The Impact of In-Mold Electronics on Resource Efficiency and Circular Economy Initiatives

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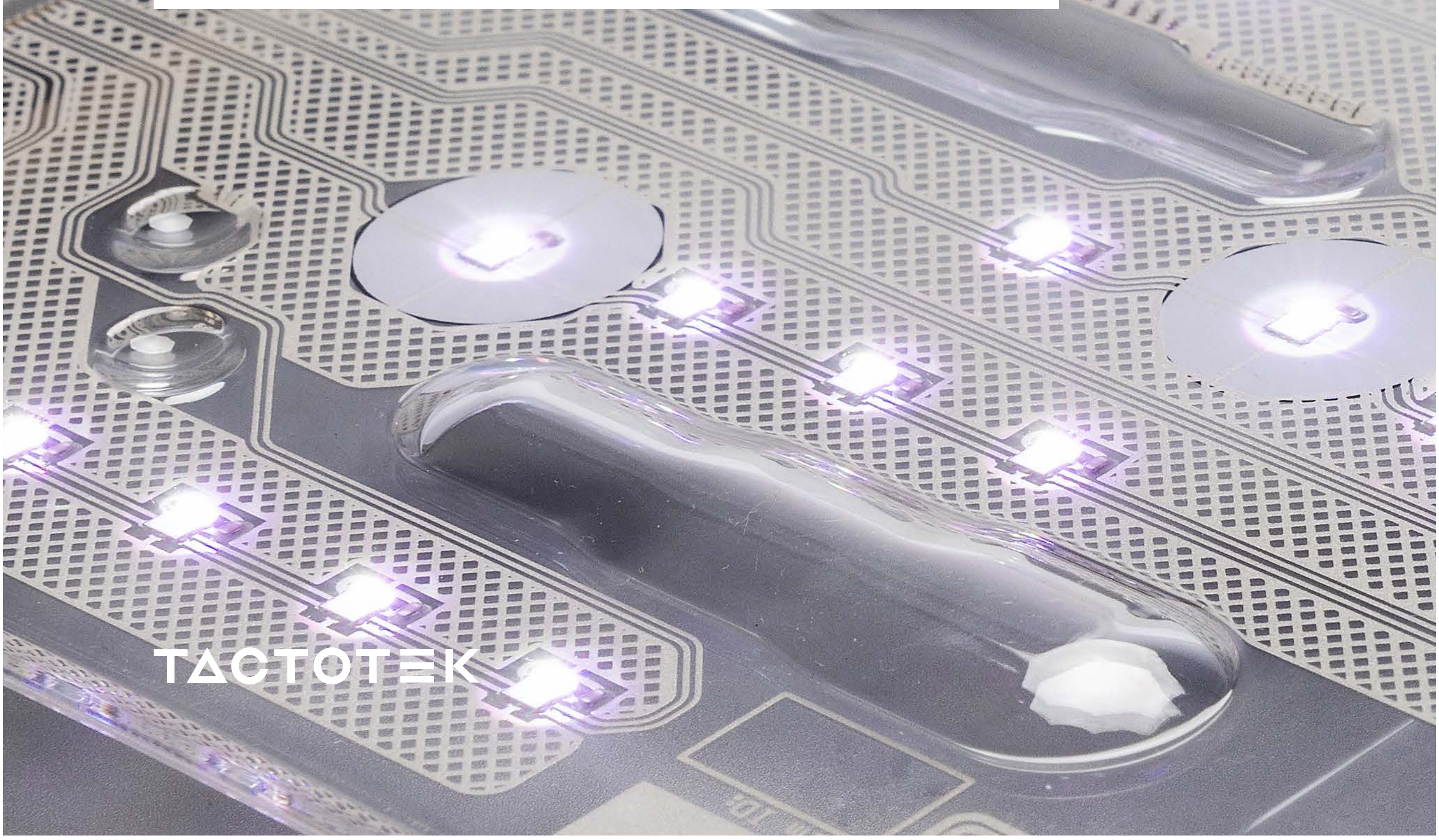

Abstract

The scope of this paper is sustainability of in-mold electronics. This technology has many benefits, such as decreasing material usage, using additive manufacturing processes and simplifying supply chain. Results from an automotive life cycle assessment quantify the impact of these benefits. This paper presents recycling and other activities for further improving sustainability. It also outlines two major initiatives targeting a circular economy: EU's Circular Economy Action Plan and the World Economic Forum's Circular Cars Initiative.

