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Repairing of in-mold electronics and life cycle assessment

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ABSTRACT

Repairing electronics remains challenging due to manufacturing processes in which molten thermoplastics solidify directly onto semiconductor components. In-Mold Electronics (IME) exemplify this issue, often encapsulated in several millimeters of plastic. This study demonstrates a successful repair protocol involving dismantling, circuitry repair, component replacement, and re-encapsulation via injection molding. Repair-induced quality loss was quantified as a 2 ± 2% increase in power consumption. A cradle-to-grave life cycle assessment (LCA) revealed that circular strategies—repair and recycling—can reduce the global warming potential by up to 41%, assuming a 4% increase in power consumption. Additional environmental benefits include an 80% reduction in mineral scarcity impacts, particularly due to silver recovery. Avoiding the manufacture of replacement devices and reclaiming embedded high-value components significantly lowered environmental burdens and improved cost efficiency. These findings underscore the importance of circular strategies that prioritize repair and material recovery to extend device lifespans and reduce reliance on virgin resources.

1. Introduction

For electronics and electronic equipment (EEE), reduced carbon emissions are accomplished by various strategies involving reducing material usage, maximizing the lifespan, and improving energy efficiency (Cole et al., 2016). Strategies focused on lifetime extension involve refurbishing, remanufacturing and repair (Apprey et al., 2024; Bakker et al., 2023; Bovea et al., 2020; Cole et al., 2016; Davies, 1975; Richmond et al., 2022; Rudolf et al., 2022), and may be quite beneficial as the burdens from materials and producing are avoided. Repair should be beneficial for the environment, but should also be economically viable, technically achievable, and manageable. In the EU, legislation to ensure the consumer's Right to Repair is in development, however, not yet fully established in its member states (Bakker et al., 2023; Ganapini, 2024). For a few, but common household and electronic appliances, the existing regulations not only enabled the availability of tools and spare parts for a certain period but actually made it mandatory and affordable as of 2026 (Ganapini, 2024). A 2023 white paper by Leiden, Delft and Erasmus Universities (Bakker et al., 2023), however, emphasized that the Right to Repair would only apply when repair is cheaper than a replacement and does not limit the time allowed for repair. From the consumer and producer's point of view, the environmental impacts of EEE are unfortunately not a leading factor in design and sales (Nagase and Uehara, 2024). Promising though is that consumers may well be inclined to choose repair over disposal if conditions are favorable, such as low effort, low costs and easy accessibility to repair options (Šajn, 2022). Repair of EEE is, however, associated with high labor costs. Moreover, the success rate may be considerably lower than 100 % (Rudolf et al., 2022). Several barriers were identified in a UK study in 2016, especially related to damage during collection for reuse and necessary skills for testing and repairs (Cole et al., 2016). Fortunately, producers like Fairphone actively pursue higher sustainability by including a more accessible and modular design, more sustainable materials, enabling repairability for consumers as a conscious choice (Reuter et al., 2018; Sánchez et al., 2022).

Many aspects may complicate repair though: liability, responsibility, component availability, expertise, confidentiality, sufficient locations for consumers to turn to, warranty and acceptance, to name a few. Some aspects related to expertise, protocols and limitations to the extent to which repairing should be done, have been described decades ago (Davies, 1975) and have been covered by modern standards for e.g. printed circuitry boards. The repair of printed circuitry boards (PCBs) is

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covered a.o. by IPC standards IPC-7711/7721, IPC-A-610 and IPC-J-STD-001. For In-Mold Electronics, however, repairing has not yet become possible and does not fit into PCB standards.

In this article, we focus on the technical feasibility for repair of in-mold electronics (IME) and associated environmental impacts. IME is a rigid variant of hybrid & printed electronics in which printed circuitry is applied to a flat and formable thermoplastic substrate, typically polycarbonate, by printing metal pastes (Beltrão et al., 2022; Goument et al., 2023; Jääskä et al., 2023; Srinivasan and Muthuramalingam, 2021). By adding discrete SMD components, such as light emitting diodes (LEDs), sensors, resistors, capacitors and driving chips, IME provides a great deal of added functionalities (e.g. light source, sensors, actuators). Unique to IME is the combination of printed electronics onto 2D substrates with high-pressure thermoforming to achieve the 2½ or 3D shape of the final product. Subsequent injection molding provides stability, rigidity, and encapsulation of printed electronics protecting it from environmental influences. A previous article on IME dismantling described its complexities (Harkema et al., 2024). A perfect execution of dismantling was described to result in full recovery of the functional substrate including all components. Repair was suggested but has not been demonstrated for IME in any study at the time of writing to the best of our knowledge.

