Eco-Design for In-Mold Electronics

Stephan Harkema, Maarten Bakker, and Corné Rentrop

Abstract In-Mold Electronics (IME) is an attractive technology platform for smart surfaces based on printed electronics. Electronic devices are manufactured on and fully embedded within thermoplastics to protect the electronic functionalities from external influences. IME devices for automotive and household applications are on the verge of mass production. Any early-stage considerations regarding the environmental impact of IME, potential improvements to its sustainability and possible circular strategies that may technologically be feasible may enable designers and producers to incorporate suitable eco-design measures that will save costs and reduce the overall environmental impact. Moreover, they may enable complying with existing and/or upcoming EU legislation targeting consumer rights and supply chain independence through efficient recycling and effective repairing. In this Chapter, we will discuss the IME technology and recent scientific results obtained in the EU CIRC-uits project on lifetime extension of IME. The introduction to IME will continue with a lifecycle assessment to pinpoint the major contributors to the environmental impact. In the framework of EU CIRC-uits, we extended the design-for-recycling principles explored in previous and existing EU projects Treasure and Unicorn to achieve repairability of IME. In addition to the technical feasibility of repairing, we determined that repairing is environmentally less impactful than replacing a defective device, even when using incineration. Recycling of plastics and metals would, however, greatly contribute to a further reduction of the environmental impact.

Keywords Eco-design · In-mold electronics · Circular economy · Circular strategies

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P. Rosa and S. Terzi (eds.), *Circular Approaches for the Ecodesign, Repair and Remanufacturing of Car and Mass Electronics*,
PoliMI SpringerBriefs, https://doi.org/10.1007/978-3-032-04301-6_7

1 Introduction

Scientific evidence that printed electronics is a suitable green alternative to printed circuitry boards is increasing [7, 12, 14, 27–30, 33, 37, 43, 41, 46]. In some versions, the likeness of printed electronics applications to printed circuitry boards is quite striking, as multilayer metal circuitry is combined with discrete semiconductor components, such as chips, resistors, light-emitting diodes, capacitors, and so on. There are significant differences, however. The printed circuitry boards, or PCBs, have pure metal circuitries realized by plating or lamination of copper films and are patterned to form the circuitry elements by wet chemical etching. The substrate is typically based on epoxy with glass-fibers, also known as FR4 [15, 33, 35], or flexible polyimide in what are called the flexPCBs. In printed electronics, PET, PU and PC are most typically used instead. These materials are not thermosets, but thermoplastics, meaning that these materials become soft again at elevated temperatures. This is beneficial for processibility, but also for recyclability. Epoxies crosslink under i.e. chemical reaction or UV treatment and remain stiff when heated. This is beneficial for certain applications that need to tolerate higher temperatures, but not ideal from a recycling point of view. Moreover, the various thermoplastic substrates used in printed electronics are thin and often transparent, more flexible, formable and comfortable on the body, enabling a plethora of new applications.

In-Mold Electronics, or IME, is an attractive alternative for conventional electronics based on printed circuitry boards (PCBs) for e.g. domestic appliances and automotive due to its form-factor, light weight, seamless design, diversity in functionalities, and high level of integration. IME is a version of printed electronics in which a formable thermoplastic, often polycarbonate, is chosen as a substrate onto which the circuitry and semiconductor components are applied. High pressure forming of this functional substrate creates a custom shape, potentially unique for each application. On one or both sides of the substrate, additional layers of one or more types of plastic are applied, e.g. PC, PC/ABS, PUR, PMMA, by means of injection molding, among others. This fully embeds and protects the circuitry and components. In-mold electronics may also be realized by two separate films, one for decorative and the other for functional purposes. Injection molding of the encapsulating resin or resins is done in between the two films or foils, thereby bonding these together.

In this chapter, we will describe the application of In-Mold Electronics in an automotive mid-console unit as an example of its possibilities. Subsequently, the IME developments and goals are described in the framework of EU project CIRCuits. Following this technological introduction in Sect. 2, the so-called hotspots from a recent life cycle assessment are described in Sect. 3. Section 4 focuses on the potential circular pathways towards reducing the environmental impact of IME from a material and production point of view, including material circularity and repairing of IME. Section 5 offers concluding remarks.

2 IME Devices: Composition and Manufacturing

Like many other electronics and electronic devices, IME combines plastics with metals, semiconductor technology and coatings that improve aesthetics or provide a function within the layer stacking for protection, adhesion, sensing or alike. The coatings and plastics are chosen to provide a highly reliable part that can last for years. Metals and components are largely embedded within these plastics. While this is highly favorable for protecting the electronic functionalities, this is less than favorable for recycling at end-of-life.

The CEN workshop document CWA 18119:2024 by the EU Treasure project [6] provided proposals for effective end-of-life recycling of automotive parts, including IME. It also provided a general composition of IME. IME largely comprises thermoplastics, such as polycarbonate (PC) and Acrylonitrile Butadiene Styrene (ABS). Silver is printed as a metal ink to provide functionalities as circuitry and sensors, and as conductive adhesive for semiconductor components. Silver is typically present in a low concentration, often in the range of 0–1 w-%. Other strategic and/or critical metals may be present in lower amounts in surface-mounted devices. Polycarbonate, ABS and possibly polyurethane make up a total amount of 95–98%. The rest of the polymers are used to create binders, adhesives, graphic layers and/or thin anti-scratch layers.

