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Sustainable and Green Electronics for Circular Economy

# Deliverable 4.2

# Analysis of life cycle-based environmental impacts and end-of-life processes of sustainable materials in electronics

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# Management Summary

D4.2 of SUSTRONICS project (Analysis of life cycle-based environmental impacts and end-of-life processes of sustainable materials in electronics) completed at M18 provides a comprehensive analysis of the life cycle-based environmental impacts and end-of-life processes of sustainable materials in electronics, focusing on bio-based and biodegradable materials. The main objective is to address LCA (Life Cycle Assessment) problems with bio-based and biodegradable materials in electronics, providing a framework for environmental benchmarking and analysis. The document contains a literature review on sustainability and end-of-life processes of different new materials potential for electronics manufacturing, and an experimental part focusing on LCA benchmarking of different technologies found technically feasible for SUSTRONICS project.

Various substrates like paper, PLA, Bio-PET, and nanocellulose are evaluated for their environmental friendliness and end-of-life processes. For the conductive inks used in printed electronics, silver ink has the highest environmental impact, while copper and carbon inks are identified as more sustainable alternatives. The energy requirements for curing different adhesives are analysed to find the most sustainable option for component assembly from energy consumption perspective.

Future plans include experiments on biodegradability and recyclability of materials, aiming to develop end-of-life strategies for sustainable electronics.

The LCA comparisons presented in this report rely on raw material extraction and manufacturing or energy consumption during manufacturing. Further aspects will be added in the future for pilot and use case specific LCA benchmarking. For the substrates, cellulose based materials are the most environmentally friendly option. The impact from biopolymers can be compensated during their end-of-life. Carbon inks are considered as the most environmentally friendly ink option based on literature. Silver has the biggest environmental footprint (impact category carbon footprint). The environmental impact of adhesives can be decreased by using a shorter curing time and lower curing temperature.

# Table of Contents

# List of abbreviations

| | |
|---|---|
| EoL | End-of-Life |
| FR | Flame Retardant |
| GWP | Global Warming Potential |
| ICA | Isotropic Conductive Adhesive |
| LCIA | Life Cycle Inventory Analysis |
| LCA | Life Cycle Assessment |
| NCA | Non-Conductive Adhesive |
| PCB | Printed Circuit Board |
| PEF | Polyethylene furanoate |
| PET | Polyethylene terephthalate |
| PLA | Polylactic acid |
| PP | Polypropylene |
| RFID | Radio Frequency Identification |
| TDS | Technical Data Sheet |
| UV | Ultraviolet |

# 1. Introduction

## 1.1. Purpose of the document

Bio-based and biodegradable materials are not yet commonly used in electronics although found in literature to be technically feasible for this purpose. There is a lack of basic data needed for environmental benchmarking of these new technologies, and guidelines for LCA (Life Cycle Assessment) and LCIA (Life Cycle Inventory Analysis) methodology is missing. The objective of this deliverable is to provide answers to these questions.

This deliverable D4.2 reports the intermediate results of T4.2 (Solving LCA problems with bio-based and bio-degradable materials in electronic products) at M18, while the task continues until M24. The objective of T4.2 is to (1) map relevant bio-based and biodegradable materials with (potential) application in electronics; (2) assess climate change impacts of bio-based materials; and (3) implement LCA case studies of bio-based and bio-degradable materials compared to conventional materials.

The results have been derived in collaboration with Pilots#2.1-2.3 when carrying out LCA benchmarking of sustainable materials planned for the pilots in Gen1. Furthermore, a literature survey on sustainable materials for electronics and their end-of-life routes has been carried out.

## 1.2. Structure of the document

This deliverable is divided into a literature review part and an experimental part. The Background (Section 2) presents findings from relevant scientific literature on sustainable material alternatives for substrates, inks, and adhesives. Their environmental impact and end-of-life processes have been reviewed. Section 3 focuses on the experiments carried out to specify environmental impact of different sustainable material categories (substrates, inks, adhesives) based on LCA. Section 4 specifies future plans for end-of-life experiments during SUSTRONICS. Section 5 concludes the findings and provides recommendations for future benchmarking of sustainable materials.

## 1.3. Related documents

D4.2 is related to the following SUSTRONICS deliverables:

- **D1.3** Validation and testing plan (VTT, M15) describes the sustainable materials to be developed in SUSTRONICS.
- **D4.1** Guideline, framework and KPIs to LCI management and circular business models (FHG, M9) describes the methodology used for LCIA and LCA in SUSTRONICS.
- **D3.1** Initial system specification and design for pilots, including circularity aspects (PCL, M3) describes the sustainability goals of SUSTRONICS pilots.
- **D3.2** Gen 1 prototypes, including characterisation and updates to system specification and design for Gen 2 (IFAT, M15) describes the Gen 1 of SUSTRONICS pilots, including status of sustainability goals and the first pilot LCAs.
- **D3.3** Gen 2 prototypes, including characterisation and updates to system specification and design for Gen 3 (VTT, M27) and **D3.4** Final prototypes for Gen 3, including validation data and end user engagement (IFAG, M36) will describe the Gen 2-3 or SUSTRONICS pilots, status of their sustainability, and pilot LCAs.
- **D4.6** Life cycle assessment and handprint study results for select case studies (FHG, M35) will detail the different LCAs done during SUSTRONICS.
- **D4.4** End-of-life concepts and new processes for sustainable electronics (MIR, M30) will describe the results for the end-of-life experiments described in Section 4 of this document.