Note: This paper has originally been presented at the ECWC 16 Technical Conference. The conference does not allow the use of trademark terms, such as IMSE®. Thus, this paper uses the term IME (In-Mold Electronics) for the TactoTek patented In-Mold Structural Electronics (IMSE) technology.

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1. Introduction

This part introduces the items in the title of the paper:

- In-mold electronics technology for creating smart surfaces,
- Life cycle assessment for evaluating the sustainability of products and services.

1.1 In-Mold Electronics Decrease Material Usage

In-mold electronics (IME) transform the interaction between humans and machines by embedding electronics naturally into smart surfaces. Features, such as controls, sensors, illumination, and communications, are integrated inside thin 3D structures with plastic, wood, and other surfaces. The single piece solutions enable the programing and digitalization of structural parts. Thus, in-mold electronics can add electronic functions in locations prohibitive for traditional electronics.

Figure 1 shows an automotive human-machine-interface (HMI) concept that enables >50 % weight and 90 % thickness reduction when compared with conventional multi-part assembly. Reduced weight translates to using less materials and to increased sustainability.

Conventional Electronics

- 41 parts + 2x PCBA
- Costly assembly
- Large PCBA as a base
- 48 mm assembly depth
- 281 grams

IME Smart Molded Structure

- 1 molded part
- Integrated, in-mold PCB
- 4,5mm molded material thickness, 90% less
- 130 grams, 54% less

Figure 1. In-mold structural electronics control panel design demonstrates 54 % weight and 90 % thickness reduction when compared with a conventional multi-part assembly.

1.2 IME Manufacturing Process Are Additive

The IME designs can be illustrated as a material stack which is a combination of films, inks, electronic components, surface mounting adhesives and injection molding (IM) resin. Figure 2 shows an illustration of a material stack in a 2-film design.

