THE UNIVERSITY OF MELBOURNE

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

19 July 2023

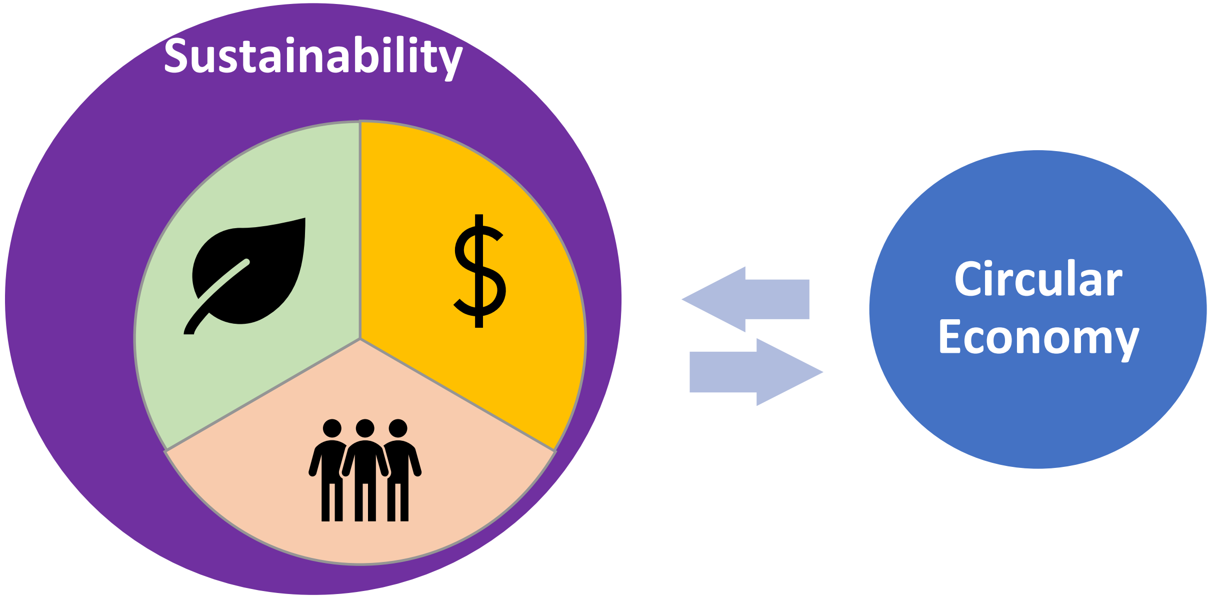
Content

Key Abbreviations

PV	Photovoltaic
EoL	End-of-Life
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MCDM	Multi-criteria Decision Making
CE	Circular Economy
C-Indicator	Circularity Indicator

1. Introduction

1.1. Key Concepts



Life cycle sustainability assessment
LCSA = LCA + LCC + S-LCA
(Klöpffer, 2008)

Three-pillar interpretation of sustainability (Brundtland, 1987)

An economic and industrial model that is restorative and regenerative by design
(Ellen MacArthur Foundation, 2013)

Counterbalances linear “take-make-waste” model (Saidani et al., 2017)

1.1. Key Concepts

1. Circular Economy (CE) =/= Sustainability. How do they relate?

Conditional: Circularity is one of the conditions for sustainability

Beneficial: Circularity enhances sustainability

Trade-off: Circularity is in conflict with sustainability

(Geissdoerfer et al., 2017)

2. Circular strategies should be simultaneously sustainable.

   CE does not always lead to sustainability and v.v.

3. Results are not generalisable for all products. (Linder et al., 2020)

   Case-by-case correlations. (Korhonen et al., 2018; Schaubroeck, 2020)

1.2. End-of-Life Photovoltaic Panel | Australia context

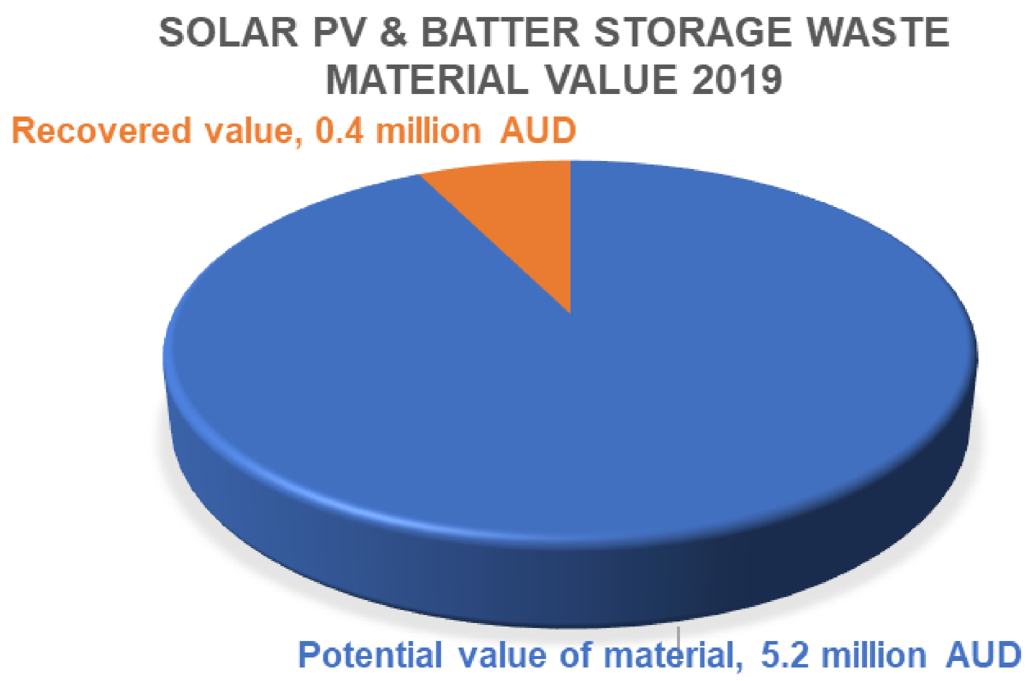
Fastest-growing electronic waste (e-waste) in Australia – 0.8 million tonnes cumulative waste by 2047 (Mahmoudi et al., 2019).