# 2. Background

In recent years, the consumption of electrical and electronic equipment (EEE) has increased significantly. It has influenced the areas of our entertainment, modes of communication, educational systems, medical procedures, and other sectors. The growing dependence on electronics has led to an increase in the production of electronic waste (e-waste) [1].

E-waste is the fastest-growing type of domestic waste worldwide, expected to double in volume between 2014 and 2030. Currently, only 20% of this waste is properly recycled globally, compared to 40% within the European Union (EU), respectively [2]. In addition, the majority of e-waste ends up in landfills, while a significant portion is also illegally shipped to developing countries [3].

In 2022, Europe was the first continent that generated the most e-waste per capita with approximately 17.6 (kg) kilograms as illustrated in Figure 1. The per capita e-waste generation in Oceania was marginally lower than in Europe. In contrast, Asia and Africa generate considerably less e-waste per capita than the other regions and the global average. Asia's e-waste generation is recorded at 6.4 kg per person, while Africa has the lowest rate, producing 2.5 kg per capita.

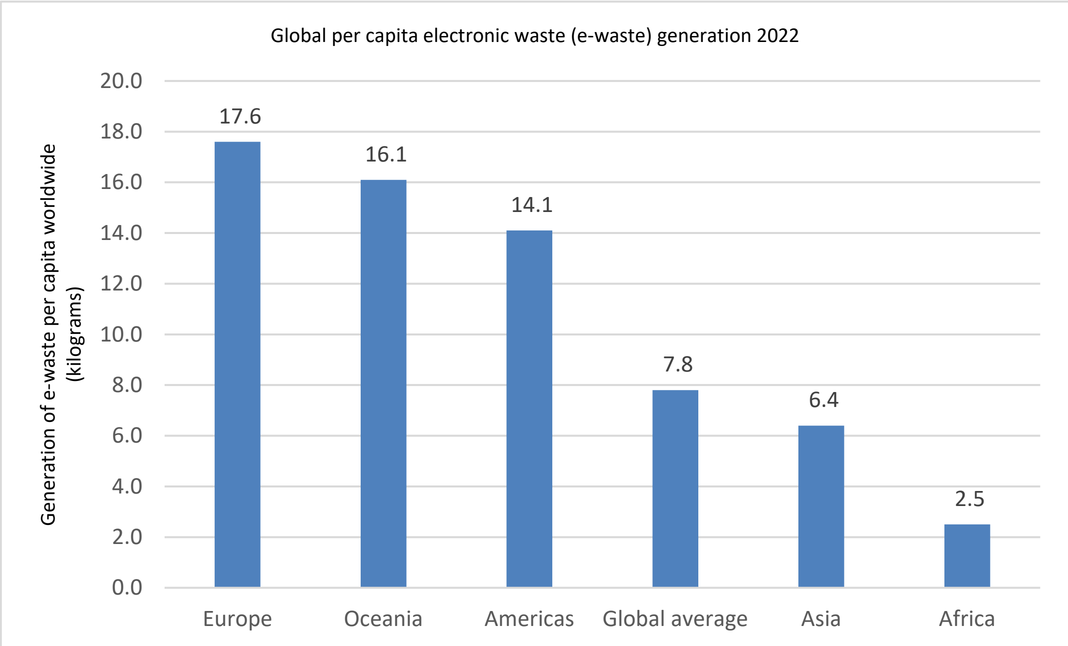


***Figure 1.*** **Global e-waste generation per capita by region in 2022 [4].**

In general, developed regions contribute significantly more e-waste per capita compared to developing regions, as shown by the data.

## 2.1. Conventional electronics

Conventional electronics refer to electronic products that have been developed primarily for functionality and cost-efficiency within a linear economy model. This approach focuses on production, consumption, and disposal, without consideration for the full product life cycle [5].

Conventional electronic devices are mainly made from polymeric and composite materials, including polyimide and flame retardant (FR4) [6]. The electronics industry can reduce its environmental footprint by transitioning from fossil-based to bio-based materials. In addition, minimizing metal usage and adopting printing-based additive manufacturing processes can further decrease its environmental impact [6]. Conventional electronics are often made from non-renewable, non-biodegradable materials and may contain toxic substances such as heavy metals and hazardous chemicals. Therefore, discarded e-waste can release these toxins, contaminating the natural ecosystem through soil and water [3].

## 2.2. Green electronics

Green electronics are designed to minimize environmental impact throughout their life cycle. These devices utilize biodegradable and eco-friendly materials in printed circuit boards (PCBs) manufacturing such as polylactic acid (PLA), cellulose/cellulose acetate, silk proteins, gelatin, polyvinyl alcohol, and wood, focusing on sustainable practices from production to disposal. This strategy minimizes the ecological impact of electronic devices [3], [7], [8].

Printed circuit boards (PCBs) are crucial in electronics, providing support and connecting components through conductive circuits that are imprinted on a non-conductive substrate [9]. They are composed of approximately 30 to 35% metals, 35 to 42% high-temperature-resistant materials, and 24 to 30% wax resins. Consequently, hazardous substances such as commercially used chemical flame retardants (FRs), epoxy resin, and glass fiber are commonly found in PCBs when they are disposed of and become waste. Major environmental issues associated with PCB waste include the reduced availability of landfill space and the risk of hazardous substances leaking into the soil. This contamination can endanger groundwater supplies and threaten the security of drinking water. Moreover, incorrect incineration of e-waste contributes to air pollution, posing health risks to nearby communities [10], [7].