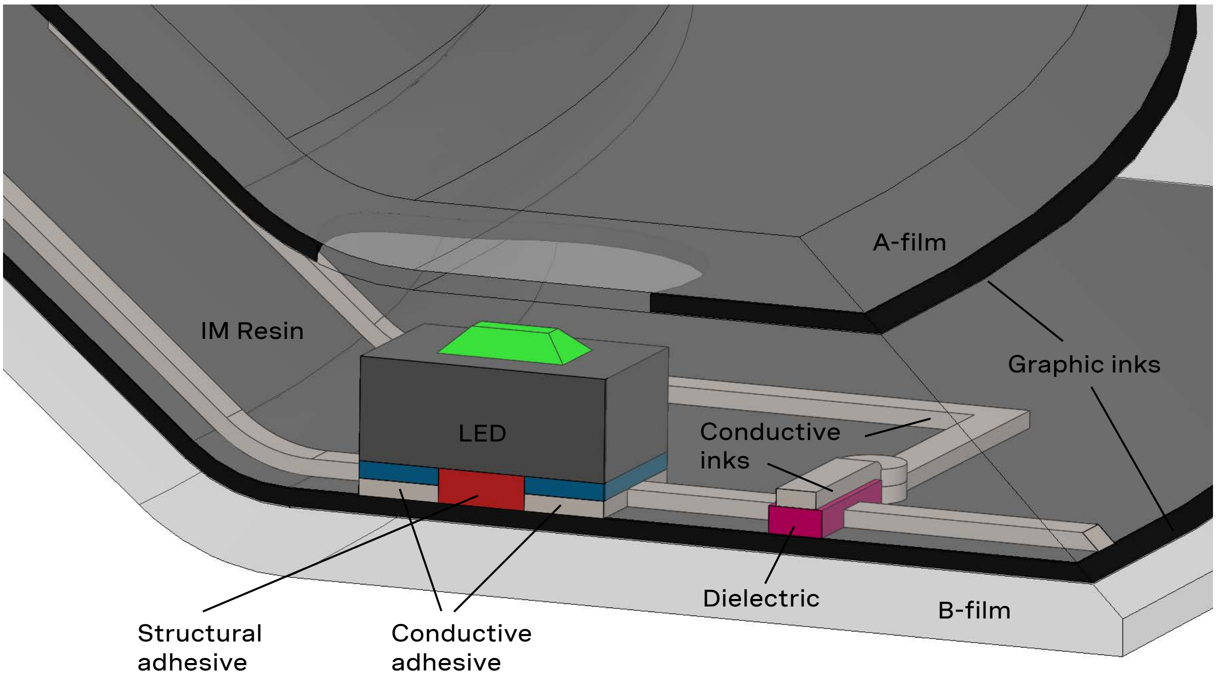

Figure 2. Illustration of a material stack in two-film design [1].

In-mold electronics manufacturing is significantly different from conventional electronics where components are reflow-soldered onto printed circuit boards (PCBs). The core processes are printing, surface mounting, forming and injection molding, Figure 3. Taken individually, these processes are mature, and use standard equipment that is suitable for mass production. However, the core processes are combined in a unique way.

Manufacturing starts with printing onto plastic film substrates, such as polycarbonate. It is an additive process that reduces waste and the usage of toxic substances. Screen printing is used because it is suitable for mass-production and enables appropriate layer thickness (range of 10 μm). Use of conductive inks and dielectric inks enables multi-layer structures.

Surface mounting is the second core process. Components are placed and bonded, mechanically, and electrically, onto conductor traces. This is done with conductive and structural (i.e., non-conductive) adhesives. Curing temperatures depend on the plastic film material. With polycarbonate (PC) films, temperatures do not exceed 130 ºC. The output is a two-dimensional film substrate with components.

Forming is the third core process. A high-pressure thermoforming process is used to form the two-dimensional films into three-dimensional shapes. The maximum temperature depends on the plastic film and for PC-films, it is typically below 150 ºC. Maximum pressure is typically below 8 MPa (80 bar).

Injection molding is the fourth core manufacturing process. In a two-film design, three-dimensional electric films and decorative films are placed as inserts in an injection molding tool. Then, molding resin, such as polycarbonate, is injected between them and electronics are overmolded. The maximum molding temperature depends on the resin material and typically ranges from 190 ºC to 340 ºC. Maximum pressures during injection molding are around 100 MPa (1000 Bar). The outcome is a single piece, electronically active part.

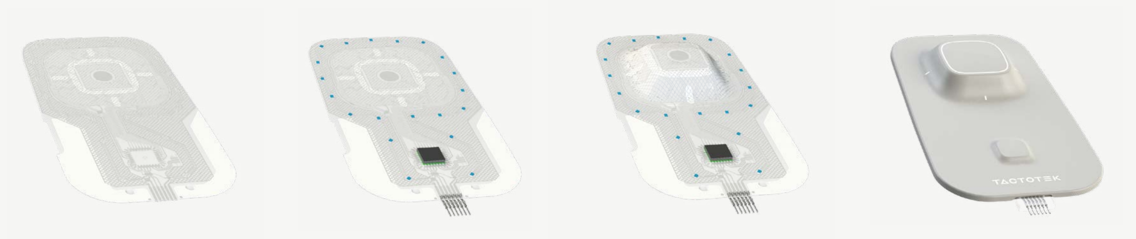

Figure 3. Core manufacturing processes for in-mold electronics.