This chapter is dedicated to one example of IME in an application, in this case a prototype automotive mid-console, made by Holst Centre, as shown in Fig. 1. This device was manufactured using a single substrate, which is one of the possible approaches for IME. IME devices may be realized with one or two substrates and with one or more consecutive injection-molding steps, see for instance a recent review on In-Mold Electronics by Beltrão et al. from 2022 [4]. In the case of the two-substrate approach, the bulk plastics are injection molded in between the two substrates where one is functional and the other serves as decorative layer. In a one-foil approach, the decorative exterior may also be realized by an injection-molding step of e.g. polyurethane (PUR). The encapsulation of the electronics is injection molded onto the electronics and may also incorporate features or segments to improve the outcoupling of light created within the device using light emitting diodes. One example approach is provided in Fig. 2 from C. Goument et al. [17]. The IME device Fig. 1 was made in similar fashion.

The IME mid-console panel in Fig. 1, that serves as the example in this chapter, was manufactured using sheet-to-sheet processing onto a 500-micron-thick polycarbonate substrate of $390 \times 260\ \text{mm}^2$ (Makrofol DE 1-1, Covestro), onto which the following layers were screen printed: (i) Ag fiducials for subsequent aligned printing steps, (ii) 3 layers of black, (iii) 3 layers of white graphic inks (Noriphan N2K 945 and 954, Proell), (iv) a first layer of Ag (DuPont ME603), (v) three layers of dielectric (DuPont ME779) and (vi) a second layer of Ag. All layers were cured using a convection oven set at 80 °C for the graphic layers (10 min), 120 °C for the Ag layers (10 min) and dielectric (20 min). Post-curing of the graphic stack, before application of the Ag circuitry, occurred for 2 h at the same temperature of 80 °C. Components

a) b)

Fig. 1 IME mid-console touchscreen, as shown in our LCA study from the front in its on-state (**a**) and back (**b**)

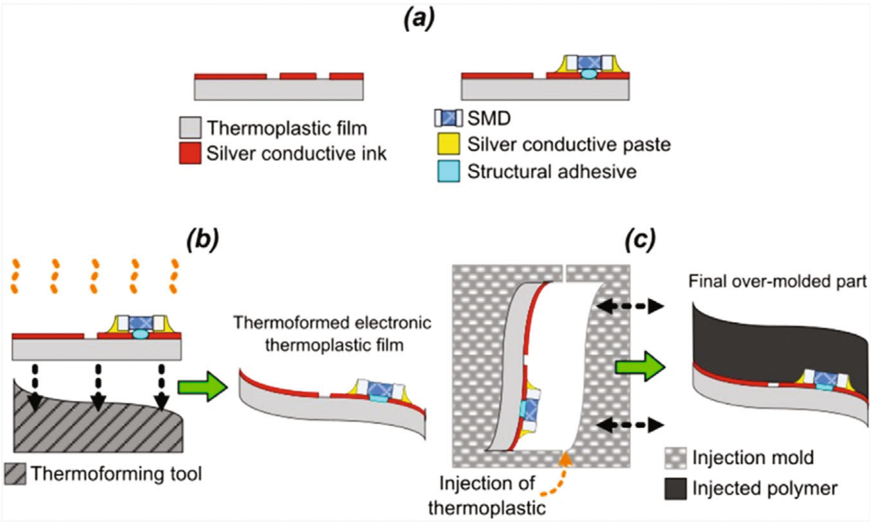


Fig. 2 Example IME production process (from: [17])

were applied onto the graphic layer with a conductive adhesive using a Mycronic My200DX-14 Pick and Place machine. A total of 134 components were applied: (i) 2 Atmell AT42QT2120 Q-touch chips, (ii) 26 RHPE 0402-IMP10k/47 k resistors, (iii) 54 CHPE 0402-IMP capacitors, (iv) 52 RGB smart side LEDs SK6812side. The conductive adhesive was cured at 120 °C for 10 min. The structural adhesive (underfill) was allowed to creep underneath the components to provide stronger adhesion to the substrate and circuitry. The flat PC substrates with circuitry and components