## 2.3. Printed electronics

Printed electronics are produced by utilizing manufacturing technology that combines printing and conductive materials to create electronic devices from different kinds of substrates [11]. It involves applying electronic materials, including conductors, semiconductors, and dielectrics, in patterns on surfaces to form functional electronic circuits and devices. This technology is widely used because it allows for the economical production of large-scale electronic devices with a smaller environmental impact compared to conventional electronics manufacturing.

As seen in Table 1, printed electronics consist of three critical aspects: techniques, ink materials, and applications.

***Table 1.*** **Three critical aspects of printed electronics.**

| | |
|---|---|
| **1. Techniques / Methods** | The printing techniques include inkjet printing, screen printing, gravure, and flexographic printing. Each technique provides different advantages based on the application, including resolution, speed, and cost [12]. |
| **2. Ink materials / Other Materials** | The inks utilized in printed electronics comprise electronic materials such as metallic nanoparticles or conductive polymers. These inks are designed to have the appropriate viscosity and surface tension for particular printing techniques [13]. In addition, the other necessary materials for printed electronics include substrates, often flexible ones. In hybrid electronics that combines printed and assembled components, conductive and non-conductive adhesives are important. |

| | |
|---|---|
| **3. Applications** | Printed electronics are used in different applications including flexible displays, solar panels, Radio Frequency Identification (RFID) tags, sensors, and even wearable electronics [14]. This technology is critical for the advancement of flexible electronics, facilitating their incorporation into a variety of innovative products [11]. |

## 2.4. Conductive inks

Green electronics refers to electronic devices that have been designed and manufactured with a focus on environmental sustainability. This includes reducing energy consumption, minimizing hazardous waste, and using materials that are less harmful to the environment. In the context of green electronics, it is vital to assess the different types of inks that are used, as silver, carbon, and copper have significantly different environmental impacts. Today they are used in various printing technologies for producing electronic circuits and components depending on the use case and production process.

The conductive inks commonly utilized in printed electronics include:

1. **Silver ink** - is employed in the printing of electronic circuits because of its high electrical conductivity. It is used in applications that require effective energy transmission, such as Radio Frequency Identification (RFID) tags and solar cells [15], [16].
2. **Carbon** (**graphite) inks** - are considered more environmentally friendly and are used as a cost-effective alternative to metals like silver. They are used in applications requiring lower conductivity, such as in resistive sensors, heating elements, and touchscreens. Carbon-based inks, including graphene and carbon nanotubes, are particularly promising for green electronics due to their potential for low environmental impact and high performance [14], [17].
3. **Copper ink** - is an alternative to silver ink, providing good conductivity at a lower cost. It is used in printing electronic circuits and antennas. Since copper is more abundant than silver, using it can reduce both costs and the environmental impact associated with its extraction and use. However, the production of copper ink needs to be carefully managed to minimize environmental degradation from copper mining and processing [18].

The implementation of these inks in printed electronics contributes to an initiative aimed at enhancing sustainable manufacturing practices. These practices are characterized by waste reduction, decreased energy consumption, and limited use of toxic substances.

Printed electronics technology enables the direct deposition of materials onto substrates, which cuts down on material waste compared to traditional electronics manufacturing methods. This approach aligns well with the goals of green electronics by promoting resource efficiency and reducing environmental impact.

## 2.5. Substrates in printed electronics and their end-of-life processes

The substrate in printed electronics refers to the material on which electronic devices are printed, and it plays a crucial role in the performance and applications of printed electronics [12]. Substrates enable the fabrication of electrical devices on different flexible materials, allowing for the creation of flexible and conformal electronic components. In addition, they are crucial for the integration of electronic circuits for power, memory, signal conditioning, and communications in devices such as wearable electronics and smart labels [19]. The substrates materials that are applicable for the SUSTRONICS use cases are categorized in six different groups such as plastics, paper, nanocellulose, biopolymers (PLA, Bio-PET), cardboard and wood-based materials such as veneer.

As stated in [14] certain substrates have been evaluated for their environmental friendliness. These substrates offer promising solutions for minimizing electronic waste (e-waste) caused by disposable electronic devices. For instance, cardboard and paper substrates are environmentally friendly options due to their lower impact during production and end-of-life treatment. Polylactic acid (PLA), although it has a similar global warming potential (GWP) to Polyethylene terephthalate (PET) during production, is still considered environmentally friendly. This is because PLA generates biogenic $CO_2$ emissions when incinerated, which are more sustainable than the emissions from fossil-based PET. Veneer emerges as an environmentally friendly choice when compared to high-impact substrates such as PET.

Cellulose, which serves as the main structural element in plant cell walls and in certain microorganisms, is the most abundant natural resource. It is primarily extracted from green plants like trees and bamboo, agricultural crops such as soybeans, wheat, and sugar beets, and agricultural residues such as rice straw and sawdust. Nanocellulose is a derivative of cellulose that shares these properties and can be chemically modified. The strength, biodegradability, and renewability of nanocellulose make it a promising material for sustainable green electronics. Nanocellulose has shown potential in various areas, including nanopaper production, coatings, sensors, biomedical engineering, as well as electronic and energy storage devices. The high thermal stability, low thermal expansion coefficient, and robust mechanical properties make nanocellulose an appropriate substrate for the development of sustainable, flexible, transparent electronics in the future. These materials, including PLA, cardboard, paper and nanocellulose, serve as sustainable substitutes in printed electronics.

Currently, there are no specific standardized requirements for the compostability of electronics. However, requirements for compostable plastics (EN 14995) and packaging materials (EN 13432) are available and should be considered when designing end-of-life strategies for electronics. According to these requirements, materials must biodegrade within a specific timeframe and under certain conditions to be industrially compostable. Requirements also include limit values for certain metals (e.g., copper) and ecotoxicity evaluations. There are no limit values for silver, likely because it is not typically used in packaging or plastics.