Added to the annual priority product list of Product Stewardship Act 2011 (repealed by Recycling and Waste Reduction Act 2020) in 2016.

E-waste landfill ban in SA (2013), VIC (2019), WA (2024), more to come.

Long-term consequences?

- Unauthorised stockpile
- Interstate waste transfer to avoid fines



(Bontinck PA and Bricout J, 2022)

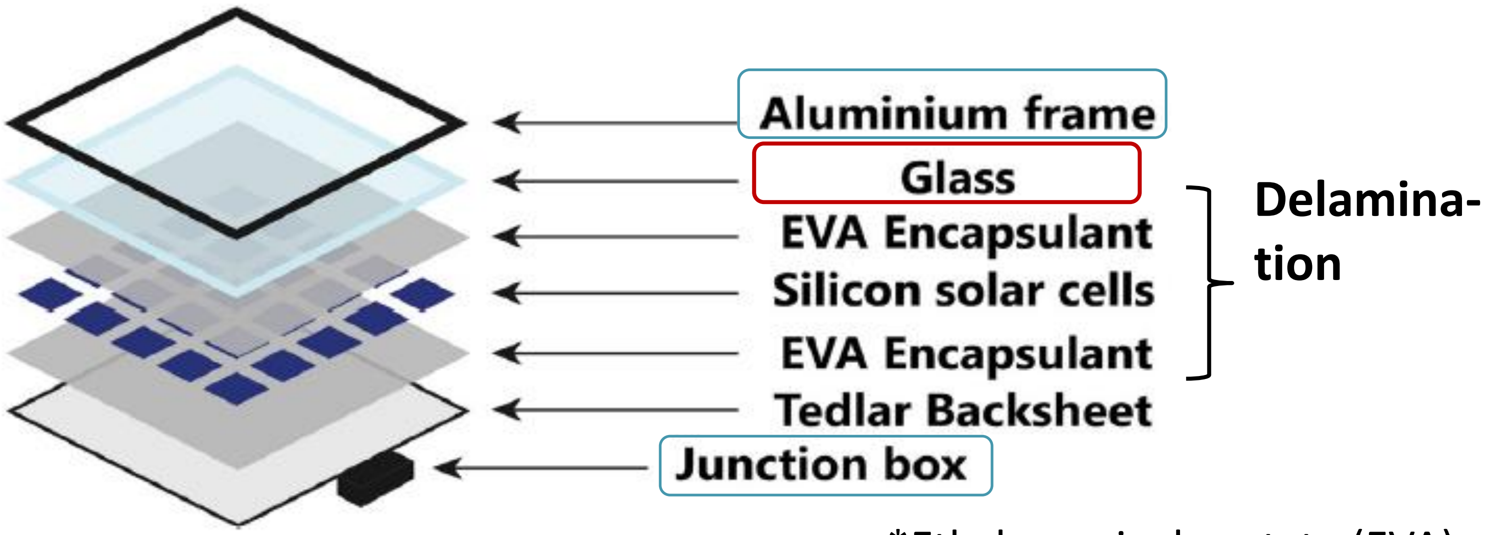
1.2. End-of-Life Photovoltaic Panel | Recycling Technologies

Based on material yield:

- **Low recovery**
  - Recover bulk material
  - Manual disassembly, glass recycling, metal scrapping
- **High recovery**
  - Recover trace constituents
  - Commercial viability is still low

Based on separation method:

- **Mechanical route**
- **Thermal route**
- **Chemical route**



*Ethylene-vinyl acetate (EVA)

(Farrell, C. C. et al., 2020)

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CIRCULAR ECONOMY

Fragmented individual assessment tools

Circular initiatives still in infancy

SUSTAINABILITY

No standardised method other than LCA

Case-by-case correlations

Solar Panel Waste

10% of total global e-waste by 2050

Lack of LCA data inventory

Private PV Stakeholders

Extended producer responsibility

Main actors

PV producers, recyclers, distributors

???