Following this introduction, section two describes the experimental details of IME device fabrication, electrical performance, dismantling of the devices, and a description of our repair actions. In section three, the life cycle assessment (LCA) is introduced. Section four focuses on experimental results of fabrication, dismantling, and repairing. Section five summarizes the LCA results. In Section six, repairing of IME from both practical and environmental aspects is discussed before presenting our conclusions in Section seven.

2. Experimental

IME devices were manufactured using polycarbonate (PC) functional substrates (Makrofol DE 1–1, Covestro) and polycarbonate resin (Sabic 123r) for injection molding using similar material and methods as described in our previous study (Harkema et al., 2024). A functional substrate comprised a blue graphic coating (Proell Noriphan N2K, dark blue in Fig. 1), a printed silver circuitry (DuPont ME604, light grey in Fig. 1) with white LEDs (SCMP13WBC8W1, Rohm) and a dismantling layer (green in Fig. 1). The dismantling layer was either a water-based non-adhering layer (Harkema et al., 2024) or a water-based adhesive (W128, Kiwo). Components were bonded with Loctite Ablestik CE 3104WXL asisotropic conductive adhesive (ICA) and Stycast A-312 for underfilling (UF). The functional foils were encapsulated with polycarbonate resin in a Engel Victory 50 injection molding tool. Mechanical disassembly of defective devices proceeded by peeling off the substrate at a speed of 50 mm per minute using a Mark 10 M7i tensile tester that was adapted with a G1109 90° Peel Fixture. Alternatively, dismantling could be done by hand in roughly 15 s. Repairing after dismantling was done manually using the same materials as during manufacturing. The devices were repaired either in limited fashion, not at all or extensively. Extensive repairing involved tracking down all microscopic cracks by microscopy and repairing these with conductive ink, strengthening the Ag circuitry at folds in the polycarbonate substrate, as these may pose a risk in a later stage of device use, and checking of proper LED placing and bonding. The repaired devices were hereafter re-encapsulated with polycarbonate (PC) resin. Electrical characterization after repairing was performed using an oscilloscope (DSO6034A, Agilent Technologies) using a high accuracy 0.1Ω resistor (accuracy 0.05 %). A typical measurement of a properly functioning single string of 33 LEDs would exhibit a steep rise and LED turn-on at 3.3 ± 0.1 mV (33 mA current) and a further increase hereafter due to heating. Separate measurements of the total power consumption were conducted using a Keithley power meter. The devices were monitored over 5 min and measurements were made with regular intervals.

A separate repair experiment was performed to determine the necessary time and materials. A single foil with a variety of defects was chosen for this purpose: i) a total of 20 LEDs were deliberately removed; ii) a set of 4 large damages was deliberately created manually using a knife, and iii) 4 micro-cracks were found in the Ag circuitry. The protocol for repair was: 1) dismantle the device in about 15 s manually after heating up the device for 5 min in a box oven; 2) determine damages, costing roughly 60 s; 3) repair damaged circuitry with 6.77 g of Ag ink (ME604) during 3 min 50 s; 4) curing for 2 min at 120 °C in a convection oven; 5) manual application of isotropic conductive adhesive (ICA) by dispensing for 20 LEDs in 6 min 36 s using 10.93 mg of the Ag adhesive; 6) placement of LEDs, either manually or by machine using the Mycronic My200DX-14; 7) cure for 10 min at 120 °C; 8) manual underfilling of 20 LEDs during 6 min 20 s using 10.72 mg of epoxy underfill adhesive in total; 9) curing for 20 min at 120 °C; 10) confirm the performance in 15 s; 11) overmold in 12 s with 65 g of polycarbonate (30 s including insertion into the Engel Victory 50 apparatus). The prescribed drying time for the material used in step 3) is 20 min, but a short drying step at this point during processing is sufficient with a large curing step at 7) and 9). The full approach to dismantle and repair is provided in detail in Table 1. As stated, LED bonding of half of the LEDs (10) was performed by machine (Mycronic pick & place tool), and the rest by hand, while all could be performed in an automated fashion. Due to local deformations in the PC substrate, the machine required a relatively long time to recalibrate for each replaced LED, leading to a total time of use of 5 min and 36 s for 10 LEDs before applying the LEDs in an additional 30 s. Material usage and power consumption during repair were used as primary data in the life cycle assessment. Recorded time frames were

