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A Simplified Sustainable Circular Economy Evaluation for End-of-Life Photovoltaic

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1. Introduction

First-generation solar photovoltaic (PV) modules around the world are reaching the end of their useful lifetime. After 20 to 30 years operational life, first generation PV installed will be consigned to the waste system (Bilbao et al. 2021; Giacchetta, Leporini & Marchetti 2013). Globally, 78 million tonnes of PV panel waste is expected by 2050, which represents 10% of all e-waste (Chaplin, Florin & Dominish 2018). Solar PV is deemed the fastest growing electronic waste (e-waste) in Australia (Sustainability Victoria 2022). Bontinck PA and Bricout J (2022) estimated 3118 tonnes of solar PV and battery-derived e-waste, having potential material value of $5.2 million, entered Australian waste system in 2019 with only $0.4 million recovered.

In spite of this mounting urgency, there is yet to be developed a standardised approach to assess the sustainability and circular economy performance of End-of-Life (EoL) PV panel. The interplay between the two interrelated but different notions are still unclear. Studies have delineated that sustainability and circular economy assessment can complement each other. End-users and product manufacturers are often left perplexed by the numerous tools available in the market without a clear comprehensive framework to ensure that all sustainability and circularity aspects are met considering potential trade-offs. The forefront of circular economy adoption lies within the PV industry. The proposed work will prove useful to instil and facilitate circular life cycle thinking,

Existing tools to assess environmental, economic, and social impacts, as well as circularity are fragmented. Life cycle assessment (LCA) is the only standardised method for environmental assessment to date. It demands life cycle expertise and intensive resources. A comprehensive tool that assesses all facets in a simple and integrated manner may reduce the barriers for private sector to adopt circular thinking. This original study aims to propose an integrated framework for private PV users to assess the environmental, economic, and social impacts of product EoL PV processing considering circular economy measures. Moreover, there is still a substantial data gap to model PV recycling in LCA (Lunardi et al. 2021). This study contributes to understanding how sustainability and circular economy can both be satisfied in the context of EoL phase of PV module.

2. Material and methods

2.1. Sustainable circular economy framework

At the forefront, it may seem intuitive that circularity improvement could contribute to the preservation of the environment and material criticality reduction. However, this is not always the case. Studies argued that circularity evaluation should not substitute sustainability evaluation. Presently LCA cannot directly measure how circular a system is. It does not advocate for linear or circular economy specifically but focuses on environmental implications throughout the life cycle.

On the other hand, circular economy often prioritises keeping individual resources within the economy (Saidani et al. 2022c). LCA and circularity indicators can complement each other in generating the most sustainable solution. Mannan and Al-Ghamdi (2022) suggested that LCA can improve different stages of circular economy evaluation in real-life scenarios and therefore can ensure proven benefits for the environment and society.

The study takes a step further by evaluating resulting sustainability and circular economy scores together. Potential trade-offs and complementary effects are investigated. Results are combined for joint analysis in an integrated manner. Multi-criteria decision making (MCDM) will be used in aggregation by normalisation and weighting.

Figure 1 exemplifies the conceptual relationship between the two broad themes of sustainability and circular economy. The study begins with a comprehensive literature review of state-of-the-art PV module recycling as well as its sustainability and circular economy practices. Initially, the two overarching concepts are treated as separate blocks of study. Before being combined for joint analysis and interpretation considering private PV stakeholder's perspective where available. The triangular radar diagram symbolises results interpretation to infer the relationship between circularity and sustainability indicators.