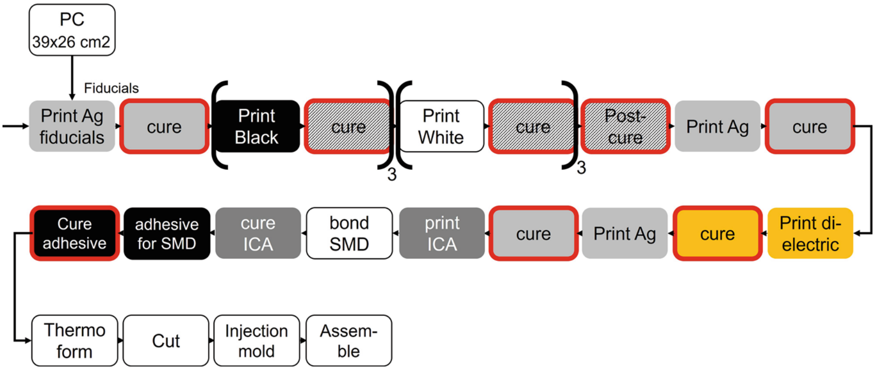


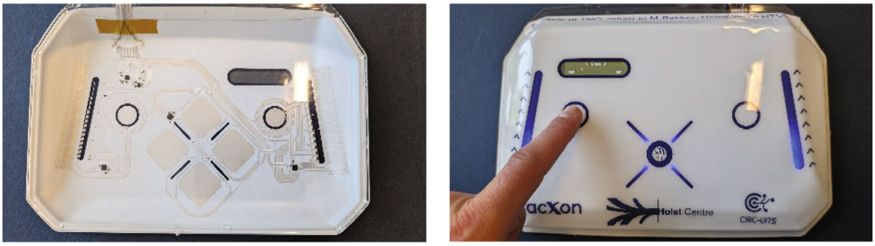
Fig. 3 Production steps for the IME mid-console prototype from Fig. 1

were thermoformed using a dedicated mold in a Niebling high-pressure thermo-forming tool. After laser cutting and subsequent milling of the edges, the prototype was finalized by injection molding an estimated 200 g of transparent polycarbonate resin for samples with a transparent backside finish. Prototypes with advanced light management solutions were developed separately. Light guides were applied onto the substrate and LEDs before injection molding to provide confinement of emitted light and improve light outcoupling efficiency. For the LCA calculations of this device, described later in this chapter, the light guides are not treated separately and are considered indiscriminate from the rest of the injected resin. The key steps to produce the IME device are shown in Fig. 3.

Within the framework of EU CIRC-uits, IME is developed towards improved sustainability by (1) embedding all of the functionalities of the external printed circuitry board (PCB) and (2) repairability. PCBs are known to cause considerable environmental impact [15, 35, 41] and reducing the size or omitting the PCB as a whole is a strategy towards reducing the overall environmental impact of IME [25, 26]. Figure 4 shows the IME demonstrator that was developed by TNO at Holst Centre and TracXon. The external PCB was made redundant by embedding all functionalities within the device (touch sensing, light, gesture sensing, OLED (organic light-emitting diode) display and all driving electronics). At the time of writing, an LCA is in preparation by project partner SUPSI. The second point of repairability is addressed in this Chapter and focuses on demonstrating the technical feasibility of repairing IME, including an impression of the impact on the environment and costs.

3 Environmental Impact of In-Mold Electronics

For printed electronics in general, considerable scientific support the claim that printed electronics are more sustainable than their conventional PCB counterpart, however, IME parts contain a significantly larger amount of plastic. Various example



a) b)

Fig. 4 **a** backside of the EU CIRC-uits IME pilot demonstrator before laminating the OLED and further encapsulation, **b** frontside view showing light emission from LEDs as well as the OLED display and operation of one of the capacitive touch buttons

applications are e.g. 2–3 mm thick, instead of 100–250 microns, which are typical substrate thicknesses. The additional plastics add considerably to the environmental impact. In literature, few assessments are available that quantify the environmental impact for IME. In the next section, the life cycle assessment (LCA) of the IME automotive mid-console from Fig. 1 is elaborated on.

3.1 Life Cycle Assessment of an Automotive Mid-Console IME Panel

Godoi Bizarro et al. studied the environmental impact for the mid-console panel that combines an IME touchscreen and a PCB-based driving unit [16]. The aim of that study was to obtain a complete overview of the environmental impact of IME devices and their PCB counterparts from cradle-to-grave. Here, we only refer to the parts of that life cycle assessment that address the manufacturing and end-of-life to describe relevant environmental hotspots and to address eco-designing of IME in subsequent sections of this chapter.

Adapted results of the LCA, shown in Fig. 5, illustrate the contributions of raw materials and manufacturing of the IME part to the overall environmental impact. Quite clearly, polycarbonate provides a considerable contribution to several midpoint categories as the primary plastic in this plastic-rich part. Aside from the contribution of power consumption during production, Ag provides a significant contribution to multiple categories, including marine and freshwater ecotoxicity and mineral resource scarcity, but not so much to the global warming potential (GWP). A focus on eco-designing IME based on the GWP would thus underestimate the overall impact of Ag on the total environmental impact of this metal despite its minor weight contribution to the part. Major improvements may be expected when addressing the primary plastic, Ag and power consumption during production.

Regarding end-of-life, it was assumed by the authors that the IME and PCB would be separated at EoL and are disposed of in two different waste streams. The

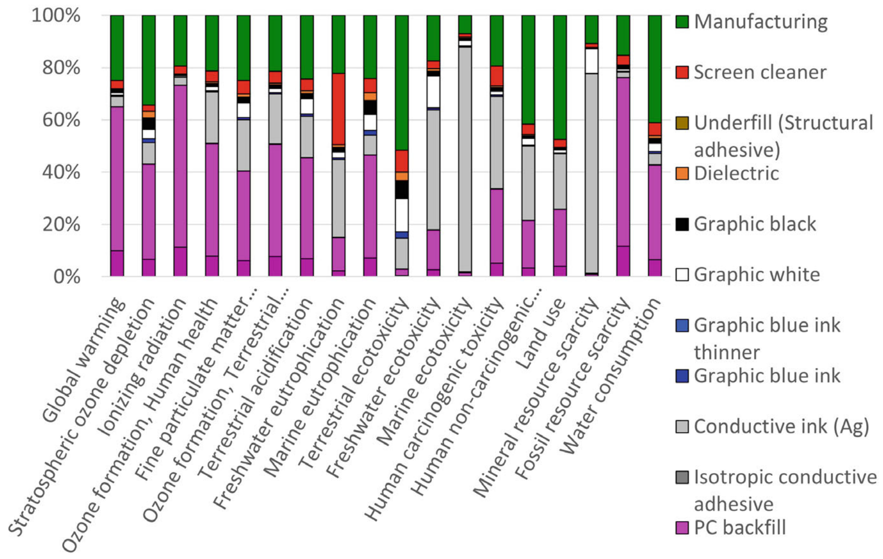


Fig. 5 Environmental impact of the IME mid-console in Fig. 1 consisting of contributions of raw materials and production