Printed electronics utilize various conductive inks, including those based on silver, carbon (graphite), and copper. Each has a different environmental impact based on its production, use, and disposal. Table 2 presents the proposed applications and end-of-life strategies for a variety of substrates and ink materials used in printed electronics.

***Table 2.*** **Proposed applications and end-of-life processes for different combinations of inks and substrates.**

| Inks type | Substrates | Application | Proposed end of life process |
|---|---|---|---|
| • Silver<br>• Carbon (Graphite)<br>• Copper | Paper | Logistics and sensory technology in packaging, such as RFID and NFC tags. | Recycling: Limited material recovery due to losses in the end-of-life phase [14], [20]. |
| | Biopolymer: PLA | Utilizing sensor technology in food packaging and good UV resistance and transparent [21]. | Biodegradable in industrial composting facilities [14] |
| | Biopolymer: Bio-PET | Tracking health status [22]. | Treating medical waste: recycling and incineration. |
| | Cardboard | Logistics and sensory technology in packaging, such as RFID and NFC tags [14]. | Package recycling, may be compostable. |
| | Wood base: Veneer | Measuring environmental impact [22]. | Veneer may be compostable or biodegradable [6], [14]. |
| | Nanocellulose | • Suitable for electronic and energy storage devices.<br>• High mechanical strength, biodegradability, renewability, ease of chemical modification.<br>• Particularly useful in green electronics development such as circuits, transistors, antennas, sensors, electrochromic devices. [3] | Biodegradable and compostable- |

## 2.6. Environmental impacts of various inks in printed electronics

Silver ink offers the highest conductivity and performance. However, it comes with environmental concerns, high costs, and challenging recycling processes. Copper ink provides a lower environmental impact and cost compared to silver, with feasible recycling and suitable conductivity, making it a good substitute. In addition, carbon ink, the most cost-effective, has the lowest conductivity but minimal environmental impact and less hazardous disposal, making it another viable alternative to silver. Hence, copper and carbon inks are identified as promising substitutes for silver ink, considering their environmental and cost benefits.

A comparative analysis of three ink materials, including silver, copper, and carbon, highlighting their environmental impacts, costs, conductivity, end-of-life (EoL), and potential for substitution is presented in Table 3.

***Table 3.*** **Comparison of environmental impacts, costs, conductivity, EoL, and substitution for inks.**

| Inks material | Environmental impacts | Cost | Electrical conductivity | EoL | Potential for Substitution |
|---|---|---|---|---|---|
| Silver | • Energy-intensive and involves harmful chemicals [2].<br>• Highest environmental impact including ecotoxicological concerns at EoL [14], [21]. | High | Highest electrical conductivity - superior performance. | • Low recycling rates.<br>• Significant material loss at EoL.<br>• Challenges with separation of materials. | Copper and graphite inks could potentially replace this material due to environmental and cost benefits [2]. |
| Copper | Lower environmental impact compared to silver ink. | Medium | Lower conductivity than silver but higher than graphite. | Recycling is more feasible than silver, but sorting materials for efficient recycling is still an obstacle. | • A suitable replacement for silver.<br>• Minimizes environmental impact [14]. |
| Carbon | Lower environmental impact, similar to copper. | Low | Lowest conductivity, but sufficient for certain applications [23]. | Similar recycling challenges as copper and silver but less hazardous / toxic at disposal. | Cost-effective substitute for silver. |

Material recycling, composting, and biodegradability play critical roles in the management of EoL processes for sustainable materials utilized in electronic devices. These processes aim to minimize waste and environmental impact by returning materials to the production cycle. The recycling process for materials such as silver, carbon, and copper, which are commonly used in inks and conductive adhesives includes sorting, treatment, and cycling these materials back into the supply chain [24]. This practice helps reduce the reliance on virgin material extraction and minimizes associated environmental degradation. However, the environmental impact of recycling depends on the specific recycling processes and technologies employed, which can vary in energy consumption and emissions [14].

A comparison between silver, copper and carbon inks global warming potential (GWP) impacts when printed on different substrates was done by Nassajfar et al [25]. The results of that are depicted below in Figure 2 and show that when silver ink was used as the conductive ink, it was responsible for over 80% of the GWP impacts. Copper and carbon alternatives have significantly lower GWP.