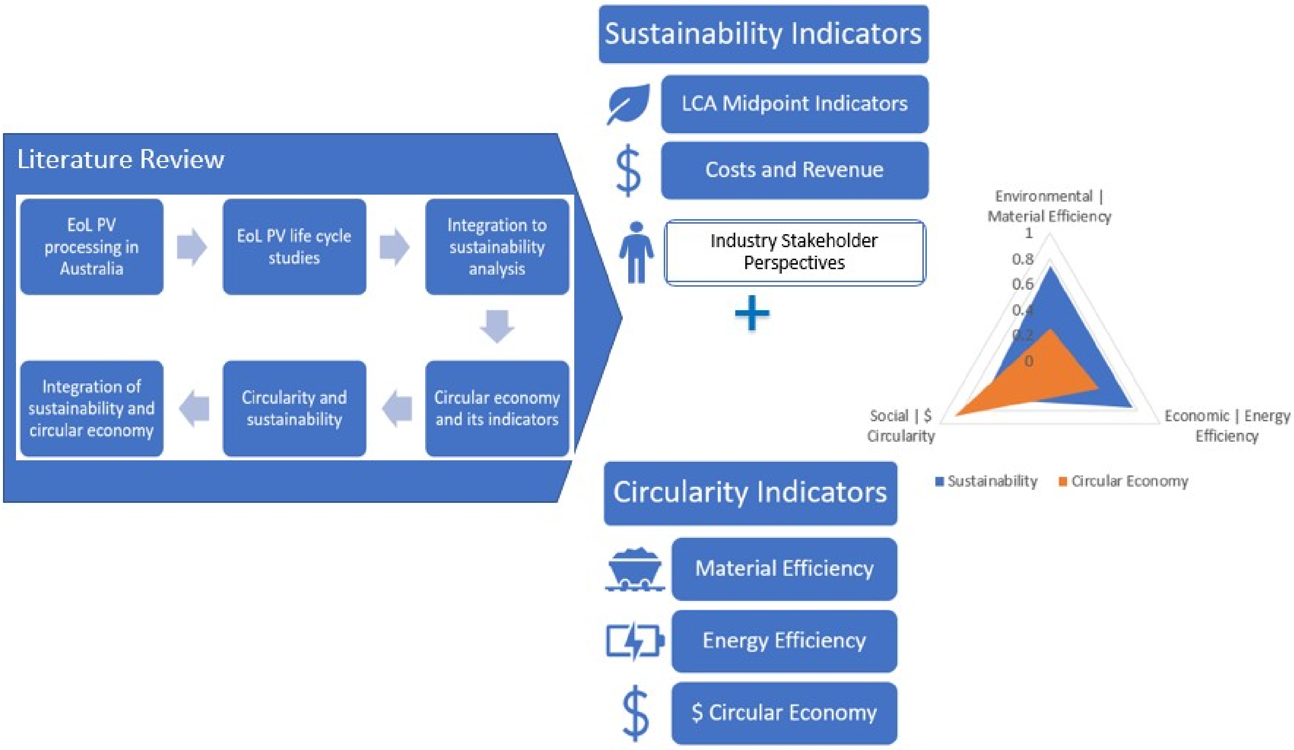

Figure 1. Graphical depiction of overarching key concepts.

2.2. Sustainability front

Within the sustainability aspect of the framework, life cycle sustainability assessment considers three pillar interpretation of sustainability as deducted from the Brundtland report (1987) which encompasses environmental, economic, and social equity (Klöpffer 2008). It is also considered as an ideal tool to assess circular economy strategies objectively to prevent burden shifting between stakeholders within the value chain (Niero & Hauschild 2017).

Environmental and economic input is taken from the first part of the study (Suyanto et al. 2023). The simplified analysis modified semi-quantitative Material, Energy, Chemical, and Other (MECO) method from Wenzel, Hauschild and Alting (1997) and Pommer et al. (2003). It streamlines conventional LCA and life cycle costing (LCC) without the need for an LCA software.

A chance to include social perspective is made possible through MCDM to combine the three pillars of sustainability as well as circular economy quantitative results. The lack of social LCA data for PV waste stream processes can be partially substituted by stakeholder survey with private PV industry participants such as PV panel producers, distributors, and recyclers. Weighting system in this paper are for mere demonstration. Social survey for MCDM weighting factor selection is out of the scope of this paper.