IME is expected to be incinerated for energy recovery while the PCB is disposed of as electronic waste. The metals from the PCB may be efficiently metallurgically recovered. Figure 6 provides an overview of the burdens and benefits of incinerating the IME part for the recovery of heat and electricity. The minor amount of Ag was not considered in this EoL calculation due to its small weight contribution to the part. Metallurgic recovery of the Ag from IME is environmentally desirable and possibly cost-effective due to the high pricing of Ag at this moment, however, is a challenge for IME devices due to the full encasing of all semiconductor components and printed Ag in the plastics.

The next section of this chapter continues with Eco-designing of IME for improved end-of-life material recovery and lifetime extension.

4 Eco-designing In-Mold Electronics for EoL Treatment and Extension

4.1 Improving Material Circularity

In the waste hierarchy for a circular economy [11, 13, 27], landfill and disposal without recovery of materials are least preferred, followed by incineration that at least provides benefits in the form of recovery of heat and electricity. Rethinking and

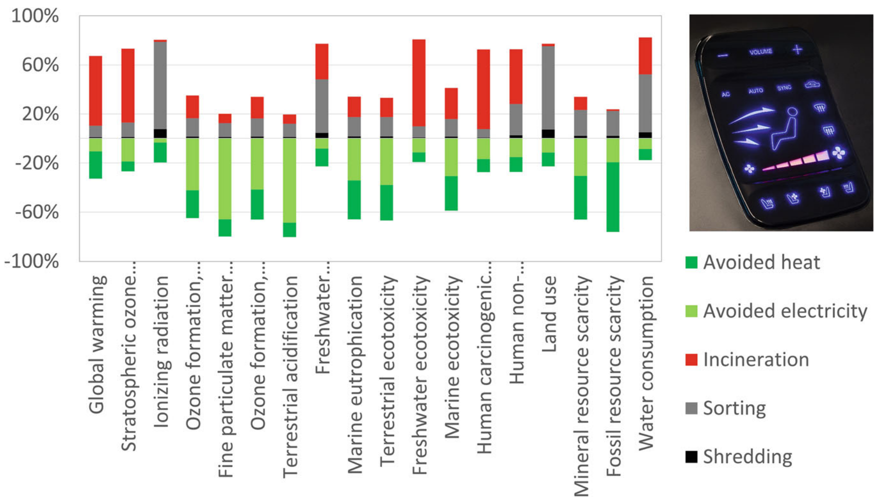


Fig. 6 Environmental impact of the incineration of the IME mid-console for the recovery of heat and electricity. Values > 0% are additional burdens/emissions, while values < 0% are benefits/reduced emissions

refusing hazardous materials, impactful disposables, excessive packaging and low-lifetime products are at the top of the hierarchy [10, 13, 27]. In between, a circular economy is benefited by material circularity: recovery of materials at end-of-life, minimizing production scrap and alternative services and business cases, such as components as a service [21]. Preferred manufacturing techniques for IME in EU CIRC-uits and EU Unicorn involve digitizable additive manufacturing techniques by applying conductive layers only where needed, thereby avoiding the necessity to remove excess metals and the subsequent recycling thereof. Material circularity achieved by recovery and reuse of materials from H&PE devices, however, is not straightforward. Recycling of H&PE in existing WEEE (Waste from Electrical and Electronic Equipment) recycling plants may be quite challenging, surprisingly due to their unique selling points: their flexibility, light weight, low metal content and protection from environmental influences such as moisture. In traditional recycling plants, ferrous and high-metallic fractions are separable from other waste by magnetic and eddy current methods. PCBs are magnetizable and can be ejected by eddy current. H&PE remains part of the plastic waste stream due to the lack of detectable and magnetizable metal content. Within the plastic waste stream, H&PE forms a polluted fraction made of either PET, PC, TPU, ABS, PUR or even a combination of some of these, depending on the application. As a result, H&PE in the plastic waste stream will likely face being incinerated with recovery of heat and electricity instead of being recycled. For that, H&PE must first be recognized as metallized plastics, potentially also containing semiconductor components.