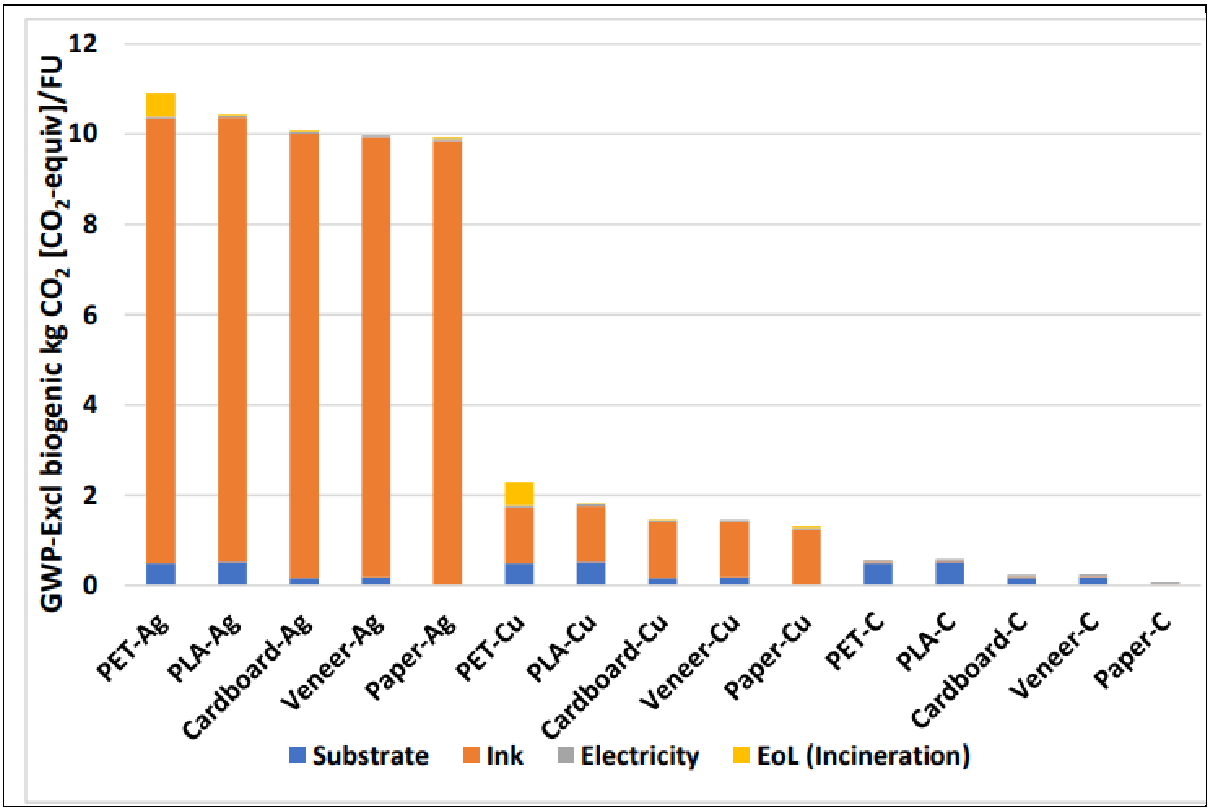


***Figure 2.*** **Contribution analysis of processes in GWP, excluding biogenic $CO_2$ [25].**

# 3. Environmental impact of sustainable materials

Environmental impacts of sustainable materials were studied using pilot #2.2 and the materials studied there. A life cycle assessment focusing on carbon footprint was conducted to assess the materials sustainability. The following results are based partly on calculations done by material suppliers and partly by VTT using SULCA life cycle assessment tool and ecoinvent 3.10 database with cut-off allocation. Impact assessment by VTT was done using EF3.1.

## 3.1. Substrates

The sustainability of substrates was assessed by calculating the carbon footprint of different materials. The chosen materials were two types of paper substrates, one PLA substrate, one bio-PP (polypropylene), one PEF (polyethylene furanoate) and a reference fossil PET. The materials technical performance has been studied as part of pilot #2.2 and all have shown potential to be used in further generations of pilot #2.2. The studied substrates were supplied by project partners TER, SCR, UPM, ARNP and VTT. Not all of them manufacture the substrates but use them frequently.

In an ideal assessment, primary data regarding substrate manufacturing would be provided by the manufacturer. This would include material and energy demand as well as information on waste generation during manufacturing. Primary data for these substrates was asked from suppliers with varying results. Publicly available literature was also used to find usable data for the analysis. Four suppliers had done a study of their substrates carbon footprint, and those results were available for our analysis. The PLA material has been studied extensively in an article by Morão and de Bie [26], the results of which were used also in this study.

As the goal of SUSTRONICS is to study the lifetime impacts of these materials, it is important to set the system boundary of the LCA to match that ambition. Therefore, the complete life cycle assessment at the end of the project is done cradle to grave, meaning all impact from raw material extraction up till end-of-life processes are considered. Setting the system boundary as such, brings up an important notice considering biogenic carbon. All substrates under study are either cellulose based or contain other biobased materials which in turn contain biogenic carbon. According to [27] biogenic carbon can be considered in two ways:

1) Biogenic carbon is accounted for as carbon storage considering $CO_2$ is captured from atmosphere during photosynthesis and retained within the material (cradle to gate LCA)
2) Biogenic carbon is considered $CO_2$ neutral and excluded from the analysis at the end of life (cradle to grave LCA)

The final LCA study of this project will be cradle to grave, and therefore approach (2) is followed through-out this study as well when possible. It is important to notice that all carbon storages are reversed when the product is either burned or biologically degraded at end of life. For the assessment results to be comparable, it is imperative that all substrates consider biogenic carbon in the same way. At the moment that is not done due to data availability issues. Therefore, the results of this study cannot be used to make definitive decisions.

To do a comprehensive life cycle assessment on all substrates would require detailed information about the production processes of each material including chemical, material and energy balances, which the manufacturers are not always willing to share. Thus, the assessment relies on pre-existing assessments the manufacturers have commissioned on their own and their willingness to share those results. Unfortunately, not all studies are made with the same system boundary or use the same assumptions. Companies want to promote their own products and show the assessment results in a way that highlights the best parts of their material. This leads to differences in how biogenic carbon is handled.

Figure 3 below shows the carbon footprint results for all six alternative substrate materials per kg substance. This is the typical way of comparing materials, but it does not consider material properties in the use case. Carbon footprints of bio-PP substrate, PEF substrate and paper substrates 1 and 2 were based on the suppliers' own calculations. PLA substrates carbon footprint was taken from literature and the reference PET was from ecoinvent v.3.10., *market for polyethylene terephthalate, granulate, amorphous* together with extrusion data also from ecoinvent, a process called *extrusion, plastic film*.