2.2. Circular economy front

On the other hand, within the circularity aspect of the framework, circular economy is defined as an economic and industrial model that is restorative and regenerative by design (Ellen MacArthur Foundation 2013). While there is no standardised definition of the circular economy as of now, literatures agree that this concept stands opposed to the linear "make-take-waste" model (Saidani et al. 2017). Circular economy initiatives can be realised in macro level as regional or national, meso level such as eco-industrial parks, and micro level at products, companies, and consumers level applications (Ghisellini, Cialani & Ulgiati 2016). There is still a gap in research focusing on individual product and company level circular economy indicators (Elia, Gnoni & Tornese 2017). In alignment to this knowledge gap, this work only focuses on circularity indicators at micro level within products, components, and materials operation.

The aim of this section is to identify existing quantitative micro circularity indicators that are suitable for EoL PV application that cover prominent facets of circular economy paradigm. A taxonomy of 55 sets of existing circularity indicators (C-Indicator) by Saidani et al. (2019a) was used as a starting point. The micro circularity indicator screening process is depicted in Figure 2. The twelve shortlisted indicators are further categorised into six facets based on how circular economy performance is derived.

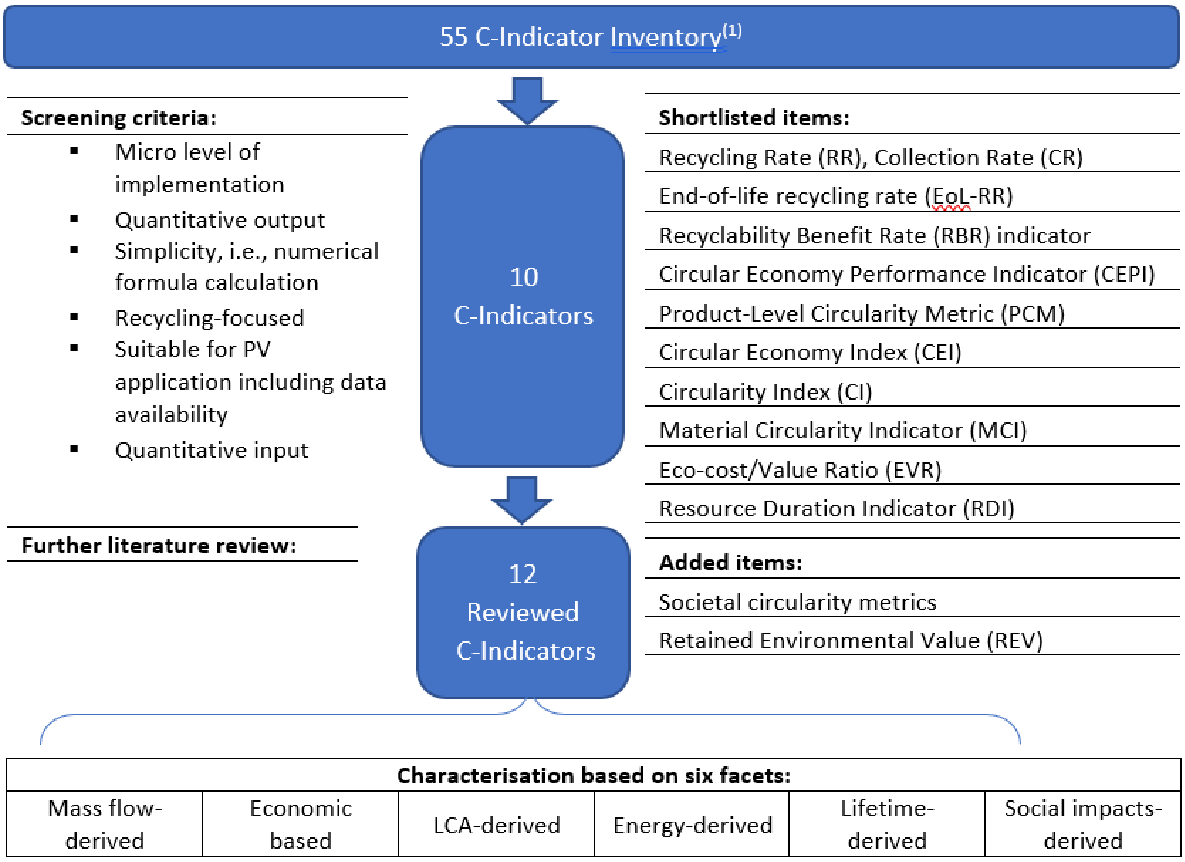

Figure 2. Micro-level circularity indicators screening process for EoL PV application.
(1) Saidani et al. (2019a)