Like WEEE based on H&PE, recycling of automotive electronics based on In-Mold Electronics faces the same challenges. In CEN Workshop Agreement CWA

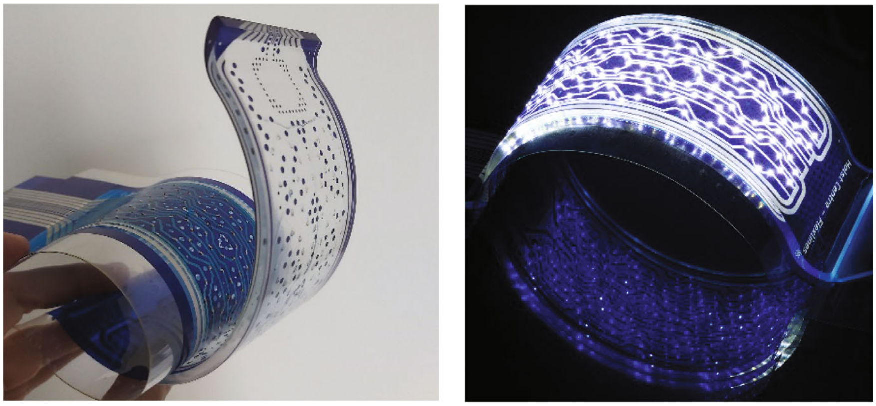
18119 [6], a similar end-of-life outcome was believed to be likely. Recent studies on the inclusion of design-for-recycling principles in IME [18, 5] offer a different outcome as these enable dismantling at end-of-life with the potential to improve the recycling rates for EoL of IME.

At present, if and when offered for recycling, IME is most likely incinerated at end-of-life for the recovery of heat and electricity. Closed-loop thermal mechanical recycling is not suitable for IME, as IME devices contain a significant number of pollutants, including precious metals (Ag), various graphic inks, possibly other plastics (ABS, PUR and/or PMMA), as well as semiconductor components. Other recycling methods may prove more useful, such as (smart) pyrolysis, and focus then on the liberation of metals rather than the recuperation of plastics [1]. Alternatively, plastics may be recovered by physical recycling via dissolution instead [3, 9, 32, 36, 44, 47]. How and how efficiently metals will be recovered from the IME device is a topic for further research.

The application of design-for-recycling principles has allowed project partners in EU project Treasure to target the Ag for recovery. Following necessary device separation to allow dissolution of the silver, the IME functional substrates were provided by TNO at Holst Centre to University of L'Aquila for hydrometallurgy [23, 40]. Public reports from the EU Treasure project provide further information on the recovery of silver [42]. A two-stage leaching process at laboratory scale yielded 85% dissolved Ag. Electrowinning of Ag from the solution was achieved at a yield of 87.5%, however, it was noted that at industrial scale the yield will be 95% or more. On the pilot scale, a yield of 81.2% was obtained for a two-stage leaching process. By optimizing the electrodeposition stage, and conducting pilot testing for each cycle's solution, an overall silver recovery of 97.5% was obtained for electrowinning. This efficiency was achieved with an energy consumption of 8.5 kWh/kg of recovered silver [24]. MARAS described in the same report the yields of metal recovery from IME parts using metallurgy at economy-of-scale: through the combination of energy recovery processing and Cu processing (reductive smelter), 98.4% of the Ag may be recovered [42]. To enable the recovery of plastics from this process, the IME devices need to be dismantled first to avoid incinerating plastics as an energy source. This separation process also brings the Ag vs plastic content in a more favorable range. IME devices from Figs.1, 4 and 7 have 0.08, 0.09 and 0.19 w-% Ag, respectively. By dismantling, the percentage of Ag in the resulting waste can be increased by a factor of ~ 7, ~ 5, ~ 13.

4.2 Lifetime Optimization/Extension

Circular strategies with a higher priority than recovery of materials from end-of-life products include e.g. repair, refurbishment and reuse. These focus on lifetime extension as or in a similar or lower-grade product and avoid the manufacturing of new replacement products. It should be noted that a more extensive description of the



a) b)

Fig. 7 **a** Dismantled IME device with detached functional substrate and encapsulant and **b** repaired IME device

experiments and life cycle assessments are available in a recently submitted paper [19].

At the end of a product's lifetime, materials captured within need to be liberated and recovered. It is well-known that product designs may be tuned towards maximizing the recycling rates. Such design-for-recycling approaches are essential to avoid the loss of precious, strategic and critical metals [8, 34, 38, 39]. In a recent paper, we applied design-for-recycling principles to In-Mold Electronics [18] and studied the dismantling approach and potential consequences to device reliability. Lifetime extension was proposed as a logical next step. The challenge of repairing IME is like recycling: the circuitry and all semiconductor components are typically embedded within the plastics. When dismantling yields functional substrates that contain undamaged circuitry and all components in place, repair may be attempted.

In the EU project CIRC-uits, lifetime extension of IME by means of repair was investigated. Devices that were not fully functional immediately after injection molding were selected for this study. The approach to enable recycling or repair was to incorporate a dismantling layer within the device, either a water-based non-adhering dismantling layer (NADL) [18], or a water-based adhesive [19]. In the EU Unicorn project, other solvent-based commercial and research-grade adhesives were investigated. Dismantling was accomplished, either mechanically for the NADL or thermo-mechanically for the adhesive, by exposure to heat prior to applying mechanical force. The IME device was split in such a way that the functional substrate was obtained alongside the encapsulant formed by polycarbonate resin during injection molding (Fig. 7a). Glob-tops applied onto the components using the same material as the dismantling layer avoided detachment of the components from the substrate. After repair, the device could be re-encapsulated by means of injection molding (Fig. 7b).