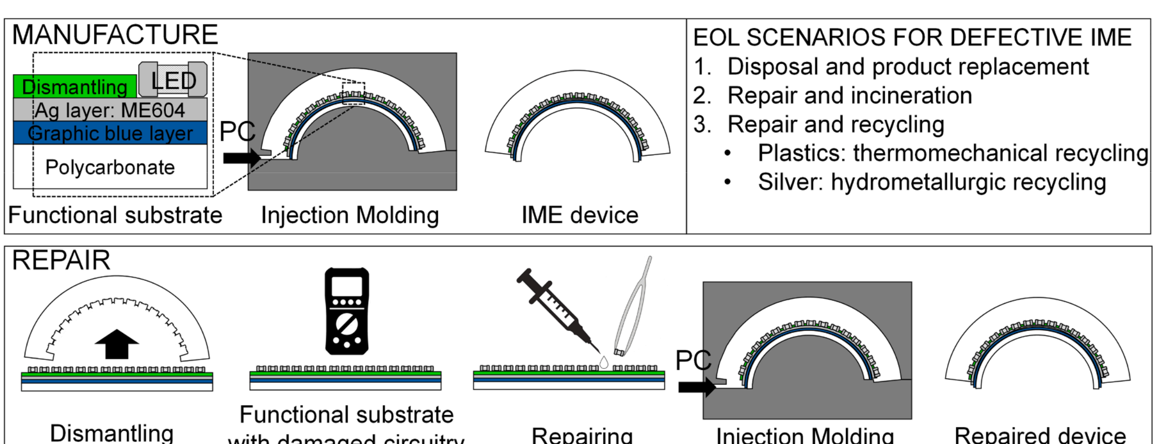

Fig. 1. Schematic representation of manufacturing and repair with the three end-of-life scenarios considered in this study.

Table 1
Procedure and details of IME repair upon manufacturing failure.

Repair step		Description	Time (s) per unit	Total time (min)	Time (hr)	Power (kWh)
1	Heating step	Thermal step; dismantling requiring 5 min of heating in a box oven for 5 min at 145 °C; a batch of 4 devices is assumed	300	5.00	0.08	0.89
	Dismantling	Manual dismantling of IME for 15 s	15	0.25	0.00	
2	Measure	Manual check for damages to circuitry using multimeter for 60 s	60	1.00	0.02	~0
3	Circuitry repair	Manual repair of damages to circuitry for 3:50 min	230	3.83	0.06	
	Ink usage	Ag ink used for the repairs: 6.77 mg Ag ink				
4	Curing	Thermal step; curing of Ag ink for 2 min at 120 °C; a batch of 4 devices is assumed.	120	2.00	0.03	0.71
5	Apply ICA	Manual application of isotropic conductive adhesive (ICA) by dispensing during 6 min 36 s for 20 LEDs	396	6.60	0.11	
	ICA usage	Ag adhesive used for 20 LED bonding: 10.93 mg				
6	Recalibration of Mycronic	Automated step: recalibration of the Mycronic pick&place tool for 5 min 6 s for 10 LEDs due to foil distortions	306	5.10	0.09	1.50
	Pick & place	Automated step: pick and place costing 30 s for half of the total amount of LEDs in total	30	0.50	0.01	1.50
	Manual application	Manual step: application of remaining 10 LEDs by hand during 9 min 22s	562	9.37	0.16	
7	Curing	Thermal step; curing of ICA for 10 min in a box oven at 120 °C; a batch of 4 devices is assumed.	600	10	0.17	0.71
8	Apply underfill	Manual dispensing of underfill (UF) adhesive during 6 min for all 20 LEDs	380	6.33	0.11	
	UF usage	Underfill material usage: 10.72 mg				
9	Curing	Thermal step; curing of UF for 20 min at 120 °C; a batch of 4 devices is assumed.	1200	20	0.33	0.74
10	Measure	Manual activation of device using power source or battery taking 15s	15	0.25	0.00	~0
11	IJM	Injection molding of 0.078 kg PC (incl. 20 % IJM production losses) for 30 s per part	30	0.50	0.01	
	IJM electricity	Power consumption: 0.078 kg PC costing 0.481 kW/kg PC (Engel Victory 50 primary data)				0.481 kW/kg
	PC usage	0.078 PC was applied (incl. 20 % IJM production losses)				

used to assess the costs for repair. Repair times and approaches were not optimized in our feasibility study to minimize labor and cost of repairs.