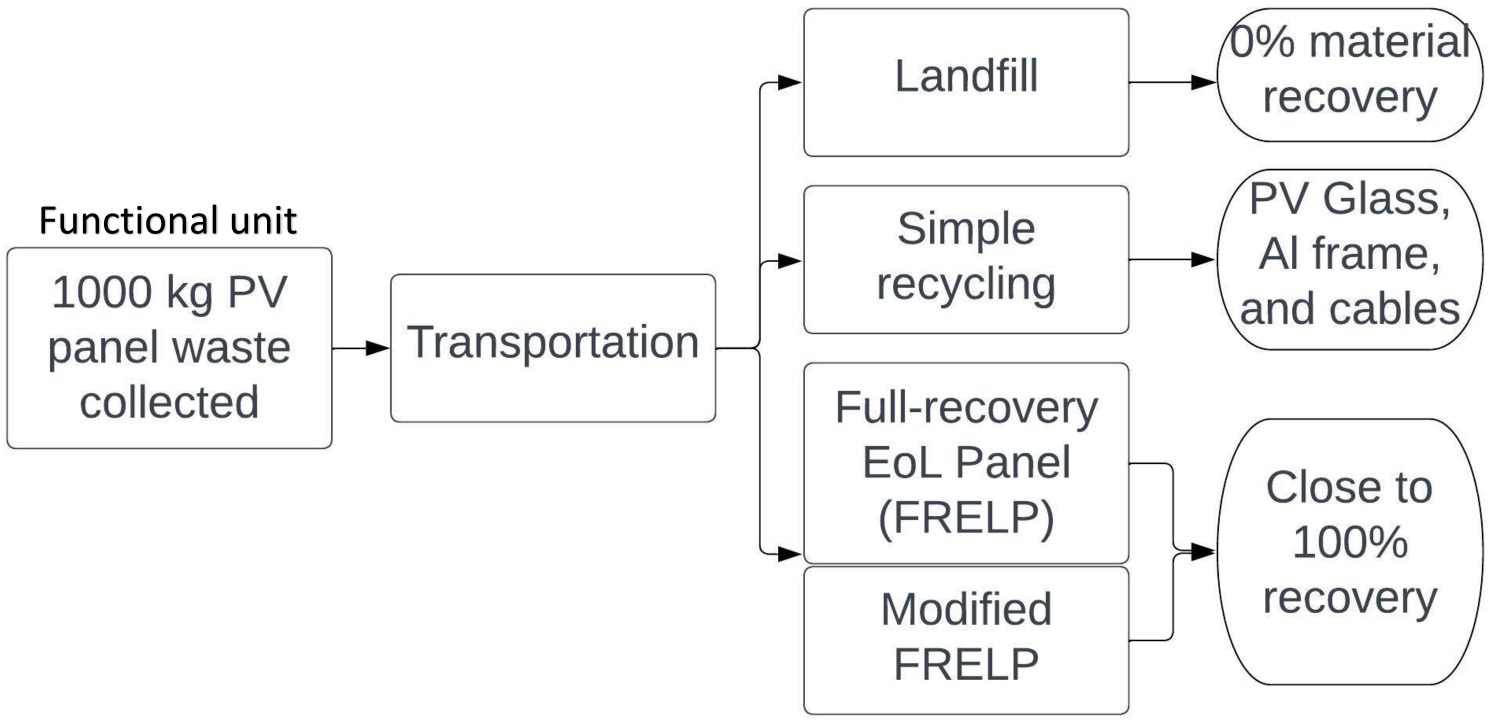
1.4. Research Aim

To propose a framework to evaluate sustainability and circular economy performance of EoL PV panel in an integrated manner to promote usage within the private PV sector.

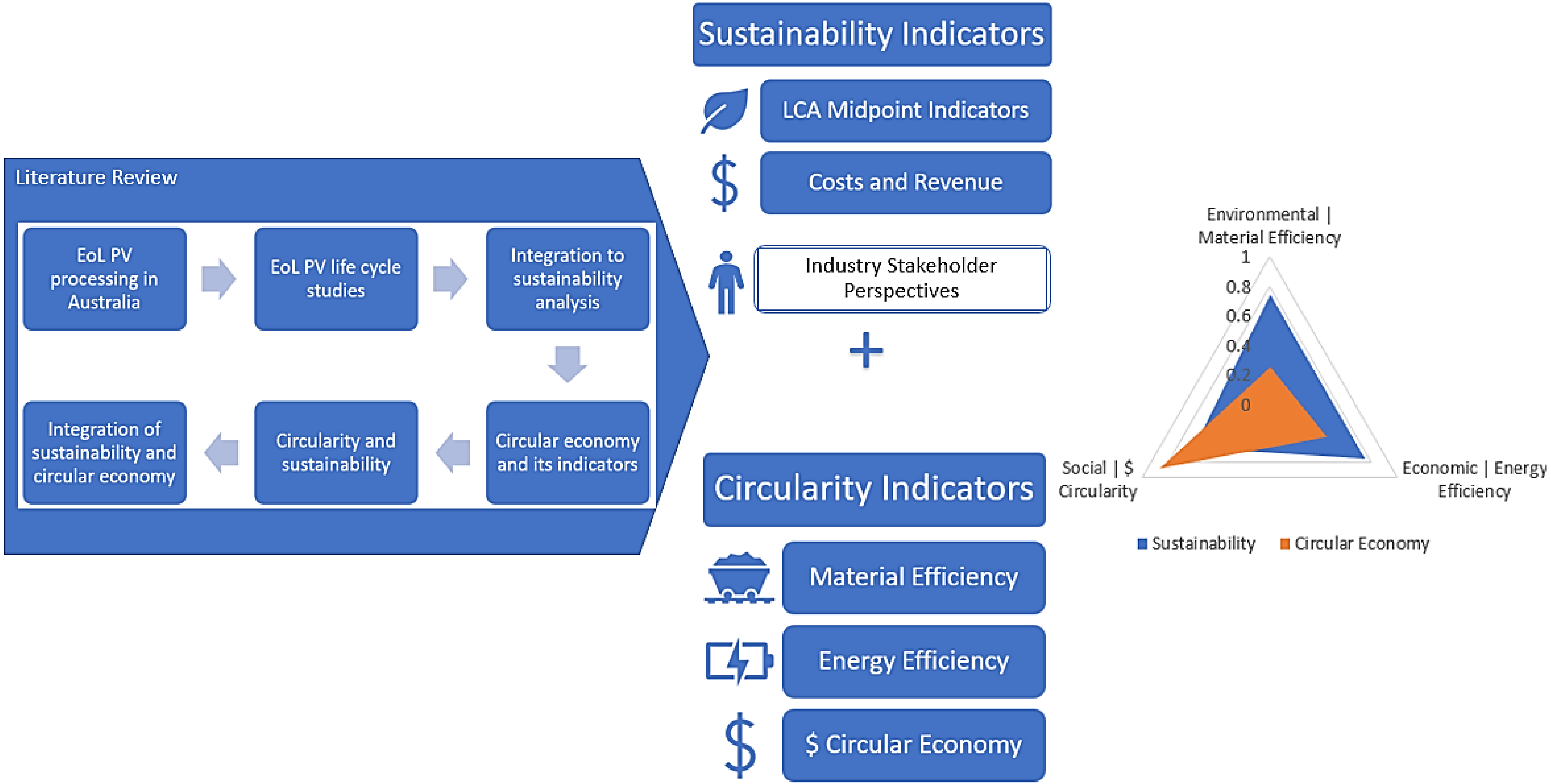
Research in progress

2. Methods

System Boundary



Proposed Framework Development



2.1. Sustainability Front | Simplified LCA-LCC

	Material	Manufacture	Use	Disposal	Transport
1. Materials *a*) quantity *b*) resource					
2. Energy *a*) primary *b*) resource					
3. Chemicals					
4. Others					