Repairing of the functional substrates depended on the observed damages and thus varied between devices. Defects that arose from processing involved cracks in the Ag circuitry, or folds in the polycarbonate due to thermal expansion during the injection molding process: a technical issue that was resolved during the project. The microcracks stemmed from the sheer forces at high temperatures subjected to the printed layers and components during injection molding and occur close to the components. Other defects were caused by e.g. the pick and place process due to the small size of the LED components and the shaking of the LEDs in the reel during bonding with our Mycronic tool. This caused an occasional LED to be mounted upside down. The IME devices were either extensively examined and repaired (2 out of 4), minimally repaired (1 out of 4) or left untouched (1 out of 4).

Separately, a dismantled substrate with 4 large and 4 small damages to the printed Ag circuitry was repaired. This sample also needed replacing of 20 LEDs along with the conductive adhesive that was torn off along with the LEDs. These repairs were recorded in terms of time of repair and materials used, which was then used as primary data for a life cycle assessment of the repair action.

The approach to repairing the separate IME substrate was as follows: (1) dismantle the IME device in about 15 s, either mechanically or thermo-mechanically, after heating up the device for 5 min; (2) determine damages, taking roughly 60 s; (3) repair in-circuitry damage with 6.77 g of Ag ink during 3 min 50 s; (4) cure for 2 min at 120 °C in a convection oven; (5) manual ICA dispensing for 20 LEDs in 6 min 36 s using 10.93 mg Ag adhesive; (6) placement of 20 LEDs, half manually and half with the Mycronic P&P tool; (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 adhesive in total; (9) cure for 20 min at 120 °C; (10) confirm the performance in 15 s; (11) over-mold with polycarbonate (30 s including insertion into the tool). The prescribed drying time for the material used in step (4) is 20 min, but a short drying step at this point during processing is sufficient with a large curing step at (7) and (9). LED bonding was done manually and in an automated fashion using the pick and place machine, while all could be performed with the Mycronic. Due to local warping of the polycarbonate substrate, caused by dismantling, the tool needed to be recalibrated to compensate. This required a total calibration time of 5 min and 6 s for 10 LEDs. Picking and placing of 10 LEDs after recalibration took 30 s in total. Manual bonding of the other 10 LEDs took 9 min 22 s in total. Manual repairs and automated repairs have different contributions to the environmental impact and the costs involved: manual repairs contribute heavily to the costs, but automated repairs have quantifiable contributions to power consumptions that will show up in the LCA.

The electric performance of the repaired and reference devices was measured using an oscilloscope (DSO6034A, Agilent Technologies). Vosc values for repaired devices and their references are provided in Fig. 8. Two types of reference devices are provided: without any dismantling layer (white) or with a water-based dismantling layer (cyan). For the repaired devices, two correspond to extensively repaired, one to left untouched and one to minimal repairs. The first three have a similar average Vosc, but the repaired device with minimal repairs exhibited issues related to microcracks

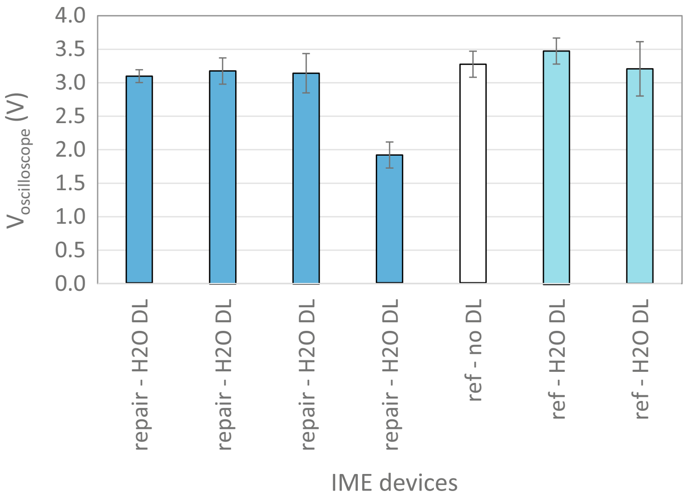


Fig. 8 Vosc for repaired IME lighting devices and references

and failing LED strings, causing the Vosc to be considerably lower. Equal electrical performance was further demonstrated with additional power measurements [19].

One question addressed in the study concerned the benefits of repair to the overall environmental impact. For this, the scenario of repairing immediately after product screening was chosen instead of repairing during the use phase. This allowed comparing two scenarios with equal life span, namely (1) a failing device that is replaced by a new device with a certain lifespan, and (2) a failing device that is repaired and has the same lifespan as the device in scenario (1). The devices in (1) would be disposed of and incinerated for recovery of heat and electricity. The devices in (2) are dismantled and repaired while the separated PC encapsulant is incinerated in scenario (2a) and recycled in scenario (2b). In scenario (2b), also the IME devices are recycled at end-of-life. With recycling, thermomechanical recycling is meant for plastics and hydro-metallurgic recycling for the Ag. Hydrometallurgy was modelled using a recent study on the LCA of EoL recycling of PCBs [22].

Figure 9 shows the relative contributions of manufacturing and EoL incineration for IME lighting devices for the recovery of heat and electricity (scenario 1). The raw materials for two devices contribute 1.72 kg CO_2 eq. to the GWP, manufacturing 0.34 kg CO_2 eq. incl IJM based on primary data for electricity and 0.21 kg CO_2 eq. of additional injection-molding impact based on secondary data (EcoInvent). End-of-life incineration provided additional burdens for both devices of 0.28 kg CO_2 kg eq. in total. Only minor benefits were obtained for a few impact categories.

