Setting the Stage for a Circular Solar Economy

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The world has been transitioning to renewable energy sources under threats of climate change, supply security and worldwide depletion [1]. Solar energy in the form of photovoltaics has seen mass adoption and exploitation since the 2000s. As a result, a record breaking 175 GW of new solar capacity was installed in 2021 with 55 GW installed in China, 27 GW contributed by America and 27 GW added by the European Union. This brings the cumulative global capacity up to 942 GW and it is expected to exceed 4,500 GW by 2050 [2, 3]. The mass rollout of photovoltaic technology has generated the lagging issue of rising volumes of decommissioned solar modules at the end of their lifetime of 25 – 30 years [3, 4]. Modelling conducted by the International Renewable Energy Agency (IRENA) and International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS) forecasts that the cumulative mass of end-of-life panels could be upwards of 80 million tonnes by 2050. The looming issues of overwhelming amounts of solar waste brings together an environmental challenge with a unique opportunity. The potential value of recoverable materials in waste modules by 2050 has been valued at $50 billion USD, with the capacity to produce 2 billion new panels equivalent to 630 GW of new capacity [3, 4].

Current technological effort have been made to mechanically dismantle the aluminium frame and strip majority of the solar glass from the panel [5]. This process leaves behind the photovoltaic laminate, which is composed of the residual glass, solar cells, and backsheet adhered together by the ethylene vinyl-acetate (EVA). The next step required in this the solar panel recycling process is one that can efficiently delaminate these layers allowing for the removal of the polymer components while liberating the valuable materials in the solar cells. Ideally, this would be a low cost, low energy process that effectively separates the critical materials in the solar cells from the EVA and polymer backsheet. Mechanical and thermal approaches have been investigated as methods of recovering the high value materials from the EVA matrix. However, these approaches have significant short falls. Mechanical methods can not achieve complete separation and require enrichment through additional processes. Thermal techniques generate harmful pollutants and emissions due to the pyrolysis of the EVA and potentially fluorinated polymer backsheet [5-8].

Chemical delamination of solar panel laminates utilises a solvent to penetrate the EVA component and swell it into a gel-like polymer which can liberate the valuable materials [5, 8]. Organic solvents such as acetone, toluene, ethanol, isopropanol, trichloroethylene, hexane and benzene have primarily been investigated by the literature for use in chemical delamination [9, 10]. However, these solvents are generally toxic and hazardous and as a result safer alternative would be industrially preferred [5].

This work proposes the investigation of bio-based solvents as well as deep eutectic solvents as an alternative to an organic solvent. Experiments were conducted on two different photovoltaic laminates to examine the separation effectiveness of toluene, d-limonene, Cyrene and three deep eutectic solvents based on choline chloride, urea and zinc chloride. The laminates tested were cut into 10 mm x 10 mm squares and the solid to liquid ratio was maintained at 5 mm^2/mL. The samples were stirred and heated in the solvent for 30 minutes before being filtered and the backsheet manually separated. The remaining solar cells and EVA were then sieved into three fractions (greater than 1.0 mm, 1.0 mm to 0.5 mm and less than 0.5 mm). The fractions were then

burnt under air at 550°C for 2 hours. The oxidised mass-loss component was representative of the EVA and the ash was composed of the silicon, silver and copper which constitute the solar cells.

The composition of the two different samples can be seen in Figure 1 and was found to vary mainly due to the weight of the backsheet. Sample 2 had a much denser backsheet which accounted for approximately 29% of the laminates weight, while the backsheet of sample 1 only contributed to 9% of the laminate composition. This is also consistent with the observation that the backsheet from sample 2 was thicker and more rigid than that of sample 1. Additionally, the composition with regards to the solar cells and EVA is similar across the panels as the backsheet free percentage of EVA in sample 1 and 2 is 58% and 62% respectively.