1.3 IME Designs Use Verified Materials

IME designs use REACH (Registration, Evaluation, Authorization and Restriction of Chemicals), RoHS (Restriction of Hazardous Substances) and conflict mineral compliant materials and components. Because the IME manufacturing processes are a unique combination of electronics and film-insert-molding, many off-the-shelf components and materials are not suitable for IME. Thus, all potential ones are verified before being taken to use. The verification process ensures that electric components and materials, such as polymer films, functional inks, and surface mounting adhesives, form a reliable solution. The verification is done in T-process that has three review gates [2], Figure 4.

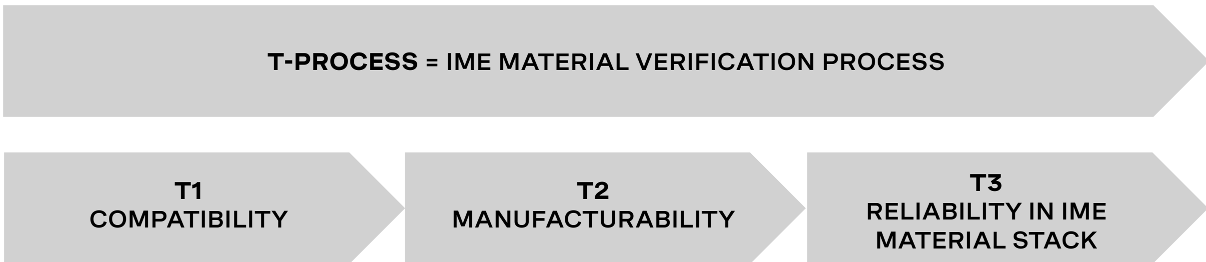

Figure 4. Technology verification is made according to T-process with three review gates.

1.4 In-Mold Electronics Simplify Supply Chain

The HMI concept in Figure 1 also demonstrates how the IME design reduces the number of parts from over 40 to one, not considering the control board being part of the assembly. Thus, in-mold electronics designs replace multi-part structures and ease labor-intensive electro-mechanical assembly. Reducing the number of parts has a direct impact on sustainability because it simplifies the individual supply chains and subsequent processes behind every part. This has a positive effect on several phases such as design & development, manufacturing & product assembly, purchasing & sourcing, logistics, quality assurance, variant management, warehousing, and after sales management.

Single-piece product structures enable high performance of the whole supply chain by reducing the complexity and total engineering effort. A thin and lightweight part enables several improvements, such as reduced number of required manufacturing tools, reduced number of assembly steps, less global logistics, as well as more effective inventory management. As the number of electronic devices is constantly growing, in-mold electronics can reduce the climatic burden in many ways. For example, by simplifying the way devices are built, resulting in reduced material usage, especially for plastics, and reducing the environmental impact over the entire value chain.

1.5 Life Cycle Assessments Provide Information on Environmental Impact

Life Cycle Assessment (LCA) is defined as a compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle. LCAs are typically based on the ISO standards 14040 and 14044 [3].

Life Cycle Assessments are a powerful tool for gathering information on the environmental impact of any product or service. Comparative LCA studies, where two or more different solutions are compared to each other, provide the necessary information to make decisions when choosing between alternative options. LCA studies are commonly used for evaluating the greenhouse gas emissions of a product or service. However, analyzing other impacts, such as particulate emissions, acidification, and land use, create a wider understanding of the total environmental impact. Additionally, LCA focus should not be only on the production of products or services. Instead, LCA should include the total life-time emissions from raw material extraction, supply chain, as well as use and disposal. [4]

2. Experimental and Results

This part presents:

- An automotive electronics LCA,
- Activities for further improving IME sustainability.

2.1 Automotive Electronics LCA Shows the Positive Impact of Mass Reduction and PCB Removal

Simplifying part structures, reducing, or removing components and printed circuit boards, as well as making parts lighter all have a large impact on product sustainability. The purpose of LCA has been to quantify the impact in an automotive application [5].

