Cost benefit analysis of photovoltaic modules recycling technologies in the Australian context

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As the growth in photovoltaic (PV) technology deployment surges in the 2000s and beyond, a significant number of PV modules will be approaching their end of life (EOL) in the coming decade. This mass retirement of existing solar panels, combined with heightened environmental consciousness and the scarcity of materials such as silver, has made studying and developing PV recycling, repair, and reuse more relevant in recent years.

Given Australia's strong emphasis on the development and deployment of PV modules, studying PV EOL management can yield substantial benefits for future PV waste management efforts. Existing studies such as the work done by Liu, Zhang and Wang (2020) and Dias et al. (2022) have examined the cost-effectiveness of PV recycling with established recycling technologies and conclude recycling is currently too expensive, however, they do not account for the Economy of Scale (EOS) and Learning Effect (LE) which drives recycling cost down over time.

This paper aims to map out the cost-benefit of employing available PV recycling options in the Australian context over time while considering the cost reduction of EOS and LE. The analysis will leverage existing data on recycling costs and the projected PV EOL waste in each Australian state to estimate the cost of recycling. Through such an analysis, Australia can gain a deeper understanding of the PV recycling cost, determine the best timing for investment, and decide if additional subsidy to the industry is required.

Modelling Methodology

Three end-of-life (EOL) technologies have been considered for the scope of this project:

1. Electrostatic + Shredding (referred to as electrostatic in later texts)
2. Full Recovery of End-of-Life Photovoltaic (referred to as FRELP)
3. Recycling of aluminium frame and Junction Box only (referred to as J-Box)

An overview of the overall workflow can be seen in Figure 1.

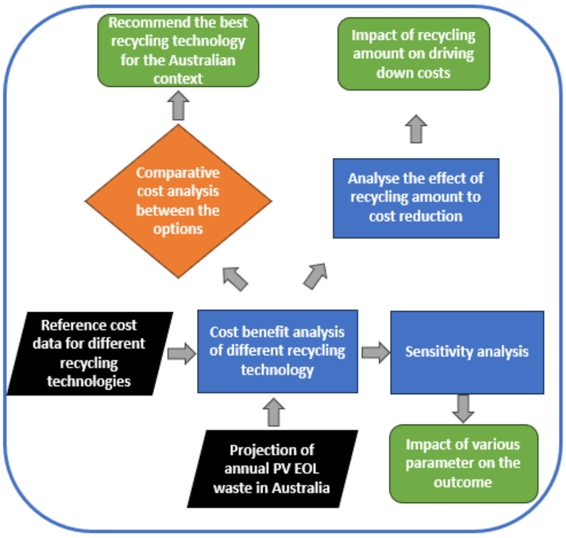

Figure 1. The overall workflow of the project

Dias et al. (2022) conducted a cost-benefit analysis on both electrostatic and FRELP processes and their reported values for landfill, raw materials, and capital costs have been used in the base case for this analysis. Labour workload and cost are approximated through the reported average hourly rate of factory workers. Annual PV EOL waste projection in Australia state-wise has been reported by Tan et al. (2023) as shown in Figure 2.

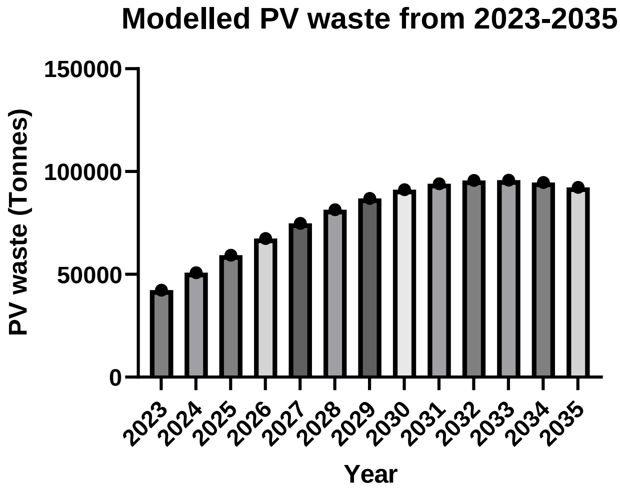

Figure 2. Annual PV waste generation data for Australia (Tan et al., 2023)

The projected PV EOL waste data are used in conjunction with the cost data to calculate the net cash flow using methods reported by Liu, Zhang, and Wang (2020), examples of equations used can be seen in Equation 1 and Equation 2.

$$Annual\ Labour\ Cost(USD) = Average\ salary\ per\ worker(USD) \times \frac{Treated\ waste\ mass\ (Tonnes)}{Workload\ per\ person\ (Tonnes)}$$

Equation 1. Calculation of labour cost reported by Liu, Zhang, and Wang (2020)

$$Annual\ linear\ depreciation\ cost\ (USD) = Capital\ cost(USD) \times \frac{1 - Salvage\ rate}{Depreciable\ life\ (years)}$$

Equation 2. Calculation of depreciation cost reported by Liu, Zhang, and Wang (2020)

The full table of all cost parameters and all equations used will be provided in the final manuscript.