For repair, especially in combination with recycling, more benefits are achievable, as shown in Fig. 10, including those stemming from the avoidance of a replacement substrate including production losses, but also from the recovery of polycarbonate and silver using thermomechanical and hydro-metallurgic recycling. Allocation of benefits from EoL in this manner is debated in literature [11] and concerns a modelling

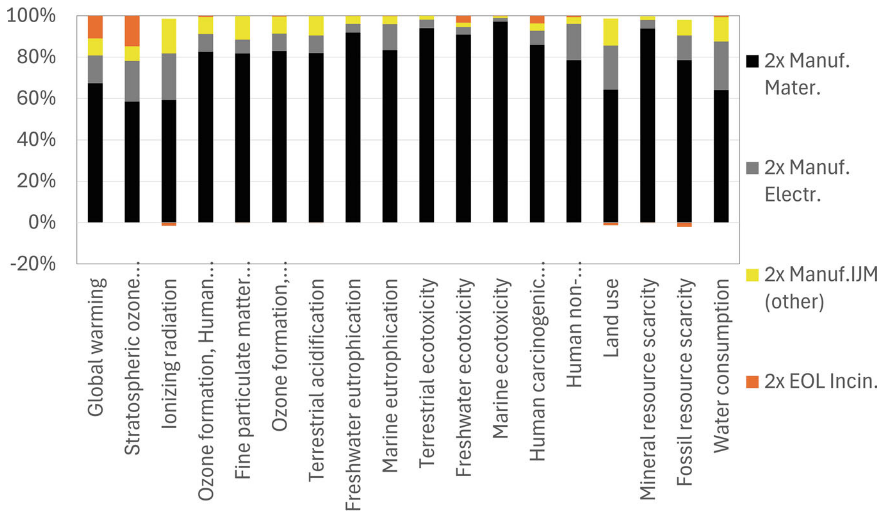


Fig. 9 Contributions to impact factors for the manufacturing and disposal of two IME devices of which one failed after manufacturing and needed to be replaced (scenario 1). At each end-of-life, the IME device is incinerated for the recovery of heat and electricity

challenge. We follow the cut-off model but extend the analysis to include a combination of circular strategies enabled by our technical solutions, thus including the benefits and burdens of repairing and recycling within the same system boundaries. Manufacturing a single IME device causes a contribution to GWP of 1.13 kg CO_2 eq. in total, while repairing an IME device contributes 0.80 kg CO_2 eq. (− 29%). Additional benefits or burdens from EoL treatment further reduce these to − 47% in case of EoL recycling and raise these to − 13% in case of EoL incineration. Additional burdens from a loss in electrical performance are relevant, as shown in Figs. 10 and 11, but do not change the overall conclusion. Experimentally, we determined that the increase in electricity consumption, relevant for the use phase, was 2 ± 2% which was low enough to avoid burdens for any of the impact categories for repairing. With a much higher increase in electricity consumption this may change, especially when incinerating obsolete parts or devices at EoL instead of recycling these.

In addition to a design that uses an adhesive or other dismantling layer, one may also use existing coatings within a device, which may be debonded using intense bursts of light. Such flashes of light may be emitted by Xenon lamps within a Pulseforge 1300 photonic curing system. The PulseForge 1300 enabled high intensity flash curing and sintering of printed metals [7], conductive adhesives and solders, but also "photonic lift-off" [2, 45]. To make repairs possible, the substrate would have to be transparent and contain a pattern of light-absorbing and light-reflecting layers. The design would have to accommodate that the circuitry would remain on the substrate, undamaged and with components still in place, while the bulk plastics are removed. Figure 12 shows an example realized on PC substrates with a flexible encapsulant (TPU/PC). Short bursts of white light were absorbed by the black graphic layer

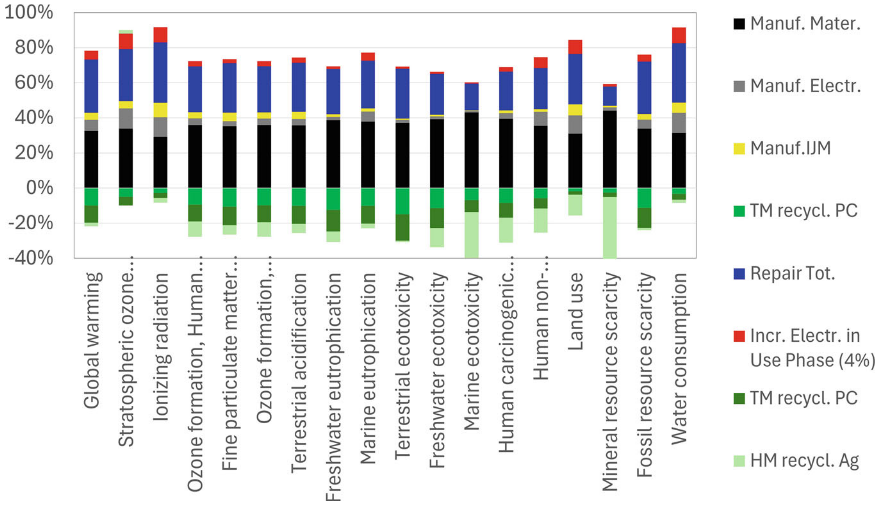


Fig. 10 Contributions to impact factors for the manufacturing and repair of an IME lighting device. At the end-of-life, the devices are recycled after dismantling (scenario 2b)

