SUPPLEMENTARY INFORMATION

Can Recycled E-Waste Polymers Power the Future of Sensors?

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1. Life cycle perspective for chemically recycled epoxy polymers

In practical applications, the life-cycle impacts of chemically recycled polymers are strongly dependent on the specific material system, the regional electricity and thermal energy supply mix, and the particular recycling pathway implemented. The values reported herein represent screening-level ranges derived from published life cycle assessment (LCA) studies and process data, and therefore do not reflect plant-specific performance. To place the techno-economic viability of the strategies examined in this Perspective within a broader environmental context, a screening-level LCA was conducted, with results summarized in Table S1. In this preliminary analysis, epoxy resin used as a key constituent of printed circuit board (PCB) substrates is selected as a representative model system. The functional unit is defined as 1 kg of epoxy-based polymer suitable for PCB substrate fabrication. Two routes are compared: (i) a conventional pathway involving virgin epoxy production from petrochemical feedstocks followed by laminate fabrication, which is energy intensive and associated with substantial CO_2 emissions arising from precursor synthesis and high-temperature curing steps [1, 2]; and (ii) the alternative route emphasized in this study, based on solvothermal depolymerization of epoxy-rich e-waste at 100–150 °C, enabling removal of halogenated flame retardants, high solvent recovery (90–95%), materials-informatics-guided reformulation, and subsequent low-temperature fabrication into PCB substrates or polymer-based sensing components [3].

The economic and environmental viability of the proposed route is further strengthened when recovered epoxy fractions are directed toward high-value [2], performance-driven applications such as PCB substrates, dielectric layers, and rigid polymer-based sensors, rather than commodity polymer markets. In such applications, low-temperature fabrication methodologies (e.g., solution processing and printing) obviate the need for the energy-intensive thermal curing steps characteristic of conventional PCB manufacturing. This advantage arises because solution- and printing-based processing of functional layers and substrates can be conducted at temperatures of $\leq$120–150 °C, or even at ambient (room) temperature. These processing temperatures are substantially lower than those required for lamination and curing of conventional FR-4 (glass-fiber-reinforced epoxy laminate, widely used as a PCB substrate), which typically necessitate $\sim$170–200 °C to achieve full curing of the epoxy–glass composite. Consequently, these reduced thermal processing requirements further enhance the LCA benefits associated with the recycled manufacturing route [4, 5]. Accordingly,

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chemically recycled epoxy can offer lower energy demand and carbon footprint, and approach cost competitiveness with virgin epoxy only under process-specific conditions such as high solvent recovery, efficient depolymerisation, and adequate scale. Within this roadmap, LCAs are therefore not treated as one-off assessments but can be performed on demand for specific recycled-polymer streams emerging from pre-treatment and cleaning processes. The resulting environmental impact and cost metrics can then be fed back as constraints in experimental design, for example by excluding formulations whose predicted footprint exceeds predefined thresholds, thereby narrowing the combinatorial search space toward polymer systems that are simultaneously fit-for-purpose and life-cycle-efficient.

Table S1: Screening-level LCA comparison for epoxy PCB substrate materials with literature sources.

Parameter (per kg polymer)	**Virgin epoxy**	**Chemically recycled epoxy**
Primary energy demand	80–100 MJ/kg, based on cumulative/primary energy demand reported for commercial petro epoxy resin [6, 7, 8, 9]	Case specific; expected to be lower than the virgin route when efficient chemical or enzymatic depolymerisation and high solvent recovery are implemented. La Rosa *et al.* reported that Recyclamine-based epoxy recycling operates at low temperatures (70–100 °C), leading to reduced energy demand as indicated by LCA.[10]
Typical process temperature	>120–250 °C; epoxy curing and FR 4 lamination commonly use 170–200 °C for 60–120 min, often above T_g ≈130–140 °C [11, 12].	Recent catalytic and enzymatic depolymerisation routes for epoxy thermosets operate at comparatively lower temperatures (often around 100–120 °C or below) than traditional high temperature routes, but the exact temperature depends on the chosen chemistry, catalyst system, and waste composition [13].
CO_2 footprint	A typical cradle to gate global warming potential (GWP) for commercial epoxy resins lies in the range 5–7 kg CO_2 eq/kg [6, 8, 14]	Recyclable systems and advanced e- waste recycling scenarios can yield substantial greenhouse gas reductions. For example, an integrative assessment of WEEE recycling in China reported national scale reductions of 8.36 million t CO_2 eq/year when resource recovery is fully accounted for [15]. However, the actual CO_2 footprint for a chemically recycled epoxy must still be evaluated case by case, using process specific inventories and system boundaries.
Key cost drivers	Petrochemical feedstocks (BPA, epichlorohydrin), multi step synthesis, and energy intensive curing/lamination [16, 17].	Dominated by waste collection and sorting, depolymerisation chemistry (chemical or enzymatic catalysts), solvent and energy use, and solvent recovery efficiency; low temperature catalytic or enzymatic routes can reduce energy and capital demand, but total cost remains highly process and scale dependent [17, 18].
Solvent recovery	–	Often targeted at ≈90–95% in design and pilot scale studies for chemical recycling of thermosets [3]; actual recovery depends on the solvent system, plant design, and operational strategy .

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Table S1 – continued from previous page

Parameter (per kg polymer)	**Virgin epoxy**	**Chemically recycled epoxy**
Estimated material cost	Typically ≈3–5 USD/kg for bulk petro epoxy, depending on grade and region. [19, 20].	La Rosa *et al.* demonstrate that if both the fibres and the recycled epoxy-based matrix are recovered and reused, the combined savings from reduced purchases of new carbon fibre and resin, along with lower disposal costs, exceed the expenses of operating the recycling process. [10].

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