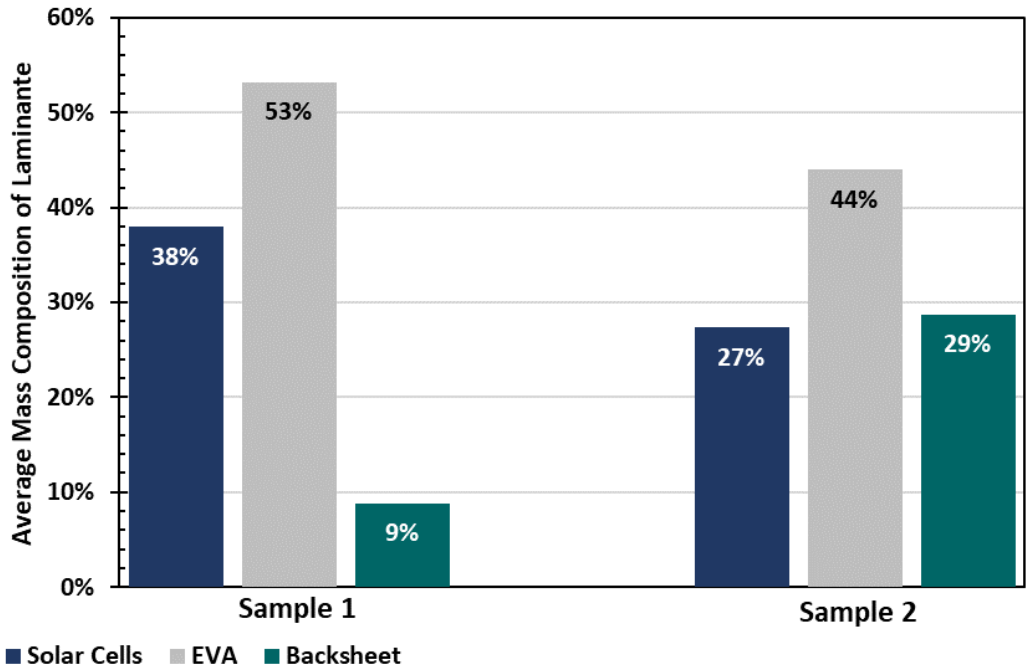

Figure 1: Average compositions of the two solar cell laminates (solar glass removed) tested.

Both toluene and d-limonene were able to successfully separate the backsheet from the EVA and solar cells. The Cyrene did not separate the layers in the sample, but it was found that the backsheet would dissolve in the solvent above 160°C. In the case of sample 1 the entire backsheet dissolved and sample 2 only had partial backsheet dissolution. When the samples were removed and the solvent cooled the dissolved backsheet precipitated out of solution. All three deep eutectic solvents used had no discernible effect on the samples and delamination was not observed for the conditions tested.

Following delamination treatment the samples that were treated with toluene and d-limonene were then sieved. Figure 2 shows the result of the sieving process and it can be seen that majority of the sample remains above 1.0 mm in size. The smaller fractions mostly contain pieces of liberated solar cell while the larger fraction appears to be unliberated solar cell material that is still tightly bonded to the EVA.