The six facets categorisation are explained hereafter:

(i) Mass flow-derived circularity metrics

A well-established quantitative measure of circularity is Material Circularity Indicator (MCI) by Ellen MacArthur Foundation (2019). It combines mass and temporal units. Other metrics reviewed are recycling rate (RR), EoL metal recycling rates (EOL-RR; i.e., the percentage of a metal in discards that is actually recycled), recycled content (RC), and old scrap ratios (OSRs; i.e., the share of old scrap in the total scrap flow). Similarly, Haupt, Vadenbo and Hellweg (2017) utilised closed- and open-loop collection rate (CR) and RR to measure the available secondary resources produced from municipal solid waste in Switzerland.

(ii) Economic-based circularity metrics

Di Maio and Rem (2015) proposed circular economy index (CEI) which represents how effectively a recycling facility processes a product. A similar index is developed by Linder, Sarasini and van Loon (2017) to quantify the degree of recirculation of a product. Product-level circularity metric (PCM) is expressed as a ratio of economic value of recirculated product parts to economic value of all parts.

(iii) LCA-derived circularity metrics

EC-JRC (European Commission – Joint Research Centre) (2012) developed product reusability/ recyclability/ recoverability (RRR) parameters including recyclability benefit rate (RBR). RBR is the ratio of potential environmental benefits from recycling divided by burdens related to virgin materials production and disposal. It takes a step beyond RR by incorporating product components' LCA impacts from selected category.

Similarly, Huysman et al. (2017) focuses on natural resources impacts in the form of exergy to quantify post-industrial plastic industry's circularity using Circular Economy Performance Indicator (CEPI). Moreover, an LCA-based model called Eco-cost/Value Ratio (EVR) is a single indicator for sustainability that demonstrates how circular economy strategies such as reuse, remanufacturing, and recycling can fulfil eco-efficient objectives. Retained Environmental Value (REV) was proposed by Haupt and Hellweg (2019) to compare the net surplus from product reuse or recycling to lifetime environmental impacts.

(iv) Energy-based circularity metrics

Cullen (2017) considered the combination of recovered EoL material quantity compared to total demand and the energy required to recover them compared to primary production in circularity index (CI).

(v) Lifetime-based circularity metrics

Franklin-Johnson, Figge and Canning (2016) introduced resource duration indicator (RDI) which utilises the length of time of material retention in a product system as a measure of its contribution to circular economy. It is computed as the sum of three main longevity drivers, i.e. initial usage, refurbishment, and recycling lifetime.

(vi) Societal circularity metrics

In addition to the circularity indicators recommended by Saidani et al. (2019a) tool, a metric proposed by Reich et al. (2023) was reviewed. It took a more holistic approach to circular economy measurements in policy making. It considers not only material flow and environmental impacts as most circularity indicators do. But also considers socio-economic impacts, linking macro and micro indicators to the assessed system.

Finally, at the end of the screening process, three of the reviewed tools are selected based on their simplicity and suitability for the purpose of this EoL PV evaluation. The maximum value representing full circularity in all three indices is equal to one.

1) Circular Economy Index (Di Maio & Rem 2015)

$$\mathrm{CEI} = \frac{\text{market value of recycled product materials (\$)}}{\text{material value of EoL product entering recyclers gate (\$)}}$$

Equation 1

In this work, recycled EoL PV module material sales revenue serves as the numerator and virgin material market value as the denominator.