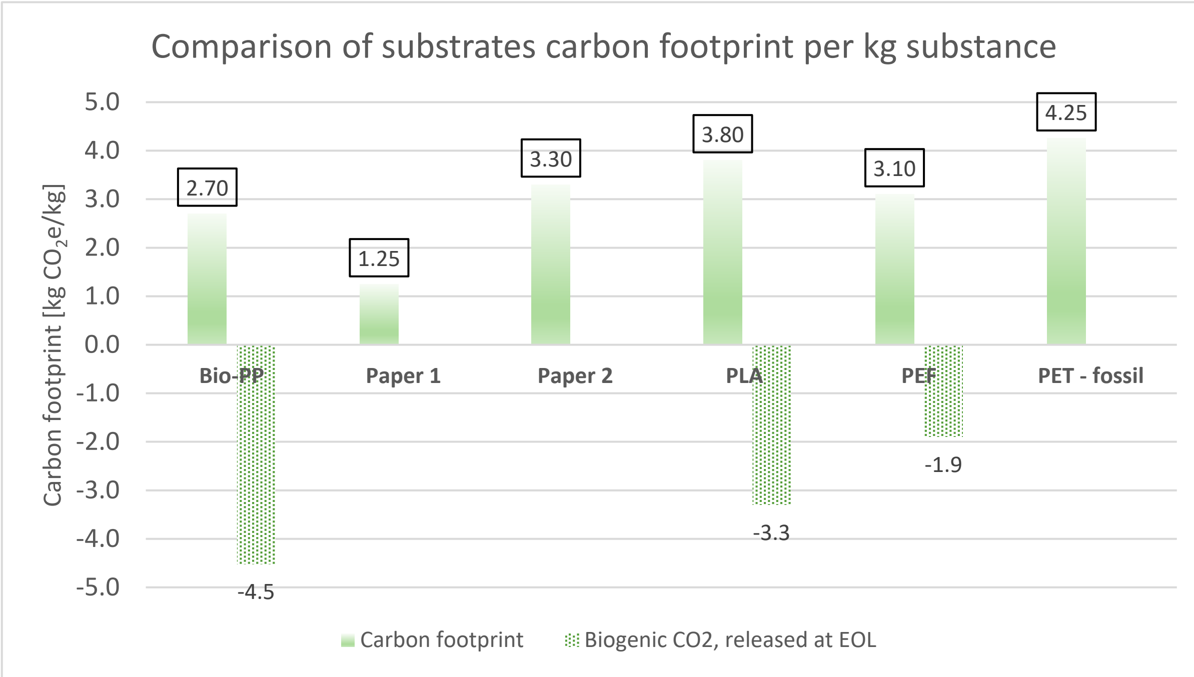


***Figure 3.*** **Carbon footprint comparison of different substrate materials per kg. The results are not fully comparable due to differences in how biogenic carbon is included.**

The studied substrates are of different thickness and their grammage varies as well. To see better the effect of these properties, Figure 4 shows the same carbon footprint results per $m^2$. For PLA, two thicknesses were chosen as it is possible to use thinner films as well. The other substrates only have one thickness. The thicknesses have been selected as such that it is possible to print the intended layers on the substrates and have the desired functionalities.

It is difficult to compare the substrates as the available data is so different. In paper substrate 1 case, it is not clear how much biogenic carbon the material contains and has the analysis been done cradle to gate, making it possible to consider biogenic carbon as a reduction in the total carbon footprint. The same question applies to paper substrate 2. It is known that the substrates main raw material is cellulose derived from wood pulp which means biogenic carbon is at play, but the amount is not known. The supplier was only able to tell that biogenic carbon is included at the point at which it occurs i.e., during the tree growing/pulp production phase but whether it is considered a reduction or not, was not divulged. From the six studied substrates, only PLA, PEF and bio-PP have a reported carbon footprint with its biogenic $CO_2$ clearly separated (depicted by light green in the figure).