3. Life cycle assessment

The goal of this LCA is to show how repairing in-mold electronics can impact their sustainability indicators and the potential trade-offs. For this purpose, the ISO 14,040:2006 and 14,044:2006 guidelines were applied. The system boundaries include all stages from production to EoL focusing on repair and its respective burdens and benefits. Primary data from our experiments was used to model production and repair. Other phases were modelled with secondary data from literature and EcoInvent 3.11. The life cycle impact assessment was done using ReCiPe 2016 midpoint (H) method (Huijbregts et al., 2017) in SimaPro.

The time frame considered for the IME lighting device is as long as the car service life in which it is installed. The service life of the vehicle is 168,000 km (Syré et al., 2020). It is assumed that the IME will fail once during this period and will need to be repaired or replaced to continue servicing the vehicle user. Thus, the functional unit for this LCA is defined as the production, use, repair, and disposal of an IME lighting device during the service life of the vehicle it is integrated into. Quality loss of the device due to repairing was included as an increase in power consumption during use phase. The increase was measured experimentally as explained in Section 2. Experimental.

Three scenarios were modelled to show the effects of repair and subsequent recycling (Fig. 1).

1. The device is produced, breaks and is replaced by a new one;
2. The device is produced, breaks, is repaired and all parts disposed of are incinerated;
3. The device is produced, breaks, is repaired and all parts disposed of, including the polycarbonate encapsulant, are recycled. At EoL, the device and its components are recycled. Ag on the functional substrate was recovered using hydrometallurgy and electrodeposition processes and modelled with data from literature (Iannicelli-zubiani et al., 2017).

The power consumption of the IME device was calculated as 6.8 kW from device operation and 1.7 kW from the contribution to the car's weight. This estimate follows the methodology described in the literature (Mamala et al., 2021; Syré et al., 2020) but is likely an overestimate since a lighting device would include an off-state during daylight and a mild on-state during night time. However, due to the lack of more precise data the peak power is used.

Adding a dismantling layer to IME devices to facilitate repair also creates the possibility to separate materials at EoL. These materials can enter different waste streams going to recyclers. Thus, to give insight into the impacts of this new possibility, two EoL scenarios were modelled (2,3 in Fig. 1) and compared to the first (1 in Fig. 1). Incineration with energy recovery after repair and at the IME's EoL and recycling with recovery of Ag and PC recycling after repair and at EoL. The burdens and benefits from these processes consider hydrometallurgical recovery of Ag and thermomechanical recycling of PC.

Hydrometallurgical recovery of Ag was modelled following a study on a pilot plant designed for the treatment of small Waste Electrical and Electronic Equipment containing a detailed LCA model. (Iannicelli-zubiani et al., 2017) The processes described in that study were reproduced by us in SimaPro and adapted to our case. The first step in the treatment is dissolution in nitric acid, followed by Ag electrodeposition and subsequent treatment of wastewater. Au recovery is not applicable to our IME devices, and was thus not included in the adapted model. (Iannicelli-zubiani et al., 2017).

Experiments on Ag recovery from IME by TNO and University of L'Aquila using methodologies developed during the EU Treasure project (Ippolito et al., 2023; Ullah et al., 2024), showed that PC substrate and the PC encapsulation could also be recovered since it had a small quality loss in the process. After hydrometallurgical recovery of 90 % of the Ag in weight, the average molecular weight of the PC substrate and PC encapsulation dropped from 51.5 to 48.1 kDa. The experiment showed the feasibility of recycling both materials.

Ag recovery was modelled using a yield of 98 % with a purity of 99 % following BAT metallurgical processing at economy of scale as assessed by MARAS B.V. (van Schaik and Reuter, 2024). For thermomechanical recycling, a sorting efficiency of 90 % was assumed along with a quality factor that allows substitution up to 80 % of the primary material in the next life cycle.

4. Experimental results

Shown in Fig. 2 is an example device that had undergone repairs successfully. Disassembly using the adapted tensile tester reduced delamination speed as intended retaining all LEDs on the foil's surface. With accurately placed glob-tops over the entire LED and ICA pads, both dismantling layers, S112 (Kiwo) (Harkema et al., 2024) and W128 (Kiwo), allowed dismantling without causing significant damage to the circuitry of the functional foil. Depending on the design of the dismantling layer, the graphical coating may also exhibit a quality loss. Our previous study (Harkema et al., 2024) describes the use of vias in the dismantling layer to improve the adhesion of PC resin with the substrate. When dismantling, the coating may show the pattern of the vias (Fig. 2b). The necessity of the coating design depends however on the use of a non-adhering dismantling layer or a strong adhesive.