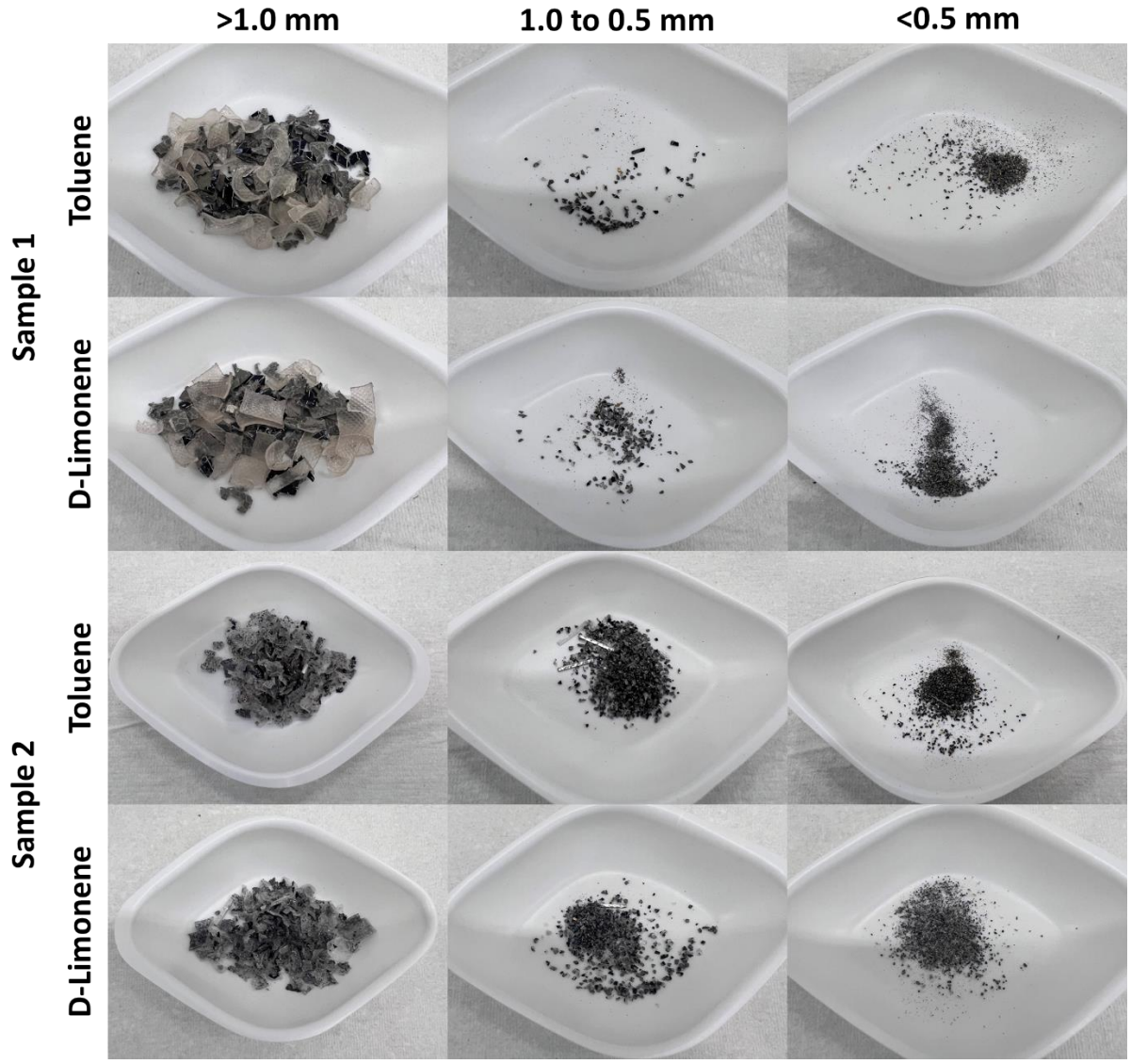

Figure 2: Size fractions of samples 1 and 2 generated as a result of treatment with either toluene or d-limonene at 90°C.

To compare the effectiveness of the solvents the remaining EVA in each size fraction was then calculated by mass loss burn off. This quantifies the amount of residual EVA in each fraction as well as the degree of liberation experience by the solar cells in their specific size fractions. Figure 3 shows the comparison of the remaining ash and removed EVA in each size fraction for the samples treated with toluene and d-limonene. Made evident by Figure 3 is that the effectiveness of d-limonene at liberating the solar cell material is very similar to toluene, as the degree of separation of the solar cell material from the EVA component is similar across both solvents.

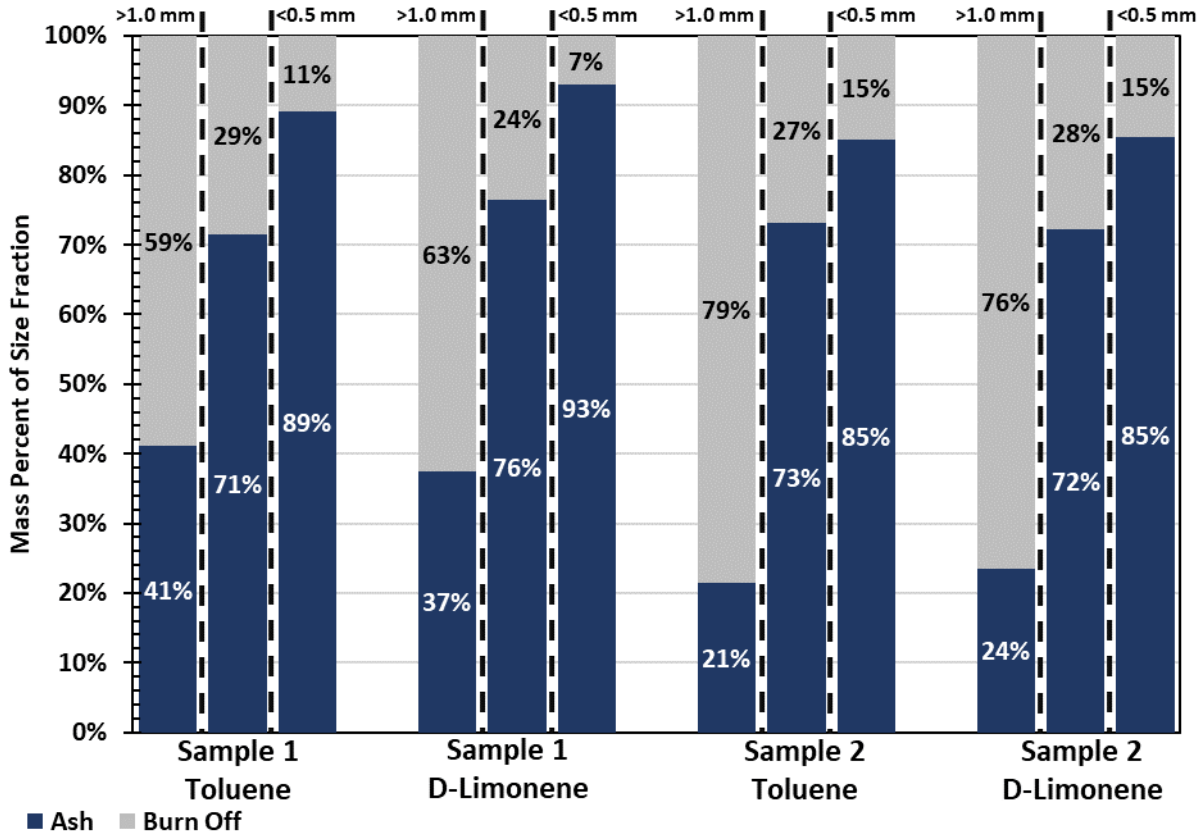

Figure 3: Comparison of the ash and burnt off material in samples 1 and 2 after treatment with toluene or d-limonene at 90°C.

These results indicate that d-limonene is a suitable green solvent alternative to toluene. A similar separation was observed, however d-limonene is derived from biomass such as citrus peels, making it a clear choice compared to the far more volatile and fossil fuel derived toluene [11].

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