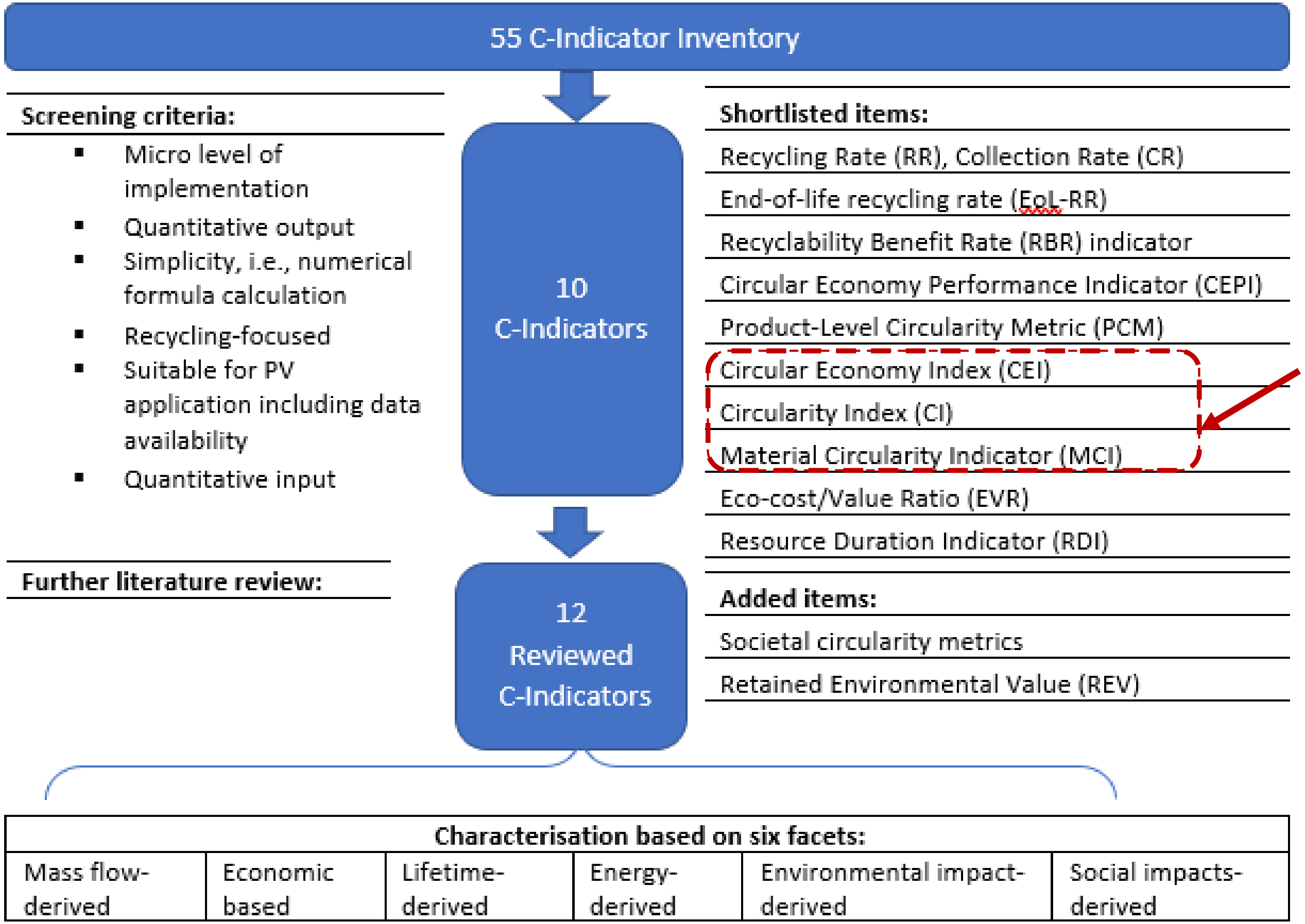
Material, Energy, Chemical and Others (Wenzel et al., 1997; Pommer, 2003)

- Semi-quantitative screening LCA modified by Suyanto et al. (2023)
- Simultaneous inventory and impact assessment
- Stepwise – one category, one life cycle phase at a time

Benefits

- Rely on material input output flows not arbitrary ranking
- Reduced subjectivity and reliance on expert judgment
- Limit effort for life cycle inventory

2.2. Circular Economy Front | Micro C-Indicators



Original 55 C-Indicator taxonomy by Saidani et al. (2019)

2.2. Circular Economy Front | Shortlisted C-Indicators

1. Circular Economy Index (Di Maio and Rem, 2015)

$$CEI = \frac{Market\ value\ of\ recycled\ product\ materials\ (\$)}{Material\ value\ of\ EoL\ product\ entering\ recyclers\ gate\ (\$)}$$