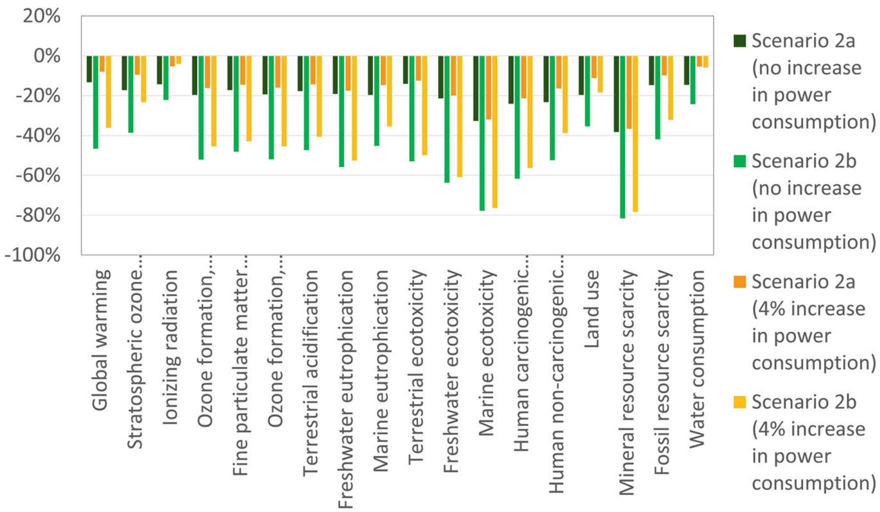


Fig. 11 Relative contributions to impact factors for the manufacturing and repair of an IME lighting device. At the end-of-life, the devices are incinerated (scenario 2a) or recycled after dismantling (scenario 2b)

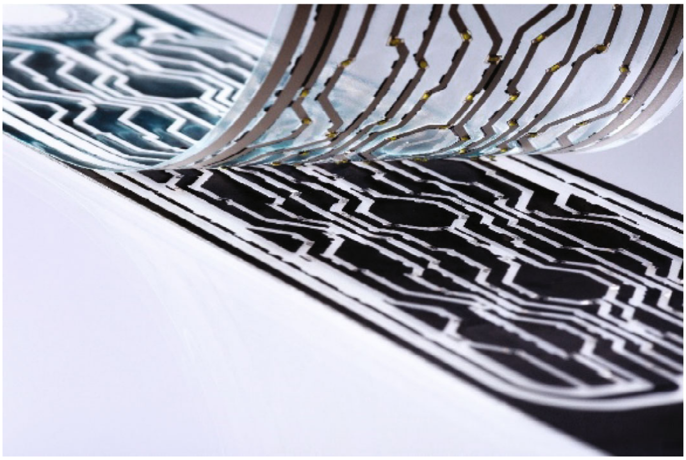


Fig. 12 Delaminated lighting device achieved by photonic debonding: at the top the functional substrate with circuitry and components in place, and at the bottom the encapsulant with light-absorbing black graphic ink

and caused local delamination, while the white graphic layer underneath the silver circuitry remained unaffected. Without further effort, the encapsulant was separated from the circuitry and components. Using transparent hotmelt or adhesives within the stack, later applying one, one may be able to reattach the encapsulant after repairs. The same approach may also serve to dismantle flexible and rigid electronic devices, including IME, for improved recycling yield [20].

5 Conclusions

In this Chapter for Eco-design for In-Mold Electronics (IME), we have explored several circular pathways that contribute to a more favorable environmental impact for this hybrid & printed electronics variant. Our approach to an eco-design for IME encompasses a multitude of solutions that target decarbonization, recyclability and repairability of IME. Through the adoption of design-for-recycling principles that introduced a dedicated coating into the device design, we have been able to introduce dismantlability to an electrical device that fully encompasses the electronics within plastics. This resulted in a multitude of achievable end-of-life approaches that either recover the components, plastics and metals at end-of-life, or enable repairability, refurbishment and similar strategies. Life cycle assessments support that our approaches contribute to a reduction of greenhouse gas emissions.

Acknowledgements This research has been funded by the Dutch Ministry of Economic Affairs, and European Union's Horizon 2020 research and innovation program under grant agreements No 101003587 (EU Treasure project), No 101070169 (EU Unicorn project) and No 101091490 (EU

CIRC-uits project). The authors would like to gratefully acknowledge the contributions from Diana Godoi Bizarro, Yvonne van Liempd, Peter Rensing, Pit Teunissen, Jeroen Schram, Gerwin Kirchner and Adri van der Waal from TNO at Holst Centre. We also acknowledge the wonderful support provided by Rick Leuven and Yibo Su from Brightlands Material Center for injection molding. Finally, we gratefully acknowledge the discussions, support and recommendations related to IMSE sustainability from Pälvi Apilo and Mikko Heikkinen from TactoTek Oy.

Funded by
the European Union

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