

The final weighted MCIs are linear combinations of individual material mass-based MCI. An example for economic allocation is shown in Eq. (7).

$$MCI = \beta_{Glass}MCI_{Glass} + \beta_{Material\ x}MCI_{Material\ x} \dots + \beta_{Silver}MCI_{Silver} \qquad \text{Eq. (7)}$$

Results

Table 1 summarises the allocation factors for five key recoverable materials. Economic allocation puts the greatest importance on the recirculation of silicon and silver. Embodied energy allocation puts the greatest emphasis on aluminium. As opposed to base case allocation, which is dominated by glass (70% of PVP mass).

Table 1 Three simplified allocation factors for comprehensive computation of MCI

Allocation basis	Factor	Glass	Al	Cu	Si	Ag
Mass	α	0.75	0.19	0.02	0.04	1E-03
Economic value	β	0.01	0.15	0.07	0.40	0.37
Energy	γ	0.23	0.60	0.06	0.09	0.02

A summary of all 18 different scenario combinations in this analysis is given in Table 2.

Table 2 MCI computation of all recycling technologies in open and closed-loop

Technological Scenario	MCI open-loop			MCI closed-loop		
	Mass allocation	Economic allocation	Energy-based allocation	Mass allocation	Economic allocation	Energy-based allocation
Simple Recycling	0.51	0.17	0.46	0.89	0.25	0.80
Modified FRELP	0.53	0.34	0.51	0.92	0.54	0.87
FRELP	0.54	0.52	0.52	0.93	0.90	0.91

FRELP which is the most elaborate recycling technique, yields the highest MCI, followed by Modified FRELP and Simple recycling in both open and closed-loop cycles. The magnitude of the MCI change is the lowest in mass-based allocation and the highest in financial allocation with varying technologies. Closing the recycling loop improves each recycling technology's MCI by on average 0.39, 0.22, and 0.36 for mass, financial, and energy-based allocation, respectively.

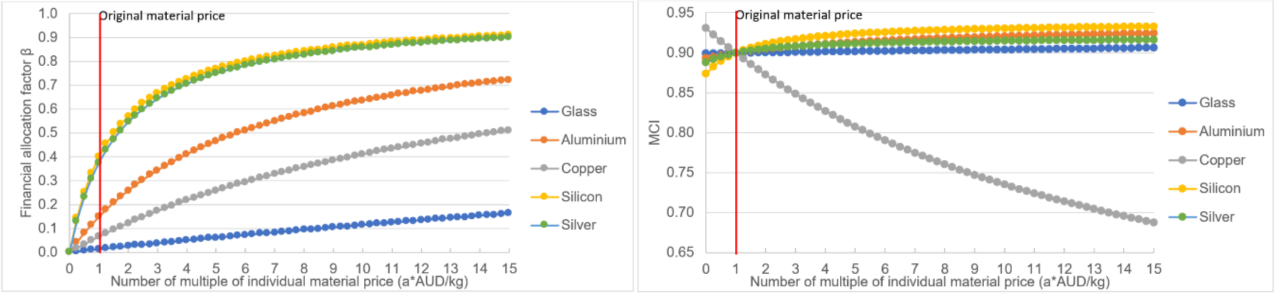

Figure 1. Sensitivity of closed-loop FRELP case (a.) financial allocation factor $\boldsymbol{\beta_x}$ to individual material price change (b.) individual material price change

It is crucial to investigate the influence of material price fluctuation on the circularity evaluation. Individual material price fluctuation is simulated using scalar multiplication factor from 0 to 15 with 0.25 increments. In Figure 1(a.), the effect towards each material's β is depicted. β for material with higher economic value such as silver (815.08 AUD/kg) increases faster than lower value material such as glass (0.04 AUD/kg).

Figure 1(b.) (a.) financial allocation factor $\boldsymbol{\beta_x}$ to individual material price change (b.) depicts the influence of commodity price fluctuation towards the overall MCI (Eq. (7)). Price change in material x brings overall MCI to converge towards respective material's unweighted mass-based MCI. As a result, in all but one case, price increase for one material at a time increases the overall MCI. For instance, MCI convergence towards 0.94 for glass, aluminium, and silicon as well as 0.92 for silicon. Contrarily, as copper price increases, MCI decreases towards its unweighted mass-based MCI of 0.45 as the limit of convergence. Most copper in PVP is mostly flowing linearly, hence it has the lowest MCI out of all five assessed materials.

The lower the β, the slower the convergence towards individual material unweighted MCI. A linear rate of convergence is found for glass, which is allocated β_x of 0.01. Whereas third-degree polynomial relationship is found for aluminium and copper. Fourth-degree polynomial relationship is found for silicon and silver, which dominates the overall β.

Discussion

Including economic and energy allocation factors allow for circularity performance comparison beyond just material quantity. For both open and closed-loop, mass-based recovery still dominates final circularity score. Allocation factors managed to ameliorate the bias towards recovered material quantity by adjusting the rate of convergence towards mass-based scores. This also means that, price increase of a material is not incentivised if most of the material quantity is still flowing linearly. However, ranking between scenarios may change with higher order of magnitude commodity price fluctuations.

β is highly sensitive to material unit price change. This is expected because of their direct correlation. While material embodied energy does not vary, these observations can inform about energy allocation factor γ. When material with higher embodied energy is used, the final MCI will be influenced more significantly by the mass-based recovery of that respective material. Future work can implement a quality factor that can outweigh recovered material quantity.