As described in Section 2, the devices were repaired either in limited fashion (Table 2, device d), not at all (device c) or extensively (devices a, b) and subsequently evaluated for the total power consumption, relative to the reference device, and for the power consumption at LED turn-on to exclude the impacts of heating. As described in Section 2, a typical LED turn-on occurs 3.3 ± 0.1 mV (33 mA current) and exhibits a further increase hereafter due to heating (Fig. 2c). It was observed that repairing both macroscopic and microscopic damages in the circuitry yielded identical oscilloscope measurements as obtained for the reference device (for a,b in Table 2, see Fig. 2c). Omission of repairs to one or both types of damages (c,d) resulted in poor electrical performance and thus a failed repair attempt. It was further observed that microscopic cracks occurred especially close to components and are most likely the result of shear stresses applied to components on the substrate by injection molding. Optimization of the combination of Ag ink, conductive and structural adhesives (underfill), possibly in combination with the use of a protective coating on the Ag ink, may resolve this issue. Compared to the reference device, the total power consumption after 5 min was

Table 2
Electrical performance of IME lighting devices after little to no repair (-), a lesser degree of repair (*), up to an extensive degree of repair (***).

	Repair	$I_{osc,\ 0.6–0.9\ s}$ (mA)	$P_{osc,\ 0.6–0.9\ s}$ (W)	$P_{relative}$	$I_{5'}$ (mA)	$P_{5'}$ (W)	$P_{relative}$
a	***	170	5.8 ± 0.4	102 ± 12 %	194 ± 1	6.6 ± 0.1	101±2 %
b	**	172	5.8 ± 0.4	103 ± 13 %	194 ± 1	6.6 ± 0.1	101±2 %
c	-	167	5.7 ± 0.4	101 ± 13 %	192 ± 1	6.5 ± 0.1	102±2 %
d	*	122	4.2 ± 0.5	74 ± 16 %	127 ± 1	4.3 ± 0.1	66±2 %
e	ref	166	5.6 ± 0.4	100 %	189 ± 1	6.4 ± 0.1	100±2 %

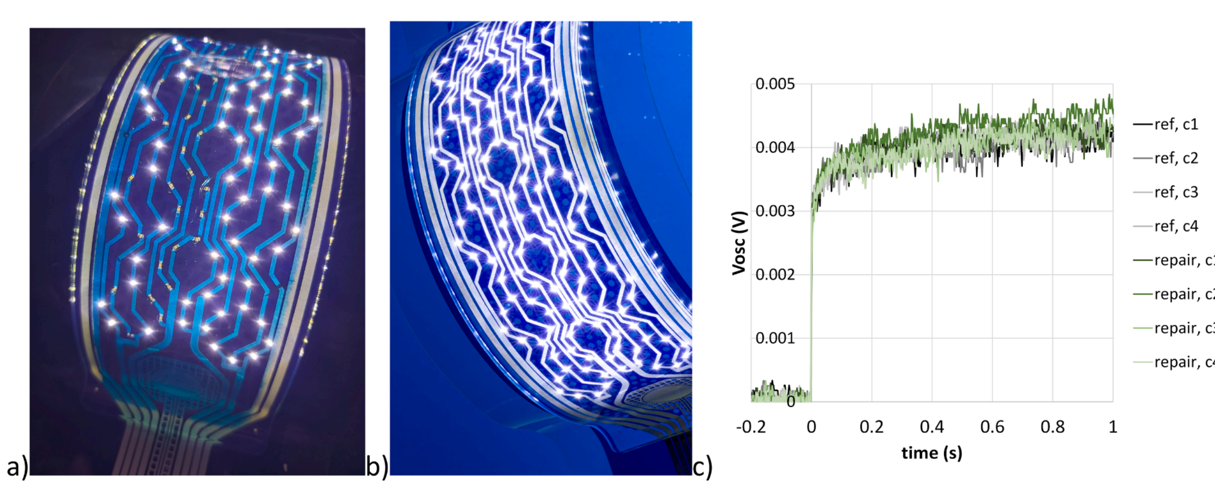

Fig. 2. a) IME lighting device after manufacturing, b) device after repair, c) electrical measurements of device in b) with an oscilloscope combined with those of a reference device.

higher by a small margin (1–2 %) with an uncertainty of 2 % (Table 2). The LCA includes values of 2 % and 4 % as loss of quality due to repairing the IME device.

