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Recycling of PV modules – framework for technical, environmental, and cost assessment

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Over the past decades, the main focus of the PV research community and industry has been to increase the efficiency and reduce the cost of PV modules in order to most rapidly increase its uptake. This effort has been very successful, with the current cost of PV generated electricity compared favourably to fossil fuel generation. Since the large and growing deployment of PV panels will eventually reach their end-of-life, there is now increasing attention being paid to how to manage the waste. In the waste hierarchy, once re-use options have been exhausted, recycling is a more desirable alternative to disposal (typically in landfill). Recycling has the benefit of recovering materials such as glass, aluminium, silicon and silver, avoiding the financial and environmental cost of mining and purifying them from primary sources. However, the economic and environmental cost of recycling – collection, separation, processing, purifying – is not zero, which may negatively impact the feasibility of its widespread adoption. Here, we present a framework of how to evaluate potential recycling pathways in terms of technical feasibility, recovery rates, environmental net impact and economic net cost. Recent results from the analysis of two such pathways are shown, indicating the key cost and revenue drivers.

The end-of-life challenge for PV

Recent reports and predictions of the amount of PV waste conclude there will be a need manage this waste stream in the future. For example, a report from IRENA and IEA (IRENA, 2016), predicts waste volumes worldwide greater than 60 million tonnes by 2050. Such waste presents both a challenge - landfill disposal takes up space and has the potential to leach toxic chemicals, and an opportunity – the materials within waste modules could be recovered for other uses.

This raises the question of what is the best way to manage this waste. As discussed by Deng (2019), there are multiple paths being explored for module recycling as an alternative to landfill, but reductions in recycling process cost or improvements to recovered material value are needed in order for it to become cost effective.

Recycling Pathway Assessment – Framework

To assess a recycling pathway, we see three inter-related aspects. The first is the technical feasibility of the method. At this point, the focus is on whether a particular pathway can technically achieve a recycling outcome. Experiments are carried out, measurements of the amount and purity of the extracted materials are made. At this stage, although not strictly necessary, it is helpful to also record information about energy use, processing time, labour, etc. This information will be fed into the next stages.

The second aspect is the net environmental impact of the recycling pathway. Energy (mostly electricity) and materials (often chemicals) are typically consumed in order to implement the recycling process, and environmentally damaging emissions can also occur – such as CO2 from thermal decomposition, toxic chemicals, particulate matter, etc. These environmental costs need to be outweighed by the environmental benefits of the materials extracted by the recycling processes. If this cannot be done, then the recycling process is not beneficial environmentally and should not proceed. The data obtained during the feasibility assessment can be used to conduct a Life Cycle Analysis that calculates the net environmental cost. Some assumptions for industrialisation of the process may be needed in order to carry out a realistic assessment.

The final aspect is economic. While it may be that a particular recycling pathway is technically feasible and also environmentally beneficial, it is also necessary that the net cost (the sales of the recovered materials less the cost of the recycling processes) is as low as possible. In the best case, the net cost would be zero or negative – so that recycling could be carried out with no cost to society (be that governments, industry or consumers), but a low net cost would also be allowable if it was sufficiently low that either i) those disposing used PV were willing to pay this out of concern for the environment, ii) the cost was lower than the cost of alternative disposal (such as landfill fees), or iii) that a stewardship scheme could be operated at an acceptable cost to the government, industry and consumers. The data obtained in the technical assessment can also be used as a basis for a net cost analysis of the recycling pathway. Additional assumptions such as equipment cost and throughput, energy and labour use at industrial scale will usually need to be made.

This framework will be illustrated with two examples of published or to be published work.

Example 1 – Toluene Recycling

The details of this analysis are published (Dias, 2021a), and an overview will be presented at the conference.

Technical Feasibility was demonstrated in the lab, with some images illustrating the process shown in Figure 1.