2. Circularity Index (Cullen, 2017)

$$CI = \alpha\beta$$

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

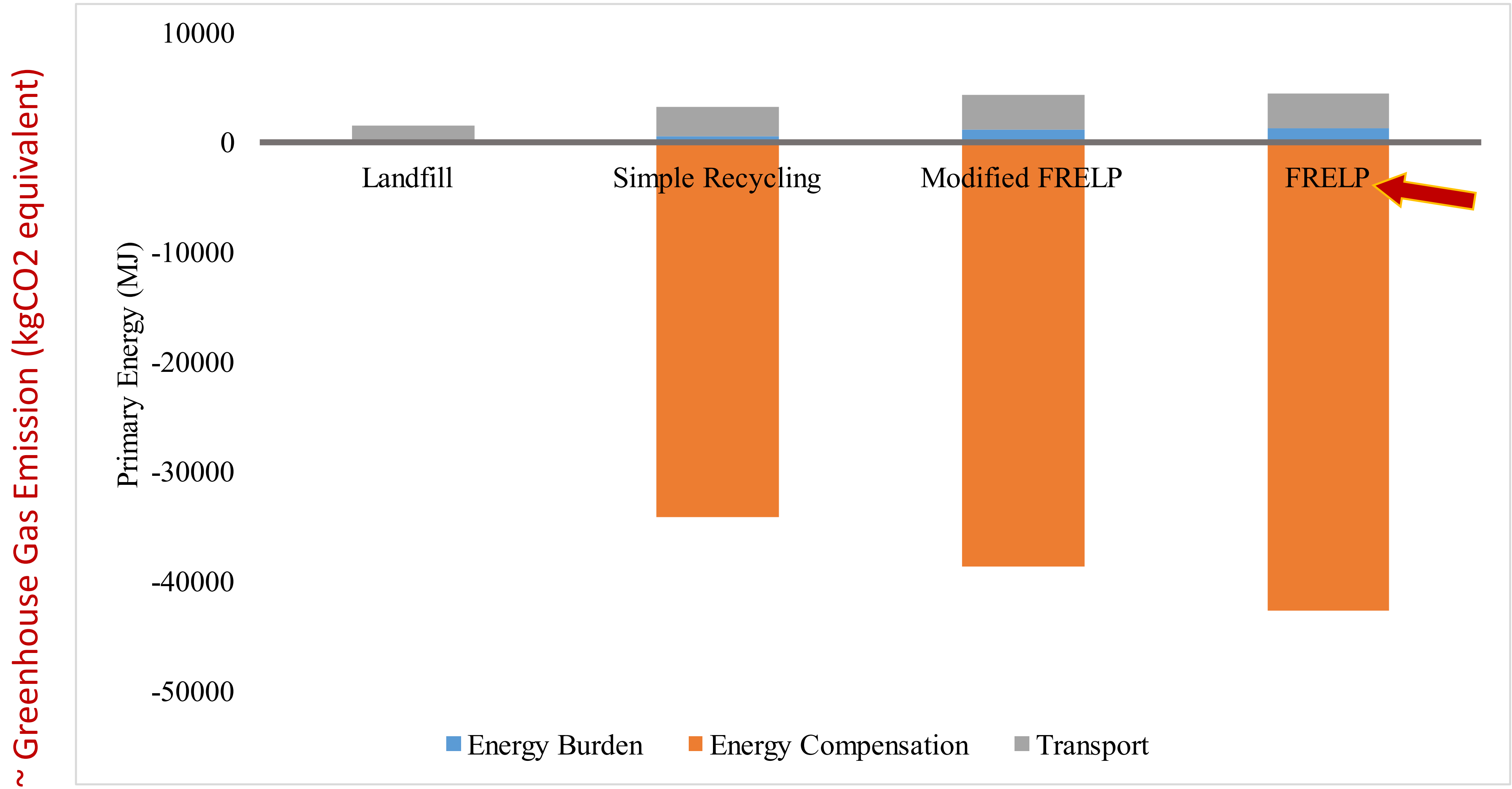
3. Material Circularity Indicator (Ellen MacArthur Foundation and Granta Design, 2016)