It is important to note that Liu, Zhang, and Wang's work (2020) takes into consideration of both economic and environmental costs of recycling. However, this analysis focuses on examining the feasibility of PV recycling for individual startups and businesses, and thus environmental impacts are not considered. This model considers the cost of transportation, collection, capital (scaled with EOS), depreciation of assets, finance, O&M, labour, management, raw materials, landfill, tax, and GST.

To further model the effect of learning, Wright's learning model of cumulative service production as shown in Equation 3 was utilised in this analysis as it is the most accepted model. In our model, the learning effect is evaluated yearly based on the previous year's cumulative recycled amount. It is assumed that each state does not have independent learning effects, rather, learning effects are calculated based on the cumulative recycling amount of Australia. For this analysis, the cumulative amount of waste between 2007-2022 is taken as the base amount. For the PV industry, a learning effect of a 20% reduction in cost for every doubling in cumulative production is observed (VDMA, 2023). For this analysis, a more conservative 15% cost reduction for every doubling in the cumulative recycled amount is taken based on the effect of learning observed in the German recycling industry for plastics (Martin Kumar Patel et al., 2000).

$$Cost\ per\ unit = Initial\ cost\ per\ unit \times (Cumulative\ recycled\ amount)^{Learning\ Coefficient}$$

Equation 3. Wright's model of learning

A sensitivity analysis is also conducted by varying key variables such as labour cost and sales benefit of materials by +/-10% to identify hot spots.

Results and discussion

The results have been revised since the last submission. Cost benefit analysis conducted for the three technologies shown in Figure 3 shows a varying but significant effect of labour cost. This variation in labour cost is due to the complexity of each process. As the FRELP is a multi-step and significantly more complex process, more workers are naturally required to oversee its operation. Furthermore, it has a higher capital cost compared to electrostatic and J-Box, which is reflected in its higher depreciation cost. Similarly, the incomplete recycling of panels of electrostatic and J-Box incurred higher landfill costs in the form of environmental costs. This applies especially in the case of J-Box, where environmental costs make up a majority of the total costs due to the majority component of a PV panel being landfilled. It is interesting to note that electrostatic is the only technology that makes a net benefit instead of a cost, as this process is still novel, sales benefit estimations may be overestimated and hence overpromising its potential.

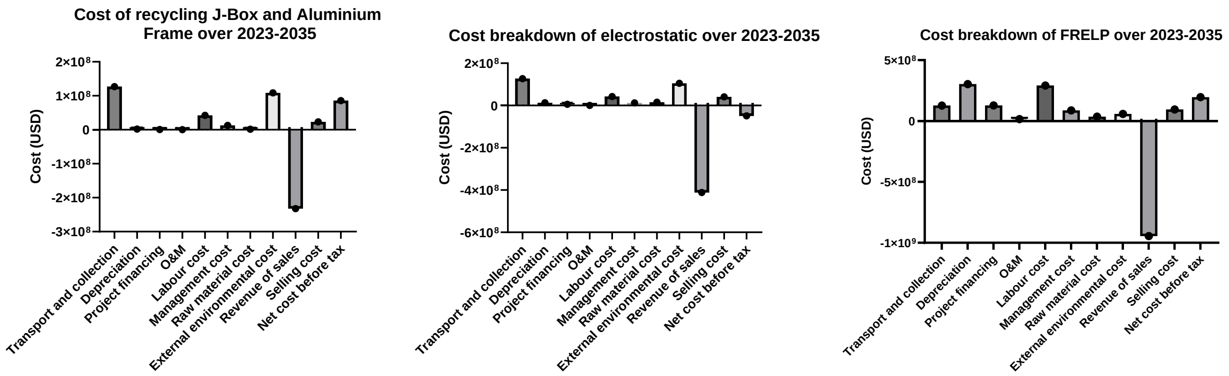

Figure 3. The cost of recycling for J-Box (left), electrostatic (middle), and FRELP (right)