The analyzed part is a gear shift indicator panel with several illuminated elements, Figure 5. The LCA compares an on-the-market part, made with conventional electronics and many mechanical parts, to IME design. In both designs, the driving of components is on the system level, i.e., the parts do not contain LED (Light Emitting Diode) driver electronics. The indicator panels connect to the car's system electronics with a standard pin-connector.

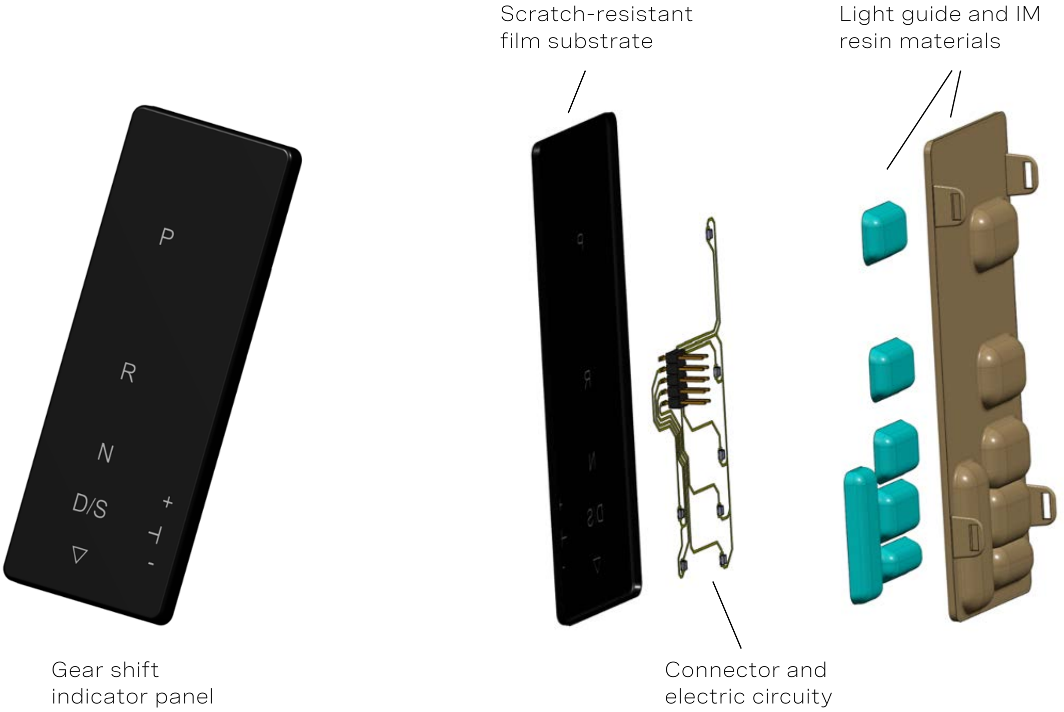

Figure 5. IME design for gear shift indicator panel

In the conventional electronics part, the illumination elements require a large PCB to house LEDs and other electronic components. The illumination elements also require structural and light guide assemblies. The IME part utilizes a novel light guide method inside the IME structure. The IME part does not have a PCB, since all of the LEDs are mounted on a plastic film substrate. Figure 5 shows the IME part structure. It contains a scratch-resistant film substrate, electric circuitry, and pin connector as well as light guide and injection molding resin materials.

Figure 6 shows the GHG (greenhouse gas) emissions over the total lifecycle [5]. The main results are:

- IME design has 52 % less GHG emissions during full lifecycle (from 1,63 to 0,78 kgCO2eq),
- IME design has 65 % less GHG emissions during production,
- IME design has 38 % less GHG emissions during product use.