Findings in this work agree with literature's techno-economic strategy that improving recycling technology efficiency and recovering trace valuable constituents remain paramount for viability and circularity (Granata et al., 2022). Only mass-based MCI can be compared to that of reported in the literature. Zubas et al. (2022) conducted a similar study using LCA and MCI, focusing only on silicon feedstock considering FRELP for recycling. MCI was 0.54 for no silicon recovery case, which is the same as mass-based MCI in this work for open-loop FRELP. Whereas silicon recovery case yields MCI of 0.80. Which is 0.13 point lower than that of mass-based MCI in this work for the closed-loop FRELP. Some limitations are that circular economy tools such as MCI are meant to be heuristics tool (Brändström & Saidani, 2022; Saidani et al., 2019) and it is not appropriate to obtain full quantitative answers.

Conclusions

Base case MCI is heavily influenced by glass recovery. MCI is also the most sensitive to recycling efficiency, restorative material share, and utility variations. Incorporating simplified life cycle impacts-derived allocation factors to MCI broadens its evaluation. In general, the lower the allocation for a material, the slower the convergence towards unweighted MCI of individual material. Financial allocation MCI (using β) is the most conservative because valuable materials are only present in trace fractions. It puts the greatest importance on the recirculation of silicon and silver. The energy allocation factor emphasises the contribution of aluminium. With closed-loop recycling, increases in MCI are 0.39, 0.220, and 0.36 for mass, financial, and energy-based allocation, respectively compared to open-loop counterparts.

This work is distinctive because it provides a simple way to consider key life cycle impact indicators integratively from the circular economy perspective. Including allocation factors can help decision makers to prioritise which materials to focus on in recycling without a full life cycle analysis. A global sensitivity analysis for varying the amount recovered for each material is recommended.

References

Brändström, J., & Saidani, M. (2022). Comparison between circularity metrics and LCA: A case study on circular economy strategies. *Journal of Cleaner Production*, *371*, 133537. https://doi.org/10.1016/j.jclepro.2022.133537

Contreras-Lisperguer, R., Muñoz-Cerón, E., de la Casa Higueras, J., & Martín, R. D. (2020). Environmental Impact Assessment of crystalline solar photovoltaic panels’ End-of-Life phase: Open and Closed-Loop Material Flow scenarios. *Sustainable Production and Consumption*, *23*, 157-173. https://doi.org/https://doi.org/10.1016/j.spc.2020.05.008

Deng, R., Chang, N. L., Ouyang, Z., & Chong, C. M. (2019). A techno-economic review of silicon photovoltaic module recycling. *Renewable and Sustainable Energy Reviews*, *109*, 532-550. https://doi.org/https://doi.org/10.1016/j.rser.2019.04.020

Ellen MacArthur Foundation. (2019). *Circularity Indicators Methodology*. https://ellenmacarthurfoundation.org/material-circularity-indicator

Fthenakis, V. M. (2000). End-of-life management and recycling of PV modules. *Energy Policy*, *28*(14), 1051-1058.

Granata, G., Altimari, P., Pagnanelli, F., & De Greef, J. (2022). Recycling of solar photovoltaic panels: Techno-economic assessment in waste management perspective. *Journal of Cleaner Production*, *363*, 132384. https://doi.org/https://doi.org/10.1016/j.jclepro.2022.132384

Latunussa C, Mancini L, Blengini G, Ardente F, & D., P. (2016a). *Analysis of material recovery from photovoltaic panels. EUR 27797.* Luxembourg (Luxembourg): Publications Office of the European Union.

Latunussa, C. E. L., Ardente, F., Blengini, G. A., & Mancini, L. (2016b). Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels. *Solar Energy Materials and Solar Cells*, *156*, 101-111. https://doi.org/https://doi.org/10.1016/j.solmat.2016.03.020

Maceno, M. M. C., Pilz, T. L., & Oliveira, D. R. (2022). Life Cycle Assessment and Circular Economy: A Case Study of a Photovoltaic Solar Panel in Brazil [Article]. *Journal of Environmental Accounting and Management*, *10*(1), 91-111. https://doi.org/10.5890/JEAM.2022.03.008

McDonough, W., & Braungart, M. (2002). *Cradle to cradle: Remaking the way we make things*. North point press.

Saidani, M., Cluzel, F., Leroy, Y., & Yannou, B. (2019). Testing the robustness of circularity indicators: empirical insights from workshops on an industrial product. Proceedings of the Design Society: International Conference on Engineering Design,

SASIL Srl. (2014). *Full recovery of photovoltaic panels*. https://sasil-life.com/ricerca-e-sviluppo/progetti-life/progetto-frelp/

Suyanto, E. R., Sofi, M., Lumantarna, E., & Aye, L. (2023). Comparison of waste photovoltaic panel processing alternatives in Australia. *Journal of Cleaner Production*, *418*, 138128. https://doi.org/10.1016/j.jclepro.2023.138128

Tao, M., Fthenakis, V., Ebin, B., Steenari, B. M., Butler, E., Sinha, P., Corkish, R., Wambach, K., & Simon, E. S. (2020). Major Challenges and Opportunities in Silicon Solar Panel Recycling. 47th IEEE Photovoltaic Specialists Conference (PVSC),

Zubas, A. R., Fischer, M., Gervais, E., Herceg, S., & Nold, S. (2022). Combining circularity and environmental metrics to guide development in PV. *EPJ Photovoltics*, *14*.