5. Life cycle impact assessment results

The contribution analysis reveals that (PC)—both in initial production and in the replacement/added PC at repair—is the dominant hotspot in most categories, with silver (Ag) conductive ink emerging as a second-order driver. Ag is the main contributor to ecotoxicity and mineral resource scarcity. For manufacturing and repair combined, PC and Ag contribute from 48 % to 95 % across all impact categories, as shown in Fig. 3. Ecotoxicity categories are specially impacted (90–95 %) by these materials. The extra polycarbonate needed after repair contributes alone between 10 % and 38 %. This highlights the importance of enabling repair and recycling to reduce the IME device impacts related to material demand.

Electricity demand for manufacturing, printing, bonding and injection molding, and repair processes have a minor contribution across most impact categories, between 3 % in Marine Ecotoxicity and 28 % in Stratospheric ozone depletion. Apart from that, Land use (29 %), Water consumption (29 %), Ionizing radiation (31 %) and Human non-carcinogenic toxicity (21 %) are the most impacted by electricity consumption.

The repairing process itself, which involved repairing a functional foil with 20 damaged LEDs and 8 damages to Ag circuitry contributes between 41 % in Terrestrial ecotoxicity and 19 % to Mineral resource scarcity. The input of extra PC for the encapsulation is the major responsible for this outcome followed by the injection molding process and electricity consumption.

The power consumption of the IME part during its lifetime was calculated to be 6.8 kW at peak consumption plus 1.7 kW in weight contribution to vehicle. Repaired devices were concluded to have a loss in quality expressed as a 2 $\pm$ 2 % energy consumption increase during use phase (Table 2). A 4 % increase in electricity demand raises the impacts of the repaired IME device by up to 10 %. Summing up the impacts of repair and the impacts of consuming 4 % more energy could offset the benefits of sparing resources due to repair. However, this is a big overestimation and the worst possible case scenario since this calculation is based on a device consuming 104 % of its original peak power during the entire service life of the vehicle (168,000 km). Three parameters for which no data was available heavily influence these results:1) the amount of time the device stays on, 2) the actual energy demand and 3) length of the life cycle after repair.

The use of a dismantling layer enables the separation of Ag and PC into distinct waste streams for recycling. Fig. 4 combines the impacts of repairing and recycling as compared to manufacturing of two devices with incineration as EoL scenario in orange and recycling in green.

Repairing combined with recycling provides an improvement over incineration with recovery of heat and electricity over all impact categories. The relative benefits of recycling to GWP stem predominantly from the recovery of polycarbonate, while hydrometallurgy contributes heavily to midpoints such as marine ecotoxicity and mineral resource scarcity. With this change in EoL from incineration to recycling, the reduction in GWP increases from 13.2 % to 46.6 %. When including a quality loss expressed as an increase in power consumption, namely 2 % and 4 %, the reduction in GWP increases from 10.6 % to 44.0 % and from 8.0 % to 41.4 %, respectively. This unexpectedly large difference stems from the thermomechanical recycling of polycarbonate that contributes twice to this effect: 1) recycling of the PC encapsulant after repair and 2) at end-of-life.

While incineration with heat recovery increases environmental burdens, PC and Ag recycling provides potential benefits to the GWP as high as 0.25 and 0.05 kg CO2 eq per functional unit. All impact factors are positively impacted, mineral resource scarcity and marine ecotoxicity decrease dramatically, by 81 % and 77 % respectively for 2 % quality loss (80 %, 77 % for 4 %), when the circular strategies of repairing and material recovery are combined.

6. Discussion

The LCA revealed a balance between burdens coming from the repairing and secondary production, including adding 65 g of polycarbonate via injection molding (78 g when including 20 % production waste), and benefits coming from the avoidance of manufacturing a new functional substrate, including associated production waste. Repairing avoided the use of 91 % of Ag ink, a new PC substrate, but cost a significant amount of electricity in our dedicated experiment (0.29 kW). A highly impactful factor in the LCA is the power usage during repair and the allocation of power usage over the number of devices. Batchwise processing enables splitting the power consumption of heating steps over a larger number of devices and will therefore decrease this impact. An increased batch size of simultaneously repaired devices from 1 to 2, 4, 8 and 12, results in a reduced GWP by 6 %, 11 %, 13 %, 14 % and 15 %, thereby showing the importance of optimizing repairing by avoiding/minimizing high power steps, use batchwise processing and/or find alternative means, e.g. low curing materials.