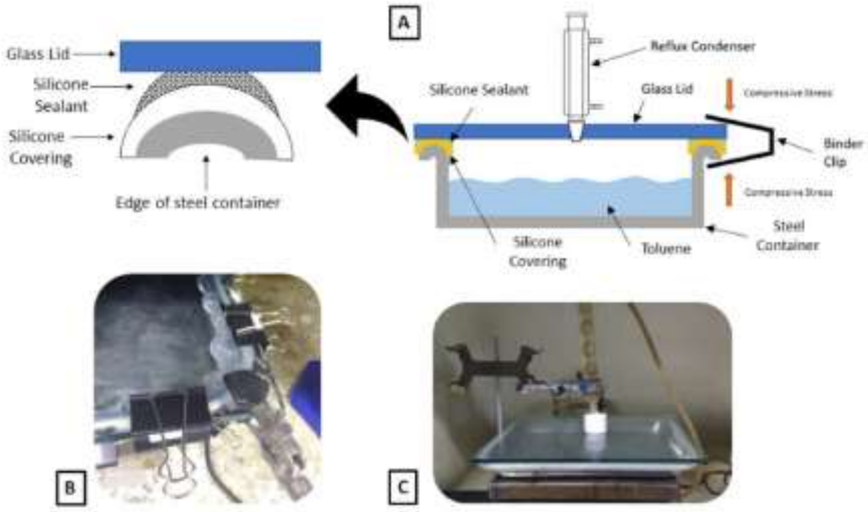

Figure 1. Reproduced from Dias, 2020. The toluene recycling lab setup.

Results from an environmental assessment is shown in Figure 2a, and the cost assessment in Figure 2b. Both the lab process and a proposed industrialised process were analysed.

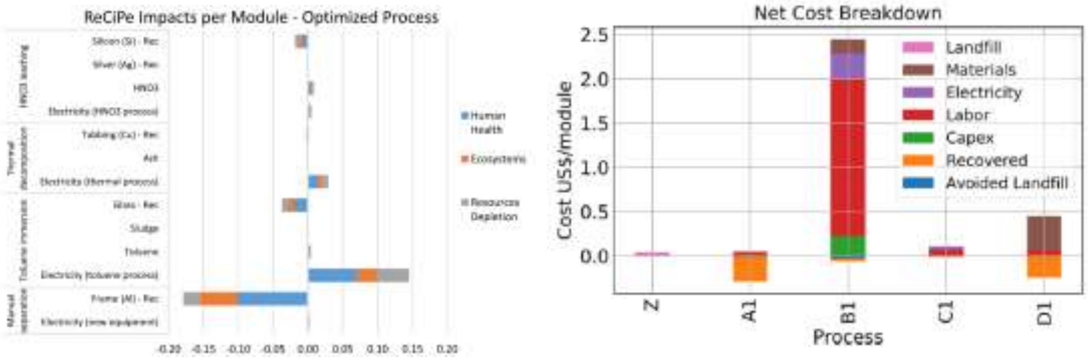

Figure 2. a) Environmental and b) cost assessment of the Toluene recycling pathway, reproduced from Dias, 2020. In b) Process Z = the cost of landfilling the module instead of recycling, A1 = frame removal, B1 = Toluene separation, C1 = thermal decomposition and D1 = metal recovery.

This analysis suggested that the industrialized process would have a net environmental benefit (Figure 2a, with the environmental benefits from recovered materials outweighing the environmental costs of the processing). However, the economic analysis showed the revenue from the recovered materials was not sufficient to compensate for the costs of the recycling processes (Figure 2b). In that figure, it is the Toluene separation process (Process B1) that has the greatest cost. It is the very long processing time for this process (multiple days) that results in high labour costs as well as significant capital costs and material wastage to evaporation. Significant improvements to this toluene process would be required in order to make this recycling pathway cost-effective.

Example 2 – Electrostatic Recycling

This analysis is currently under review (Dias, 2021b). An electrostatic recycling pathway was developed experimentally (Figure 3).