The main contributors for the GHG emission reduction are the mass reduction and total removal of the PCB. This leads to significant reductions in the cradle-to-gate and use life-cycle steps, respectively. Additionally, the LCA showed a reduction over 13 different impact categories in the 14 categories that were analyzed. [5]

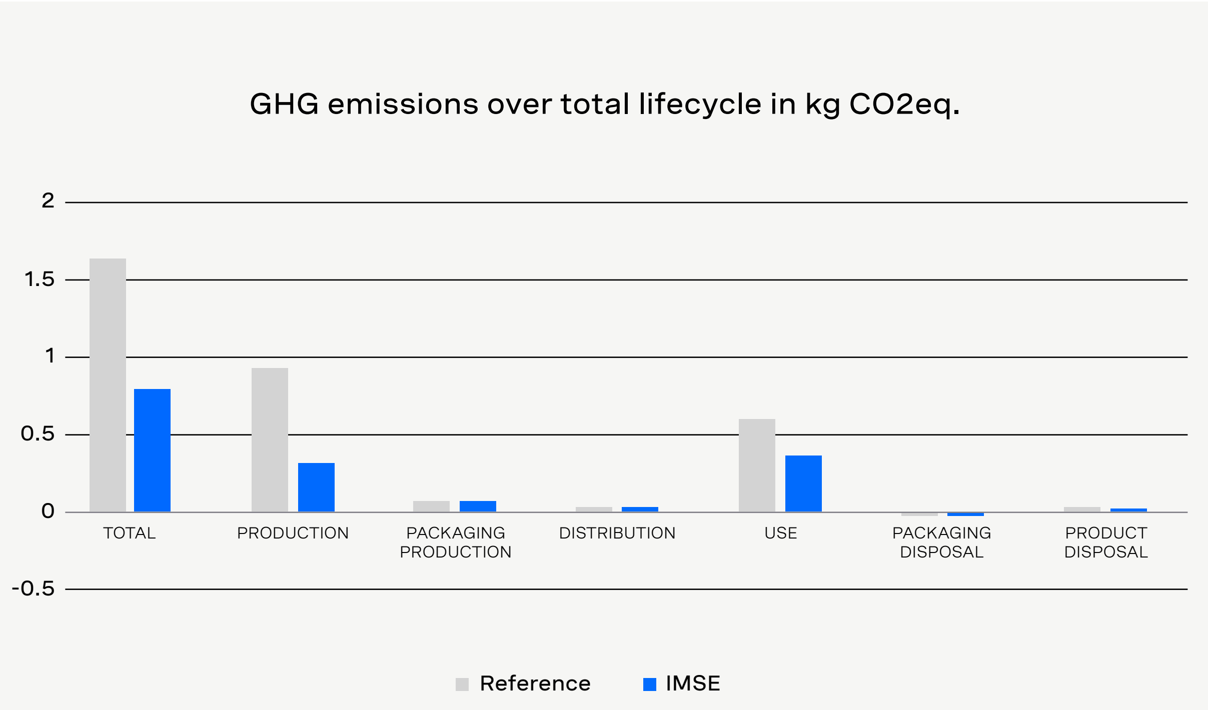

Figure 6. Comparison of the total lifecycle emissions (kgCO2eq) [5]

2.2 Sustainable Materials Are Being Studied and Verified

Using recycled silver raw material in conductive inks and adhesive will improve IME sustainability. A screening LCA, made in 2017, for car over-head-control-panel [6] showed that the conventional electronics product has a greenhouse gas emissions of 6.5 kgCO2e and the in-mold electronics product of 4.3 kgCO2e. For in-mold electronics, silver used in conductive inks and adhesives, has a 10% share of the GHG value. This LCA initiated work to verify conductive inks with recycled silver raw materials. Two such conductive inks have been verified and they have reached T3-status. Both of them are tailored for in-mold electronics, i.e., they withstand thermoforming and injection molding processes. Verification of conductive ink with copper particles has also started.

In recent years, suppliers of plastic films and molding resins have developed recycled and (partly) biobased materials for commercial use. Their suitability for in-mold electronics has been studied, and the promising ones have been subjected to the verification process. Four partly bio-based polycarbonate injection molding resins have reached T3-status by summer of 2023. The verification of recycled injection molding resins is ongoing. Same applies to polymer films; several partly bio-based polycarbonate films have entered the "verification pipe". Material properties differ from fossil-based alternatives and these materials need to go through the full verification process.