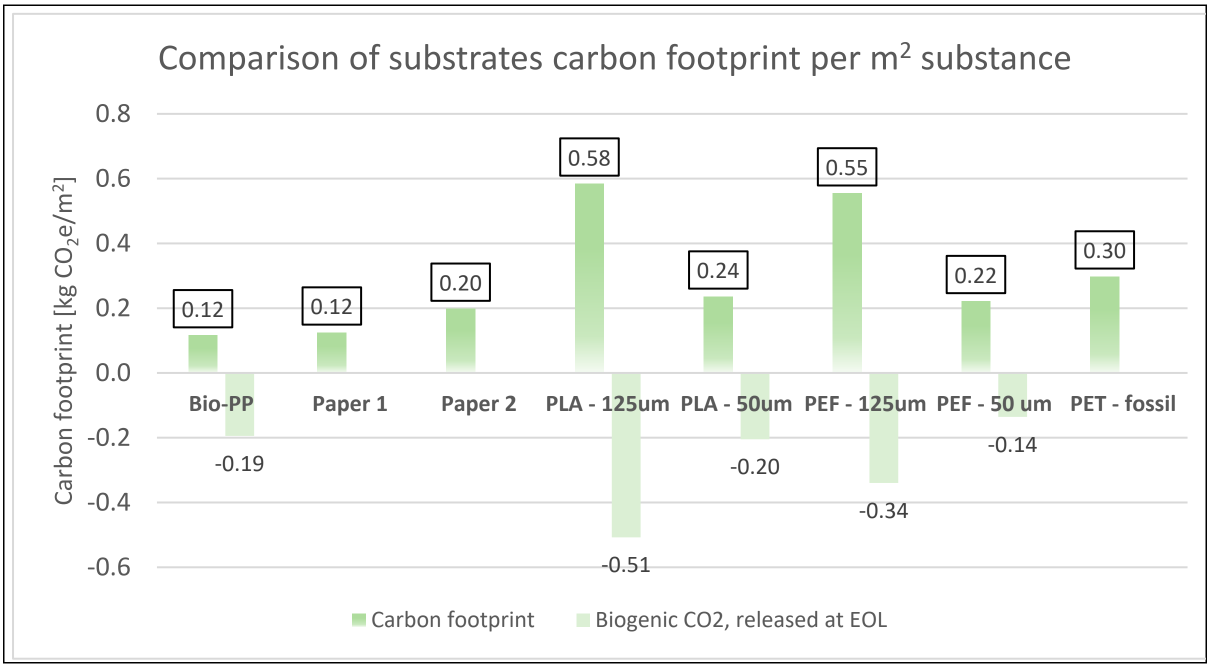


***Figure 4.*** **Carbon footprint comparison of different substrate materials per m2. The results are not fully comparable due to differences in how biogenic carbon is included.**

All in all, when comparing the five alternatives to fossil PET, all substrates have the possibility of lower carbon footprints in both per kg and per m2 comparisons. PLA and PEF substrates can achieve a lower carbon footprint if a thinner film can be used in the applications.

## 3.2. Inks

Based on initial tests done in pilot #2.2 for technical performance, four carbon inks, or pastes, were chosen for this assessment:

- Loctite – EDAG PF407C
- EMS – CI2051
- Saralon – Carbon 700A
- Bectron – GP9552

First, primary data about the production of these pastes was asked from their manufacturers along with whether any previous life cycle assessments or carbon footprint calculations had been made and would be available for use. Product technical datasheets (TDS) and material safety datasheets (MSDS) were available for all. In the end, a previous carbon footprint calculation was available only for Loctite ink. The supplier of Bectron ink was able to share its full chemical composition and that was used as basis for modelling. The other two were modelled based on chemicals that were stated in the MSDSs'.

As the ink production process requires energy as well as chemicals, and the energy inputs were not available, an estimation was needed. For that reason, ecoinvent v.3.10 process *metallization paste production, front side*, was used. It models the average production of metallization paste based on data for solder production and the chemical composition of average pastes. The underlying data is from 2006 and thus quite old, but under the circumstances it was the best available. The process includes inputs for factory infrastructure, organic chemicals, lead, silver, heat, and electricity. To utilize the energy inputs from this dataset, lead, silver and organic chemicals were removed and replaced with the actual chemicals of each ink under study.

Carbon footprint of the studied inks is shown in Figure 5. From the figure Saralon and EMS inks seem to have slightly lower carbon footprints than the other two. These results don't take into consideration the different handling techniques or temperatures required by the inks. The calculation encompassed only materials and energy for ink manufacturing, not how it is used in the pilot applications.

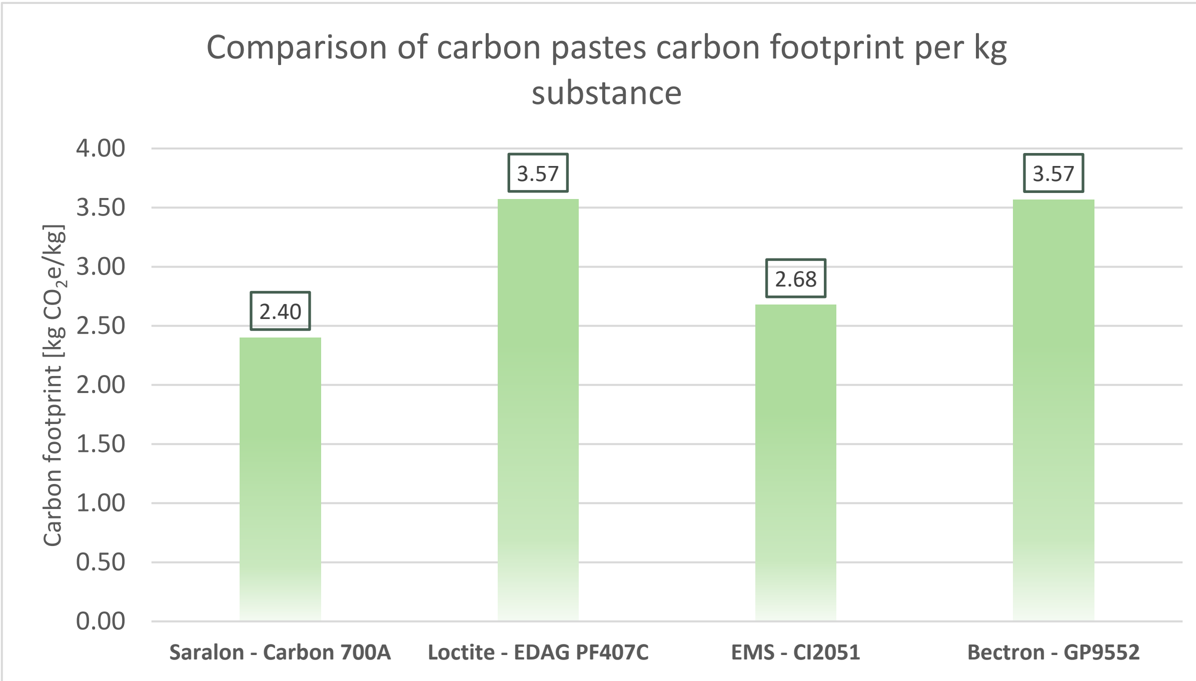


***Figure 5.*** **Carbon footprint comparison between carbon inks per kg.**

## 3.3. Adhesives

Adhesives play a crucial role in the assembly and functionality of electronic devices in various industries, including automotive, electronics, construction, and biomedical engineering. They are substances that bond materials through surface attachment, preventing separation and create a conductive contact between circuitry and components. Various types of adhesives, such as epoxy resins, epoxy-phenolic resins, epoxy-silicone compositions, silicone resins, acrylic resins, and polyimides, are utilized in different applications [28].