Figure 4 shows the average unit cost of recycling for all states, with electrostatic being the only profitable technology, agreeing with the previous results and potentially overpromised. J-Box seems to be not profitable due to the limited material that it recycles and benefits from. In the case of FRELP, although the average unit cost of all states is higher than the unit benefit, it should be noted that this is not the case in states where PV waste volume is large such as NSW and VIC. The learning effect and economy of scale drove down the capital cost for large-scale recycling and thus enabled profitability for those states in 2030 and 2031. However, since FRELP is unable to make a profit for the initial years, it still nets a cost to the recycler by the end of the 2023-2035 period, as shown previously in Figure 3.

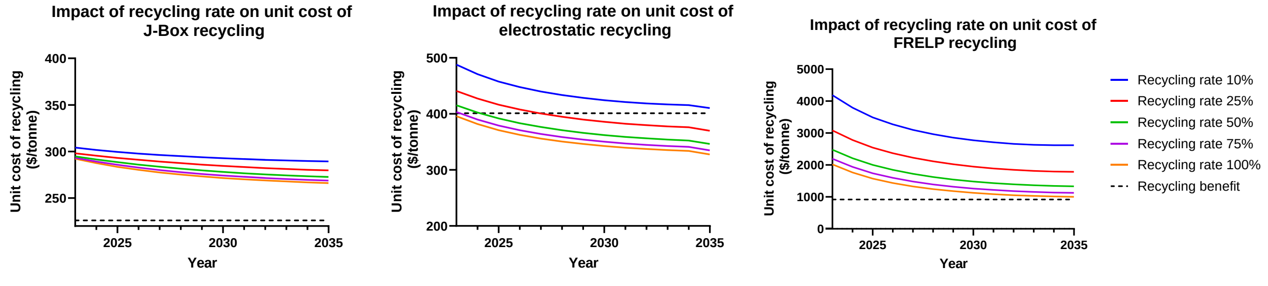

Figure 4. Unit cost of recycling for electrostatic (left) and FRELP (right) with different recycling rates.

A summarised sensitivity analysis for FRELP is also conducted by varying key parameters by +/-10%, as shown in Figure 5, the other two technologies' results and discussions are omitted here since sensitivity analysis results largely agree with what was shown in Figure 3, in terms of the impact of each cost component. Using FRELP's result as an example. it was not surprising to observe that labour and recycled material revenue are impactful and could impact the NPV of the project by up to 20% from a 10% change in those cost components.

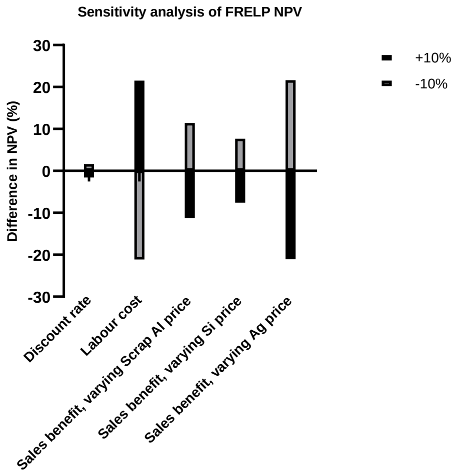

Figure 5. Sensitivity analysis of NPV for electrostatic (left) and FRELP (right)

Conclusion

From the above Figures 3-5, the dependency on labour cost and material benefit for all technologies can be confirmed, and therefore all subsequent consideration and planning of the PV recycling business in Australia should center around these two factors. This especially applies to FRELP due to the need for more labour for a more complex process. Additionally, capital cost and the associated depreciation cost make up a great proportion of the total cost for FRELP for a similar reason. For J-Box and electrostatic methods, due to the limited recovery of material and the need for landfill, the environmental cost makes up a great proportion of the cost. For all technology, the high dependency on material sales benefits also makes the profitability extremely susceptible to market fluctuation. To alleviate this dependency, and also due to the unprofitability of recycling processes, the introduction of gate fees or government subsidies may be a necessary step for the PV recycling industry to kick off and reduce financial risk and instability.

It should be noted that this project is still under some final review, and therefore some figures may change in the near future, however, no significant change is expected at the current moment. A brief analysis and suggestion on the appropriate gate fee or government subsidy required for a 10% profit margin is also planned to be included in the main report as this is crucial for the PV recycling industry to kick off. This is planned to be completed after the review of current figures has been concluded.

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