2.3 Currently IME Uses Conventional Electronics Recycling Methods

Recycling is a known challenge in the whole in-mold electronics sector since in-mold electronics contain a range of different materials integrated into a single structure. IME uses the same recycling methods as electronic waste, incineration, and subsequent material extraction from the leftover ashes. They allow the recovery of precious metals which are mainly silver. Since 2021, all waste and excess materials from technology development lab as well as excess parts from R&D have been collected. Everything containing precious metals is sent to recycling partners, universities and research centers for precious metal recovery and recycling trials. Recycling of production waste and excess parts is economically feasible due to the high silver content.

2.4 The Ultimate Aim Is 100 % Circularity

The currently used recycling methods do not recover plastics for reuse. The underlying reason appears to be that conventional recycling methods have been good enough for the majority of recycling use cases in the past where sustainability has not been a priority. Fortunately, the mindset has and is changing. A supplier of plastics for IME has developed an innovative chemical process for recycling polycarbonate [7].

In this process, plastics are converted back into their monomers, a precursor of plastics, so that they can be fed back into the production process as alternative raw materials. The newly developed process is a specific chemolysis process adapted to polycarbonate. Chemolysis uses chemical reagents to break down the polymer into its monomers or, which can then be used to produce new polycarbonate. Pre-sorted waste streams containing a product content of more than 50 percent polycarbonate can be recycled this way.

Another chemical recycling process is pyrolysis. It is a thermochemical treatment, which can be applied to carbon-based materials. However, pyrolysis requires a lot of energy. The pyrolysis output materials can be in gaseous, liquid, and solid form. It is a novel technology that is not yet widely adopted in the market. However, polycarbonate plastic has been shown to be a promising material for pyrolysis processing in mass-scale due to its homogeneity and large business potential. A research Institute has conducted an initial pyrolysis study and the results state that pyrolysis has high potential for in-mold electronics recycling.

The plastic supplier for IME has also developed processes for mechanical recycling of polycarbonate [7]. Mechanical recycling is more efficient and economically viable than chemical recycling. However, mechanical recycling requires that waste streams are sufficiently pure and the recycled polycarbonate is appropriate for future applications. The purity of the polycarbonate is a challenge for IME parts until sufficient dismantling technologies are available.

Efficient dismantling technologies are being developed in an EU-funded UNICORN-project that contributes to the sustainable and smart transformation of the EU mobility sector. The project aims to support the development of functional electronics for accelerating the transition of the automotive industry to a circular economy. UNICORN's 'car-as-a-lab' approach demonstrates the next generation of automotive electronics that are aligned with the Circular Cars Initiative. The UNICORN project started in fall of 2022 and will last for three years. A European Research Center and the IME Technology Provider are researching and developing materials and methods together to ease IME disassembly. The target is to efficiently discriminate printed circuitry, components, and plastics to different material streams for recycling. [8]

3. Discussion

This part presents:

- Circular economy and strategies for reaching it,
- EU's Circular Economy Action Plan,
- Circular Cars Initiative.

3.1 Towards Circular Economy

A circular economy (CE) can be defined as an economic model aimed at the efficient use of resources through waste minimization, long-term value retention, reduction of primary resources, and closed loops of products, product parts, and materials within the boundaries of environmental protection and socioeconomic benefits. A CE has potential to lead to sustainable development, while decoupling economic growth from the negative consequences of resource depletion and environmental degradation. [9]

In his paper [9], Morseletto structures different CE strategies into three groups, see Figure 7. The strategies for "Smarter product use and manufacture" (R0 – R2) are more potent in reaching CE than strategies for "Useful application of materials" (R8 – R9). So far, the electronics industry, including IME, has mostly used recovery (R9) and recycling (R8) methods.