2) Circularity Index (Cullen 2017)

$CI = \alpha\beta$

Equation 2

$$\alpha = \frac{\text{recovered EOL material (kg)}}{\text{total material demand (kg)}}\ ;\ \beta = 1 - \frac{\text{energy required to recover material (MJ)}}{\text{energy required for primary production (MJ)}}$$

3) Material Circularity Indicator (Ellen MacArthur Foundation 2013)

$MCI = 1 - LFI{*}F(X)$

Equation 3

Linear Flow Index $LFI = \frac{V+W}{2M+\frac{Wf-Wc}{2}}$; utility Factor $F(X) = \frac{0.9}{\frac{L}{Lav}\frac{U}{Uav}}$

$V = mass\ of\ virgin\ material;\ W = total\ waste;\ M = mass\ of\ product;$

$Wf = waste\ from\ processing\ recycled\ content\ ;Wc = waste\ from\ recycling;$

$L = lifetime;\ Lav = industry\ average\ lifetime; U = use; Uav = industry\ average\ use$

In this study, MCI calculation assumes 100% virgin PV module production feedstock in all scenarios. Moreover, it only considers recycling and no reuse nor refurbishment as an alternative circular economy initiative. Lifetime and use of PV module in all scenarios remain to be the same as industry-average.

2.3. Application on PV module waste

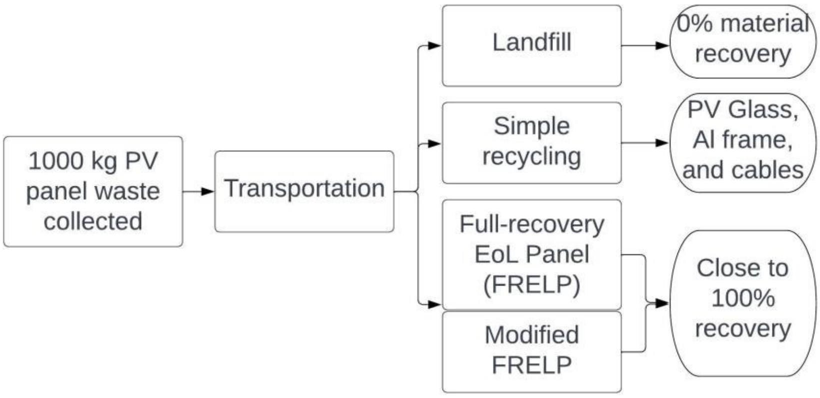

Figure 3. System boundary of EoL PV alternatives.

Four EoL PV processing alternatives in Figure 3 will be evaluated using this proposed framework. These options were previously studied in Suyanto et al. (2023). A mass-based functional unit of 1000 kg PV waste is selected for both sustainability and circular economy counterparts to ensure consistency. Landfill is the business-as-usual treatment of discarded PV modules in most countries. Simple recycling involves bulk material disassembly and glass separation. Full-recovery EoL Photovoltaic (FRELP) is a high value PV module recycling that was introduced by Latunussa C et al. (2016a). The fourth alternative is a modified version of Latunussa et al. (2016b) work. It deploys a different mechanical separation technology and focuses on solar-grade silicon recovery within the chemical separation techniques (Kang et al. 2012).

3. Results

3.1. Environmental and financial impacts of EoL PV

Following the studied framework, the sustainability aspect of EoL PV is first examined. Simplified life cycle assessment (LCA) and life cycle costing (LCC) results are taken from Suyanto et al. (2023) as summarised in Table 1. Two ecological contributions that are assessed are net primary energy impact and greenhouse gas emission. They are calculated from waste processing and transportation burden subtracted by avoided production of recovered materials and energy from recycling. In conventional LCA, these are the equivalent of cumulative energy demand and climate change impact indicators.

Table 1. Simplified environmental and financial analysis results for 1000 kg PV panel waste functional unit.