Device reliability is of paramount importance to achieve any environmental benefits of repairing. Usage of inks for repairing, Ag- or Cu-based, may impose technical challenges, including adhesion strength

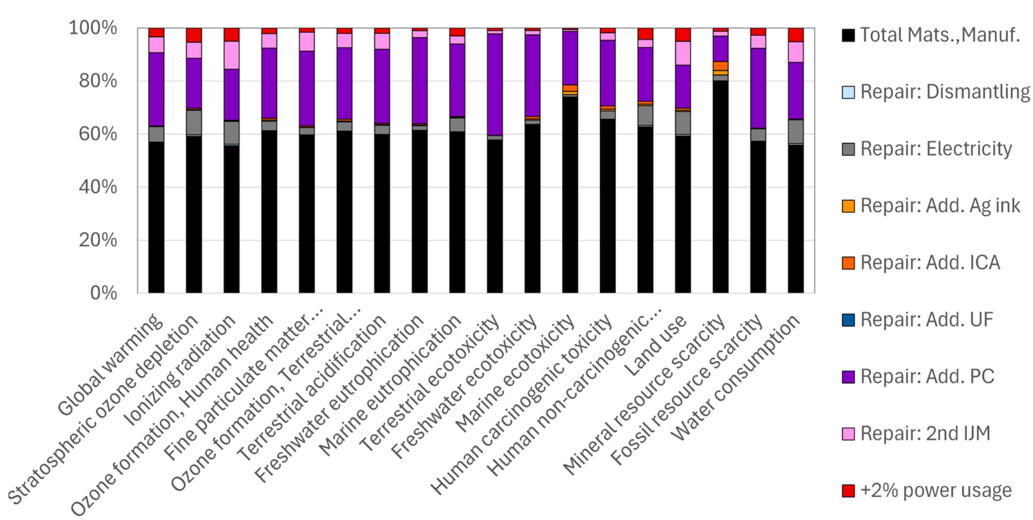

Fig. 3. Additional impacts resulting from dismantling and repairing of an IME device. Black bars correspond to the totals of first production.

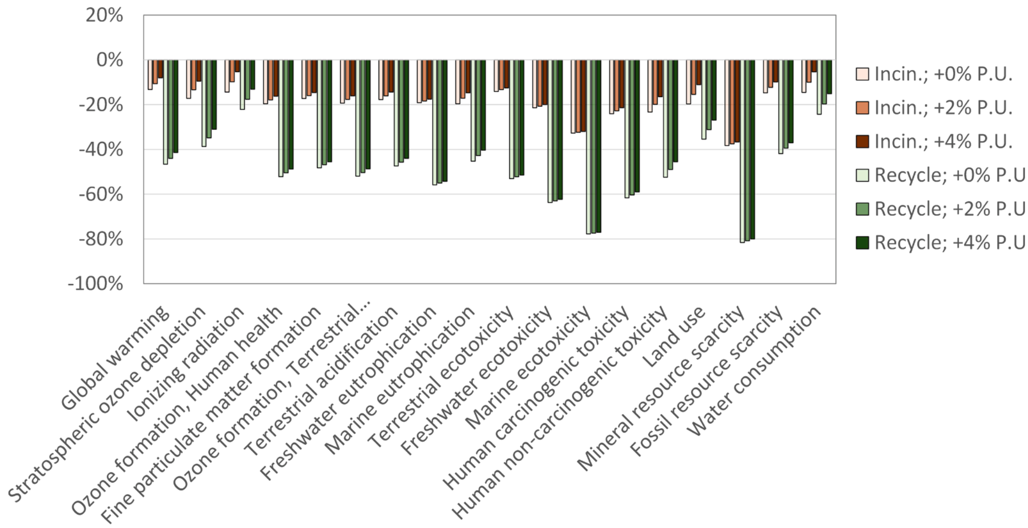

Fig. 4. benefits of repair over disposal with two end-of-life scenarios (incineration and recycling) including an increased power usage (P.U.) of 0,2,4 % during the use phase because of repairing.

to the surface, coverage of topology, additional curing, cracking of thick ink layers and printing accuracy of the conductive ink (Richmond et al., 2022). These may have measurable consequences on the performance of the devices; however, in our case, identical materials were added as in the manufacturing stage. The calculations do include an increase in power consumption, but also assume an unaffected lifetime after repairs, predominantly due to lack of data. Our limited set of repaired devices would not allow us to properly examine this aspect.