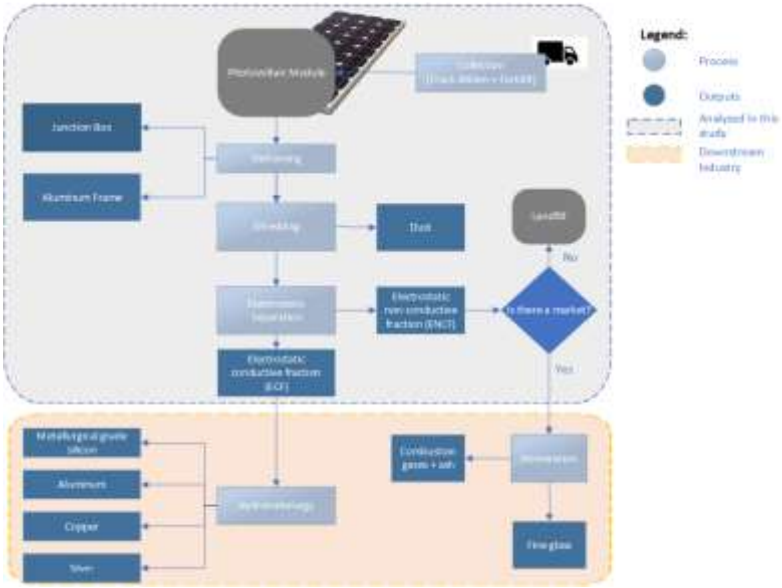

Figure 3. An electrostatic separation recycling pathway, reproduced from Dias, 2021.

From the experimental results and data collected, LCA analysis (Figure 4a) and cost analysis (Figure 4b) were completed.

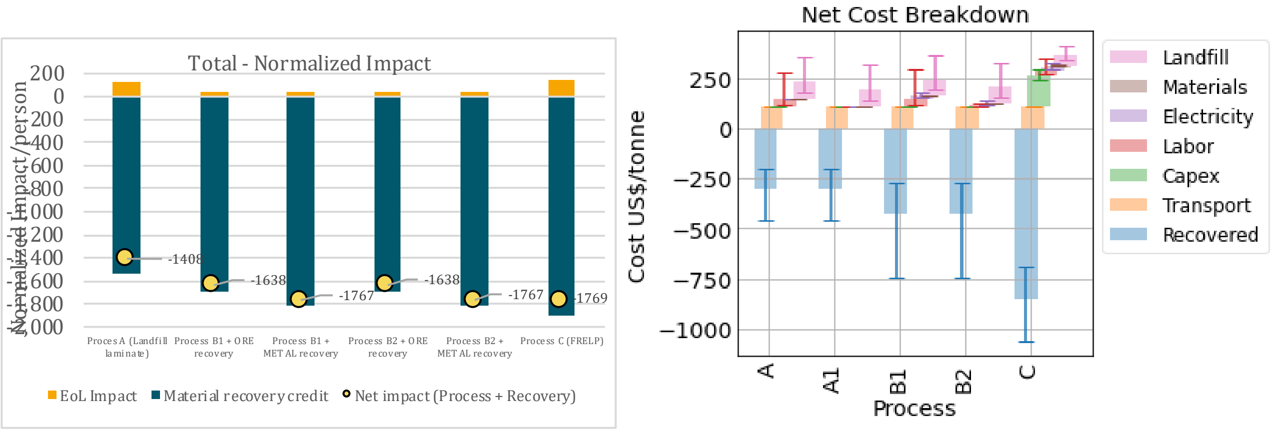

Figure 4. a) LCA analysis and b) cost analysis of the electrostatic separation recycling pathway, reproduced from Dias, 2021. In b), the error bars indicate the uncertainty bounds of each cost component in the analysis.

In a similar way to the Toluene process, the electrostatic process was more favourable environmentally (Figure 4a) when compared to Process A (“Recycle Frame, landfill laminate), although the exact environmental benefit depends on how much additional processing is required to purify and separate the metal particles for later use. The net cost breakdown (Figure 4b) showed that the electrostatic processes (B1 and B2) have marginally more cost than the frame-only processes (A and A1), but with greater revenues from recovered materials. The results are compared to an alternative more complex process (FRELP, process C) with even higher costs but more purified recovered materials. The net cost potential of process C is greater than the electrostatic processes, however the electrostatic process could implemented at relatively low capital cost, and would thus be more economical in the short-medium term when PV recycling volumes are still low.

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