	Sustainability				
	Environmental		**Financial**		
Scenario	**Net Energy Impact (MJ)**	**Net GHG Emission (kgCO2-eq)**	**Processing Cost ($)**	**Revenue ($)**	**Net Cost ($)**
Landfill	-1590.83	-120.81	-263.26	0.00	-263.26
Simple recycling	30897.73	2646.31	-228.07	355.51	127.44
FRELP	38152.86	3208.49	-312.22	926.37	614.15
Modified FRELP	34424.92	2868.99	-321.86	1080.64	758.78

*Negative value signifies burden and positive value signifies surplus through avoided virgin material production

Direct landfill of PV module waste causes overall negative impact while all recycling alternatives incur positive net ecological gain. This is due to the consideration of avoided raw material production through recycling of key materials. For instance, aluminium frame and low-iron solar glass which comprises over

70% of PV panel by weight. FRELP method is found to be the most ecologically beneficial through energy and greenhouse gas impact avoidance through material recycling and incineration of polymers. Modified version of the separation technique garners over 10% less ecological benefits.

Simplified financial analysis proves the financial gain of all three recycling activities. Bearing in mind inherent assumptions in processing cost and revenue that focus on resource consumption and no fixed costs. Modified FRELP costs the most with over $300/ tonne of processed PV waste. It also attracts the highest revenue compared to the simple recycling and original FRELP methods. In terms of overall ranking, financial results favour modified FRELP method and environmental results favour original FRELP method. Whereas landfill and simple recycling routes remain in the same relative ranking positions for environmental and financial performance.

3.2. Circular economy of EoL PV

The second half of the framework examines the circularity of EoL phase of PV modules. Table 2 summarises the computation process of three shortlisted circularity indicators from the review process. Results favour FRELP and modified FRELP recycling techniques with slight variations. Simple recycling also performs considerably well compared to the two more sophisticated routes. Except for in CEI, in which the monetary values of recovered materials become prominent in the evaluation. FRELP method is deemed the most circular based on material and energy retention through CI and MCI tools. However economic value retention through CEI favours modified FRELP due to its higher revenue from harvested material.

Table 2. Shortlisted circularity indicator computation for three recycling scenarios.

	Simple Recycling	**FRELP**	**Modified FRELP**
Circular Economy Index (CEI)	**0.05**	**0.12**	**0.14**
Market value of recycled product materials (AUD)	347.60	874.08	1080.64
Material value of EoL product entering recyclers gate (AUD)	7461.31	7461.31	7461.31
	Simple Recycling	**FRELP**	**Modified FRELP**
Circularity Index (CI)	**0.84**	**0.88**	**0.87**
α	0.858	0.903	0.891
Recovered EoL material (kg)	858.11	902.90	890.56
Total material demand (kg)	1000.00	1000.00	1000.00
β	0.981	0.973	0.974
Energy required to recover material (MJ)	3255.20	4531.43	4321.87
Energy required for primary production (MJ)	167160.84	167160.84	167160.84
	Simple Recycling	**FRELP**	**Modified FRELP**
Material Circularity Indicator (MCI)	**0.50**	**0.52**	**0.51**
Utility Fraction *F(X)*		0.9	
Linear Flow Index *LFI*	0.555	0.537	0.542

3.3. Simplified Sustainable Circular Economy Evaluation of EoL PV

The most crucial part of the study is to couple the sustainability and circular economy counterparts. All resulting sustainability indicators are normalised and plotted on the same graph as circularity indices as depicted in Figure 4.