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

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

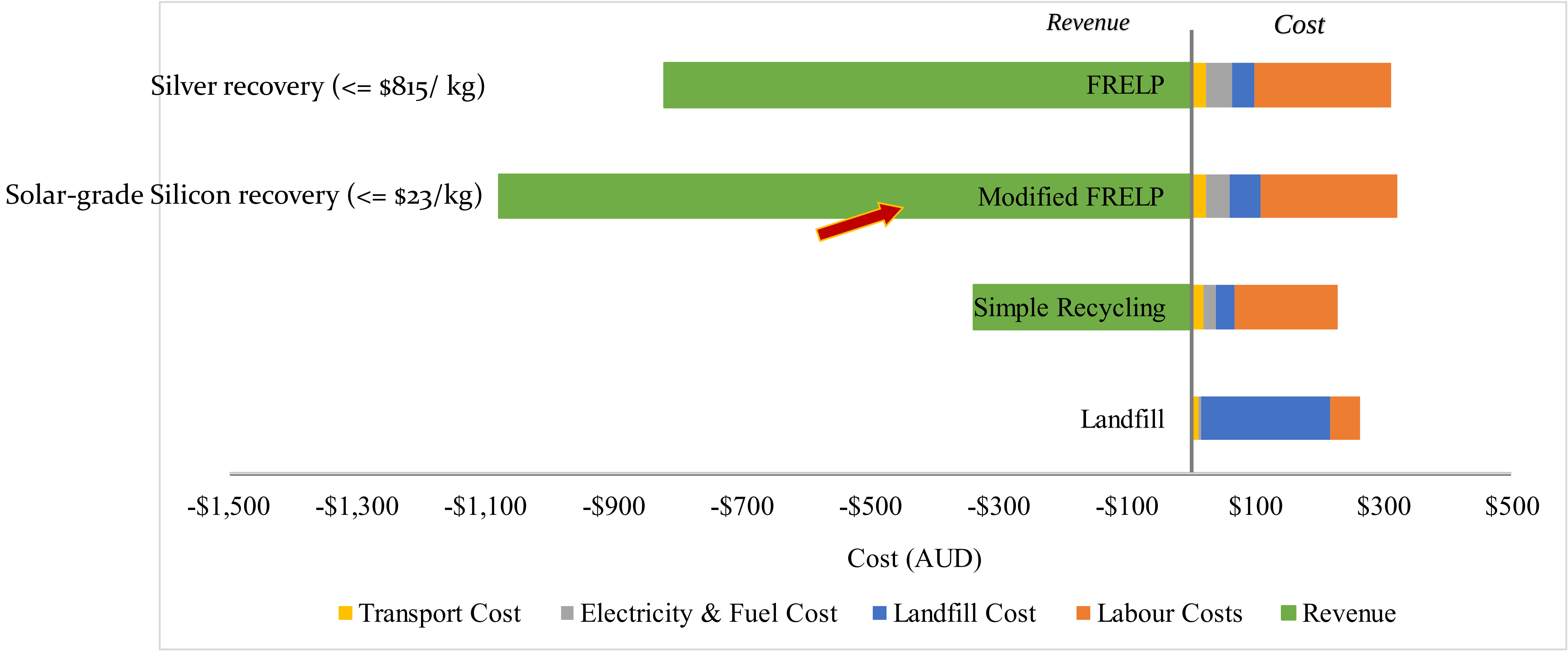
3. Results and Discussions

3.1. Sustainability Front



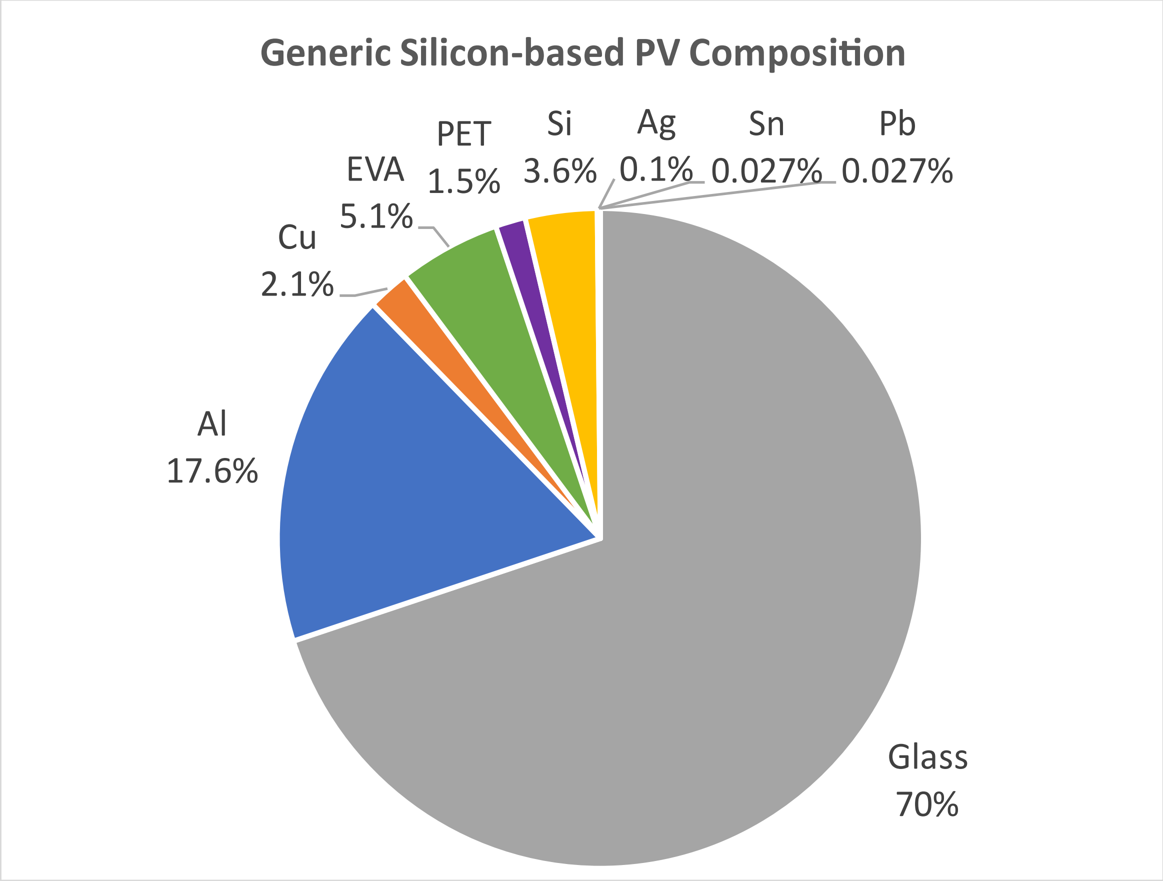
Simplified LCA-LCC Results: Primary energy consumptions for 1000 kg processed PV waste (Suyanto et al., 2023)