The question remains if repair can be cost effective. This will greatly depend on the convenience of dismantling and subsequent repair and the availability of parts and materials. The price per produced IME part was estimated at ~4.50 Eur, excluding 132 LEDs, using a separately built cost model developed for roll-to-roll production at high volume. Time for repair from dismantling to overmolding took 70 min in total (Table 1). Time allocated to human labor concerned 39 % of the total time, roughly 53 % concerned heating in an oven and 8 % of the time concerned recalibration and bonding with the pick & place machine. If repairing is treated per repaired device separately, with all actions sequentially and with an operator standing by during all heating and automated steps, repairing will greatly exceed the production costs. With automated and efficient detection and repair, as well as sufficiently large batch sizes, costs can be reduced. Economic viability may be achieved through the avoidance of new components. By repair, we avoided having to manufacture a new foil with a full set of 132 LEDs at the costs of replacing 20. Assuming a cost of 0.10 Eur per LED, using commercial prices for reels with 5000 LEDs, this saved roughly 12 Eur in costs from components alone. Excluding labor, repair cost roughly 2.50 Euro, providing a repair budget of the difference of production and repair combined with the residual value of the LEDs. If labor and other unforeseen costs remain below this price of ~14.50 Eur, this particular IME device could be economically viable for repair. Of course, material and components should be readily available. Moreover, eliminating elongated heating steps using fast-curing conductive and non-conductive inks and adhesives would aid reducing costs related to time for repair. A considerable challenge exists to provide tooling suitable for repairing within the production timeline as well as during the many years that may comprise the use phase.

7. Conclusions

In this study, we explored the technical feasibility of repairing in-mold electronics and demonstrated that IME devices can be dismantled, repaired, and subsequently re-encapsulated using injection molding. Repair was made possible by embedding a dismantling layer within the layer stack in combination with glob tops on the light-emitting diodes. This combination allowed the functional substrate to be conveniently peeled off from the encapsulating polycarbonate resin. Repair may come at a cost related to the electrical performance. The quality decrease following repair, expressed as an increase in energy consumption, was experimentally found to be minimal, namely 2 $\pm$ 2 %, when repairing a combination of defects within the devices. In addition to examining the technical feasibility, we compared the environmental impacts of repairing to disposal at end-of-life (EoL). Repairing remains favorable for most impact factors in the LCA despite adding 65 g of polycarbonate (93 % of the IME device), an additional 9 w- % Ag to repair the circuitry and including high power processes in the repairs. With incineration with recovery of heat as EoL scenario, it was found that repairing is favorable thanks to the avoidance of manufacturing a new substrate which can become quite impactful when also including the production waste. Considering in the LCA repairing with recycling of disposed of parts, both during repair and EoL, all impact factors showed a considerable reduction. The relative benefits of recycling to the global warming potential stem predominantly from the recovery of polycarbonate, while hydrometallurgy of silver contributes heavily to midpoints such as marine ecotoxicity and mineral resource scarcity. With this change in EoL from incineration to recycling, the reduction in GWP increased from 13.2 % to 46.6 %. When including a quality loss expressed as an increase in power consumption, namely 2 % and 4 %, these values drop to 10.6 % to 44.0 % and 8.0 % to 41.4 %, respectively.

Repairing was conducted on a few samples at laboratory scale and was not optimised for minimal material and energy consumption. The results show a good potential for lowering the impacts of electronic devices through a combination of repairing and recycling. Future work is necessary to examine additional consequences to the quality of IME devices after repair, including the reliability, but also to reduce resource and energy consumption, as these dominate the repair process. It may be possible to reuse the injection molded polycarbonate encapsulant instead of applying a fresh encapsulant by injection molding, for example. This may involve an additional glueing step, but may avoid significant additional burdens related to polycarbonate, and also avoid considerable complexities related to injection molding.

Regarding costs for repair, human labor and electricity during unoptimized process steps were found to be the main contributors to costs. To make repairs economically viable, repairs need to be tuned towards automated detection and repairs. This may need additional investments for the IME manufacturer, because most likely the manufacturing of the parts and repairing cannot be simultaneously accomplished in the same production line. Material developments may steer towards achieving good conductivity and adhesion during short bursts of curing. Avoiding replacing components may have an even more significant impact on the economic viability due to their high value.

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CRediT authorship contribution statement

Stephan Harkema: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Diana E. Godoi Bizarro:** Writing – review & editing, Methodology, Investigation. **Maarten H. Bakker:** Writing – original draft, Resources, Investigation. **Jan P.H. van Delft:** Resources, Investigation. **Pim R. Ostendorf:** Writing – original draft, Resources, Investigation. **Peter A. Rensing:** Resources, Investigation. **Lia de Simon:** Resources, Investigation. **A. van Schaik:** Writing – review & editing, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108685.

Data availability

One supplementary file has been submitted with this article

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