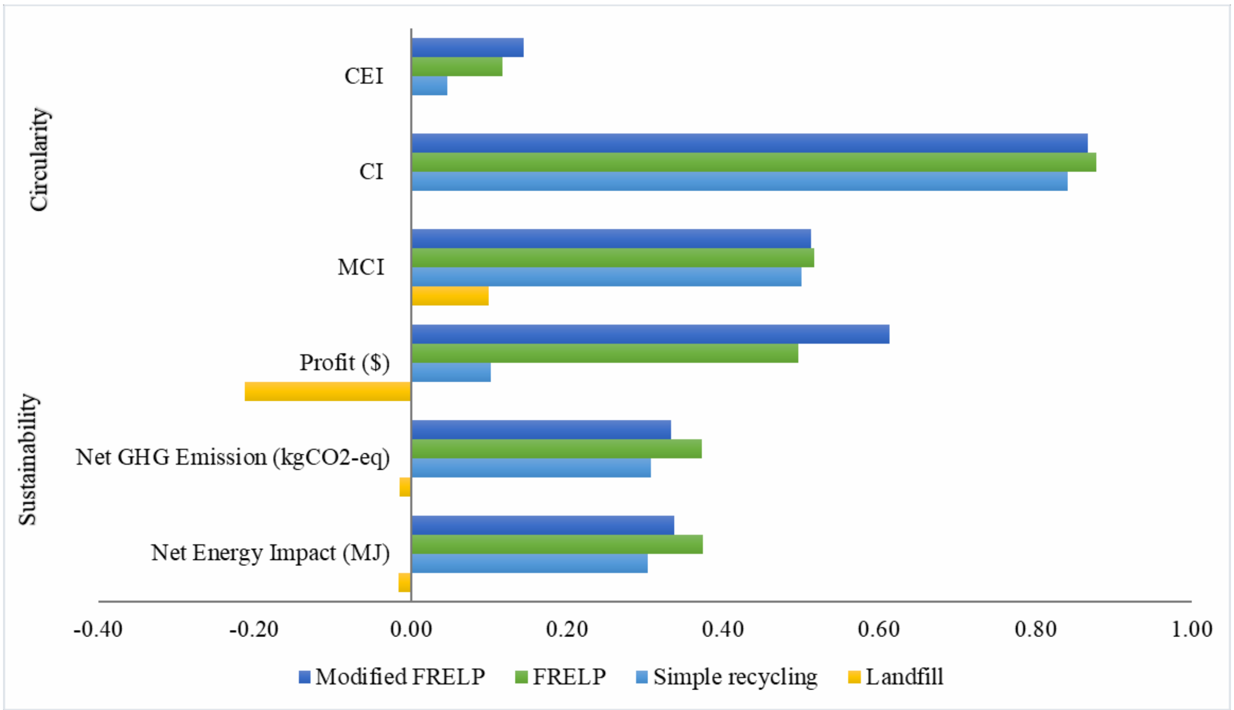

Figure 4. Normalised sustainability and circular economy indicator ranking for 1000 kg EoL PV scenarios.

General ranking of scenarios among selected simplified sustainability and circularity indicators are in agreement with each other despite variations in the degree of improvement shown by each indicator. CI results demonstrate high circularity for all recycling options due to high mass-based recovery rate of assessed recycling technologies.

The last step in the evaluation is to conduct a brief multi-criteria decision making (MCDM) based on designated weighting factors. This is designed as an opportunity for future works to incorporate social perspective through stakeholder involvement. A demonstration is presented in Table 3 with equal importance given to environmental and financial cause. Individual indicators still bear slight variations comparatively. But the resulting combined scores and rankings show an agreement between sustainability and circular economy domains. As was the case with individual indicators, negative values represent adverse impacts on sustainability and circular economy. For instance, in landfilling of EoL PV.

Table 3. Equal weighting applied on financial and environmental aspects of sustainability and circularity.

		Sustainability			Circularity		
		Environmental		**Financial**	**Material**	**Energy**	**Value Retention**
Social	**Weighting**	25%	25%	50%	25%	25%	50%
		Net Energy Impact	Net GHG Emission	Profit	MCI	CI	CEI

Scenario	Sustainability Score	Circularity Score	Sustainability Ranking	Circularity Ranking
Landfill	-0.11	0.03	4	4
Simple recycling	0.20	0.36	3	3
FRELP	0.44	0.407	2	2
Modified FRELP	0.47	0.417	1	1

4. Discussion

From an environmental perspective, energy and GHG emission savings are evident through recycling efforts. This finding that material recovery outweighs recycling burden is consistent with conventional gate-to-gate LCA of FRELP scenario by Mahmoudi, Huda and Behnia (2020) and many others. From a financial perspective, landfilling of PV waste cannot be considered as the cheapest end-of-use option when we consider the loss of material that can potentially be recirculated (Suyanto et al. 2023). Sustainability evaluation favours EoL pathway that generates less harmful impacts towards the environment and captures more revenue from waste recycling. However, it does not directly measure how well the PV modules are recirculated at the end of their useful lifetime.