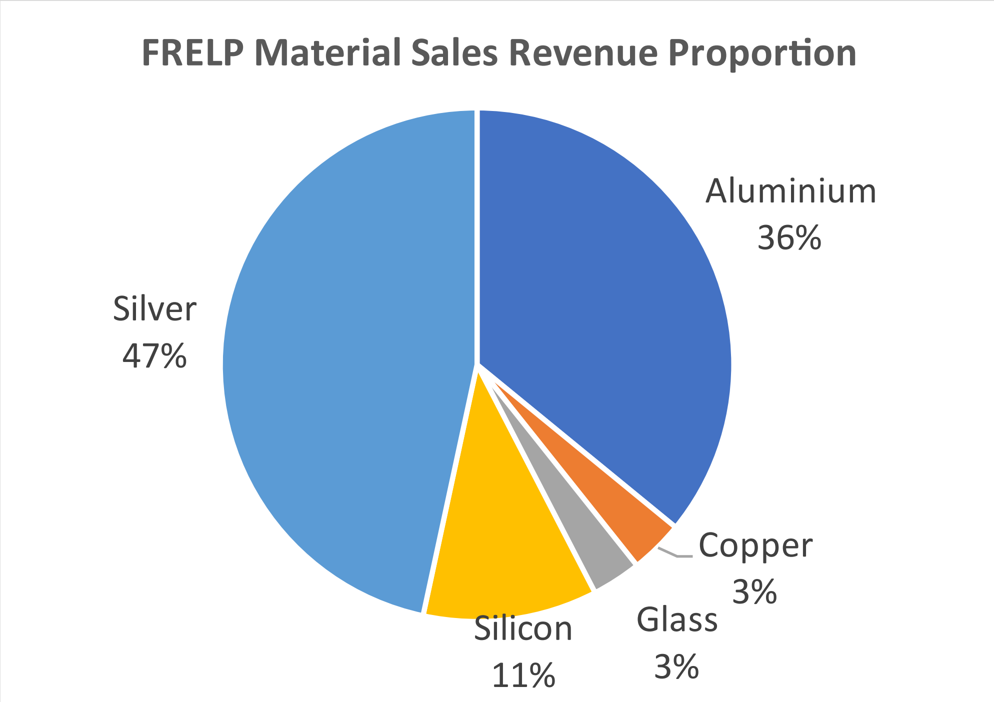
3.1. Sustainability Front

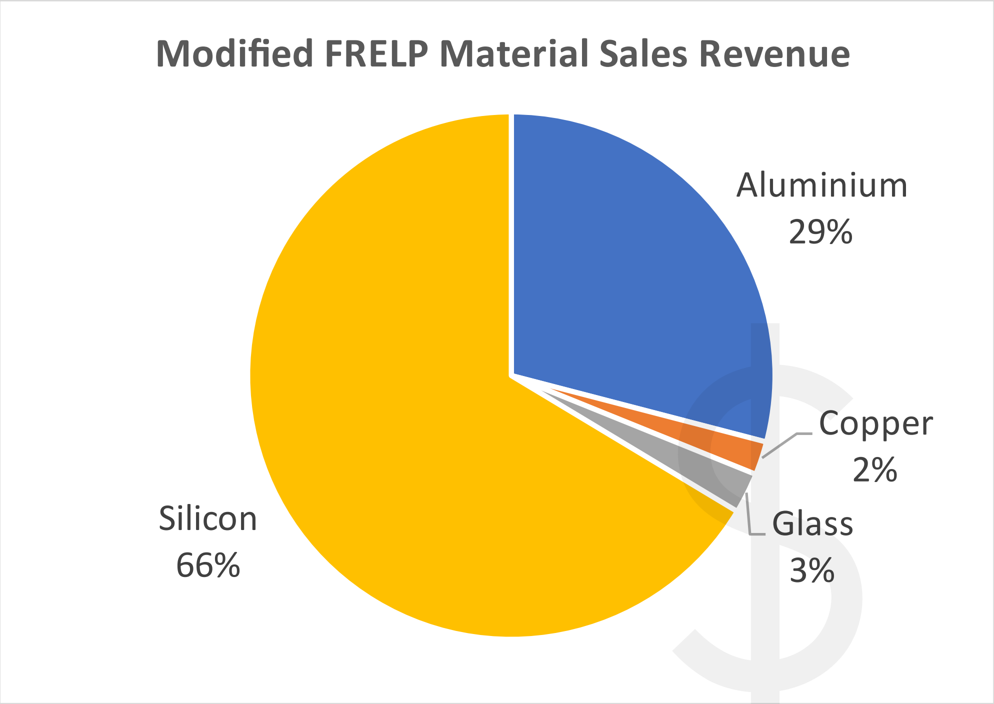


Simplified life cycle costing results: Resource consumptions for 1000 kg processed PV waste (Suyanto et al., 2023)