Morseletto [9] argues that CE elements such as closed loops, value retention and waste minimization can be realized when the targets for the strategies are appropriately designed. He gives examples of driving CE strategies with instruments, such as:

- Taxes or liabilities,
- Reporting or voluntary approaches,
- Laws or regulations,
- Standards, guidance, or recommendations.

The following sub-chapters present two examples of such instruments. The authors believe that both of them will increase the importance of sustainability to the same level as quality, performance, and cost.

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Smarter product use and manufacture	R0	**Refuse**	Make product redundant by abandoning its function or by offering the same function with a radically defferent product
	R1	**Rethink**	Make product use more intensive (e.g. through sharing products or by putting multi-functional products on market).
	R2	**Reduce**	Increase efficiency in product manufacture or use by consuming fewer natural resources.
Extend lifespan of product and its parts	R3	**Reuse**	Reuse by another consumer or discarded product which is still good condition and fulfils its original function
	R4	**Repair**	Repair and maintenance of defective product so it can be used with its original function
	R5	**Refurbish**	Restore an old product and bring it up to date
	R6	**Remanufacture**	Use parts of discarded product in a new product with the same function
	R7	**Repurpose**	Use discarded products or its part in a new product with a different function
Useful application of materials	R8	**Recycle**	Process materials to obtain the same (high grade) or lower (low grade) quaity
	R9	**Recovery**	Incineration of material with energy recovery

Figure 7. Common circular economy strategies [9].

3.2 EU Has Established Green Deal Strategy and Circular Economy Action Plan

The EU's Green Deal strategy aims for a modern, resource-efficient, and competitive economy where there are no net emissions of greenhouse gasses (GHG) in 2050. The aim is also to decouple economic growth from resource use. The EU has established the Circular Economy Action Plan (CEAP) to reach these goals [10]. CEAP drives towards closing material and energy loops. It enables the global community to move away from using only virgin materials in new products.

3.3 The World Economic Forum Has Established Circular Cars Initiative

The World Economic Forum has established the Circular Cars Initiative (CCI) in 2021 [11]. The initiative is important for Europe, which is home to 15 international car manufacturers producing around 20 million vehicles per year. Europe is also home to world-leading automotive electronics semiconductor, embedded software, and system suppliers.

The CCI report provides an overview of the four circularity principles for cars [11].

They are:

1. Expand performance assessment from tailpipe emissions to a life-cycle-based perspective along the value chain, to enable more rational and effective policy- and decision-making for the mobility and manufacturing sectors at large.
2. Accelerate the use of circular, low-carbon materials to scale demand and improve recycling markets, with a focus on metals, plastics, and battery materials.
3. Re-focus circularity on higher value retention processes by extending the practice from recycling to vehicle life extension via reuse and remanufacturing.
4. Improve the utilization of vehicles by fostering fleet management and pooled vehicles.

The current focus is on Principle 2; Accelerate the use of circular, low-carbon materials to scale demand and improve recycling markets.

Conclusion

This paper has presented in-mold electronics technology that enables sustainable smart surfaces. IME designs are lighter, require fewer parts, and simplify the supply chain. The IME manufacturing processes are additive, as well. The life cycle assessment on gear shift indicator panel showed considerable reduction of greenhouse gas emissions when the part is realized with IME instead of conventional electronics. The main contributors for the decreased GHG emission are the material reduction and not using a printed circuit board.

Currently IME uses the same recycling methods as conventional electronics; incineration and subsequent material extraction from left over ashes. Due to the high silver content in IME parts, this is economically feasible. The ultimate aim, however, is 100 % circularity of IME parts. This will require new novel processes for dismantling IME and converting the plastics back to their monomers. The novel processes will require extensive research and the whole in-mold electronics value chain needs to be involved. EU's Circular Economy Action Plan and the World Economic Forum's Circular Cars Initiative have ambitious targets for circular economy. The authors believe that both of them will increase the importance of sustainability to the same level as quality, performance, and cost.

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