Selected circularity metrics ensure that not only the selected EoL route is sustainable ecologically and socio-economically, but it also serves in closing the loop towards a fully circular economic system. They possess some inherent partialities towards material mass circularity. For instance, all the Circularity Index (CI) results obtained from simple recycling, FRELP, and modified FRELP are over 84% irrespective of the environmental and economic value of recovered materials.

Furthermore, it is inferred that each indicator cannot be treated as a standalone metric. Each have their own ‘blind spots’ or biases. For instance, simple recycling of EoL PV is scored less than 0.05 out of 1.00 in Circular Economy Index (CEI), more than 50% less than FRELP and its modified version due to its low material sales revenue, despite its relatively efficient energy performance compared to the other recycling methods. Maceno, Pilz and Oliveira (2022) reached similar conclusions from their examinations using Circular Economy Indicator Prototype (CEIP), Circular Economy Toolkit (CET), and MCI alongside LCA of PV module manufactured in Brazil. MCI proves to be complementary to LCA but should not be used in isolation to replace LCA in eco-design process. Products can yield excellent environmental performance while having a low degree of circularity.

Zubas et al. (2022) compared several circularity measures of PV silicon supply chain. Similar to this study, their LCA and MCI results mostly align. Slight variations were observed in their work as MCI favours scenarios with less virgin material usage despite longer lifetimes and higher recycling rates. Zubas et al. (2022) modelled FRELP as a closed-loop for silicon feedstock. They argued that the recovery of metallurgical grade silicon (>95% purity) can ensure the re-injection of secondary silicon to new PV module production. Their resulting MCI score was reported to be 0.80 out of 1. In an attempt to closely-represent exisiting technology, this work does not adopt the same assumption. Hence all recycling scenarios yield a more conservative average of 0.51 out of 1 for MCI scores. Additionally, they omitted impacts from recycling of discarded PV modules due to the lack of data. This study contributes to closing this gap by focusing on EoL phase in its assessments.

This study is unique in its pursuit of a streamlined framework to analyse sustainability and circular economy of EoL phase of PV modules through an array of selected key performance indicators. Some inherent limitations include the exclusions of other impact indicators such as land use and toxicology-related matters. Environmental and financial impact results can benefit from further refinement in a conventional life cycle assessment and life cycle costing. Net impacts are considered in this work. Notwithstanding that in a conventional LCA, it is always preferrable to assess ecological burden and gain separately.

5. Conclusion

Sustainability and circular economy have gained increasing traction over the years both from the academics and private PV sector. While the two paradigms are closely-related, circular economy is not synonymous to sustainability. This simplified evaluation framework strives for a balanced EoL PV alternative that ensures no burden shifting between circularity of materials and environmental, economic, or social impacts.

This work classifies six facets of circularity metrics for EoL phase of PV including material, energy, and value retention. They are heuristics tools that provide valid comparative insights to complement sustainability analysis such as LCA. Overall, environmental and financial indicators’ comparative ranking are in agreement with selected circularity indicators. Landfill is the least beneficial disposal avenue from sustainability and circular economy perspective when material recovery benefits are considered. Whereas Modified FRELP is preferred from both sustainability and circular economy standpoints.

In conclusion the proposed framework is a simple tool suitable for initial comparative analysis. But should not be utilised to replace conventional life cycle assessment. Future research should focus on garnering more social impact data on EoL PV as incoming waste influx increases with time. Furthermore, the introduction of aggregation through normalisation, weighting, and linear addition compounds uncertainty within the analysis that should be quantified in future studies. Multi-criteria decision making can also be conducted alongside sensitivity analysis to ensure that numerical results are stable. In addition, computerised simulations can be developed based on the proposed framework, making use of existing life cycle thinking and circular economy tools.

Acknowledgements

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