A Trade-off





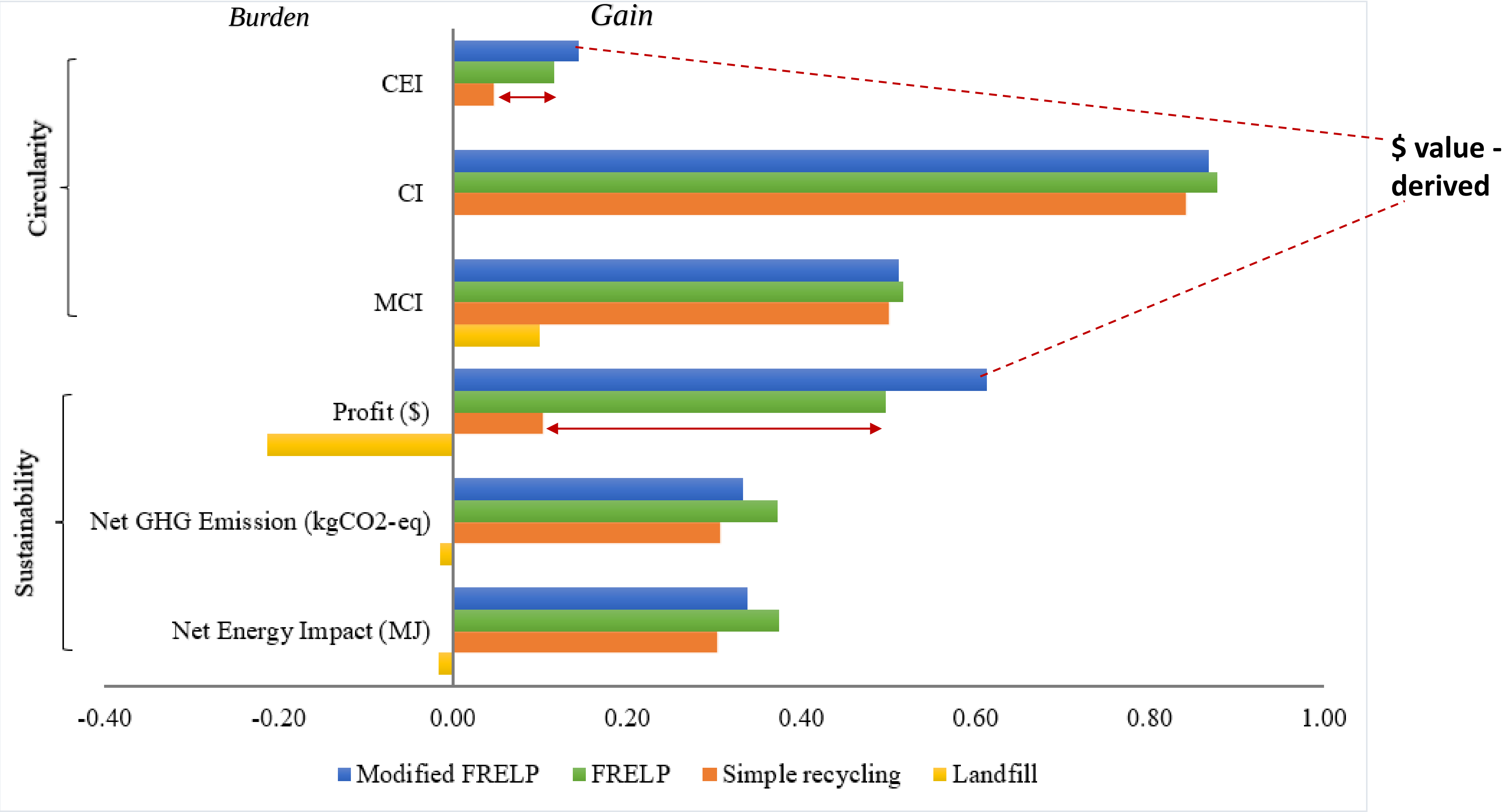


(Suyanto et al., 2023)

3.2. Circular Economy Front

	Simple Recycling	FRELP	Modified FRELP
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**
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**
MCI	0.50	0.52	0.51
Utility Fraction *F(X)*		0.9	
Linear Flow Index *LFI*	0.555	0.537	0.542

Combined Results



Normalised indicators for 1000 kg Processed PV Waste

Combined Results

		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. Summary

4.1. Conclusions and Limitations

Environmental and financial indicators' comparative rankings are **in agreement** with selected circularity indicators.

Valid for compared PV waste scenarios (case-specific).

A simple tool valid for **initial comparative** analysis.

Not to be utilised to replace conventional life cycle assessment.

Landfill is the **least beneficial** disposal avenue from sustainability and circular economy perspective.

Given that material recovery benefits are considered.

Modified FRELP is the most **sustainable and circular.**

More **profitable** due to SoG-Si recovery

Given that equal importance is given to eco - $ concerns.

4.2. Future Works

- Private PV stakeholders survey for social perspective data
- Full-scale quantitative LCA and LCC
- Uncertainty and sensitivity analysis of aggregation method
- Interactive spreadsheet to demonstrate the proposed framework

Thank you

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References

Cucchiella, F., & D'Adamo, I. (2015a). A multicriteria analysis of photovoltaic systems: energetic, environmental, and economic assessments. International Journal of Photoenergy, 2015.

Ellen MacArthur Foundation. (2013). Towards the circular economy. Journal of Industrial Ecology, 2(1), 23-44.

Elia, V., Gnoni, M. G., & Tornese, F. (2017). Measuring circular economy strategies through index methods: A critical analysis. Journal of Cleaner Production, 142, 2741-2751. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.10.196

European Energy Agency. (2016). Circular economy in Europe — Developing the knowledge base (EEA Report (ISSN 1977-8449), Issue.

Farrell, C. C., Osman, A. I., Doherty, R., Saad, M., Zhang, X., Murphy, A., Harrison, J., Vennard, A. S. M., Kumaravel, V., Al-Muhtaseb, A. H., & Rooney, D. W. (2020). Technical challenges and opportunities in realising a circular economy for waste photovoltaic modules. Renewable and Sustainable Energy Reviews, 128, 109911. https://doi.org/https://doi.org/10.1016/j.rser.2020.109911

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? Journal of Cleaner Production, 143, 757-768. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.12.048

Linder, M., Sarasini, S., & van Loon, P. (2017). A Metric for Quantifying Product-Level Circularity [https://doi.org/10.1111/jiec.12552]. Journal of Industrial Ecology, 21(3), 545-558. https://doi.org/https://doi.org/10.1111/jiec.12552

Linder, M., Boyer, R. H. W., Dahllöf, L., Vanacore, E., & Hunka, A. (2020). Product-level inherent circularity and its relationship to environmental impact. Journal of Cleaner Production, 260, 121096. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.121096

Mahmoudi, S., Huda, N., & Behnia, M. (2019). Photovoltaic waste assessment: Forecasting and screening of emerging waste in Australia. Resources, Conservation and Recycling, 146, 192-205. https://doi.org/https://doi.org/10.1016/j.resconrec.2019.03.039

Pommer, K., Bech, P., Wenzel, H., Caspersen, N., & Olsen, S. I. (2003). Handbook on environmental assessment of products. Miljøstyrelsen.

Saidani, M., Yannou, B., Leroy, Y., & Cluzel, F. (2017). How to Assess Product Performance in the Circular Economy? Proposed Requirements for the Design of a Circularity Measurement Framework. Recycling, 2(1).

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., & Kendall, A. (2019). A taxonomy of circular economy indicators. *Journal of Cleaner Production*, *207*, 542-559. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.10.014

Saidani, M., & Kim, H. (2022a). Nexus Between Life Cycle Assessment, Circularity, and Sustainability Indicators—Part I: a Review. Circular Economy and Sustainability, 2(3), 1143-1156. https://doi.org/10.1007/s43615-022-00159-9

Saidani, M., Cluzel, F., Leroy, Y., Pigosso, D., Kravchenko, M., & Kim, H. (2022b). Nexus Between Life Cycle Assessment, Circularity and Sustainability Indicators—Part II: Experimentations. Circular Economy and Sustainability. https://doi.org/10.1007/s43615-022-00160-2

Saidani, M., Le Pochat, S., Monteil, A., Yannou, B., Garcia, J., & Osset, P. (2022c). Benchmark of Circularity Indicators and Links with Life Cycle Assessment