The advancement of adhesive technologies is driven by the need for reliable bonds, durability in diverse conditions, and compatibility with new materials [29]. Adhesives are classified based on their origin, chemical composition, and curing mechanisms. Origin refers to whether the adhesive is natural or synthetic while chemical composition includes categories such as epoxy, polyurethane, and acrylic. In addition, curing mechanisms include physical drying, chemical reactions, and hot melt processes [28].

Sustainability of adhesives can be addressed by selecting products that are based on sustainable raw materials, such as bio-based or renewable ones. Another approach is to select adhesives that can be processed during component assembly will less energy i.e. that possess lower curing temperatures and/or shorter curing times. Since commercial bio-based adhesives do not exits, the approach here was to find adhesives that consume less energy during assembly.

### 3.3.1. Energy Requirements for adhesives

The selection of an appropriate adhesive not only affects the mechanical and electrical properties of the final product but also influences the overall energy consumption and environmental footprint during the manufacturing process. Understanding the energy requirements for curing adhesives is essential for optimizing production processes and enhancing sustainability. Additionally, the energy density serves as a critical functional unit in Life Cycle Assessment (LCA) studies, enabling the evaluation of the environmental impact associated with the energy consumption of adhesive curing. Hence, this sub-section aims to calculate and compare the energy density of three different adhesive combinations used in hybrid assembly of silicon-based components in printed circuitry. This comparison aims to inform decisions related to adhesive selection in electronic device manufacturing, emphasizing energy efficiency and sustainability.

The three adhesive combinations that are examined in this study are:

- Case 1: EPO-TEK H20E (Isotropic conductive adhesive (ICA)) with LOCTITE 3525 (Non-conductive adhesive (NCA)).
- Case 2: DELO Dualbond IC343 (sustainable ICA) with LOCTITE 3525
- Case 3: DELO Dualbond IC343 (sustainable ICA) with Dualbond AD345 (NCA)

Case 1 is the state-of-the-art process used in hybrid assembly. Cases 2-3 represent novel alternatives with more sustainable approach. ICA is used to provide the electronic connection between the printed circuitry and SMDs (Surface Mounted Devices) or ICs (Integrated Circuits). NCA is used in all cases to provide additional mechanical support. These adhesives are used in the electronics industry for various bonding applications, each with distinct curing properties and energy requirements. By utilizing calculations for energy density, this study evaluates the efficiency and sustainability of each case within electronic device applications. The findings highlight differences in power consumption for curing process, providing insights for Life Cycle Assessment (LCA) and the selection of adhesives based on energy efficiency and environmental impact. The processing conditions for each combination are presented in Table 4.

***Table 4.*** **Typical processing conditions for each case.**

| | **Case 1** | **Case 2** | **Case 3** |
|---|---|---|---|
| **ICA** | | | |
| Light source | - | Dual curing, UV light (LED @ wavelength of 365-400 nm) and heat (air convection oven) | Dual curing, UV light (LED @ wavelength of 365-400 nm) and heat (air convection oven) |
| Light intensity | - | 200mW/cm² @ 365 nm + Convection heat | 200mW/cm² @ 365 nm + Convection heat |
| Exposure time | 900 seconds | 1-5 seconds (UV light fixation) + 600 seconds heat curing @ 100 ℃ | 1-5 seconds (UV light fixation) + 600 seconds heat curing @ 100 ℃ |
| Curing temperature | 120 ℃ a convection air heating oven | 100℃ in a convection air heating oven | 100 ℃ in a convection air heating oven |
| **NCA** | | | |
| Light source | UV and visible light curing | UV and visible light curing | Dual curing, UV light (LED @ wavelength of 365-400 nm) and heat (air convection oven) |
| Light intensity | 50 mW/cm² @ wavelength of 365 nm | 50 mW/cm² @ wavelength of 365 nm | 200mW/cm² @ 365 nm + Convection heat |
| Exposure time | tack-free time (12 seconds) + fixture time (5 seconds) + curing time (depending on curing system and cure depth) | tack-free time (10-15 seconds) + fixture time (<5 seconds) + curing time (depending on curing system and cure depth) | 1-5 seconds (UV light fixation) + 600 seconds heat curing @ 100 ℃ |
| Curing temperature | Not applicable for UV curing. | Not applicable for UV curing. | 100℃ in a convection air heating oven |

LOCTITE AA 3525 is an adhesive that cures when exposed to ultraviolet (UV) and visible light, which is a notable departure from traditional heat-cured adhesives. The curing speed (time) is influenced by the depth of the adhesive layer and the intensity of the UV light, the so-called irradiance, and can be estimated using the graph for depth of cure vs. Irradiance. A typical curing setup involves the Zeta 7200 system, which operates at a light intensity of 50 mW/cm² and a wavelength of 365 nm. In this configuration, the tack-free time is approximately 10-15 seconds, while full curing time varies depending on the adhesive thickness (usually requiring 4 to 5 times the fixture time i.e., ≤ 5 seconds for the Zeta 7500 source, 6 mW/cm² @ 365 nm. The very short fixture time of LOCTITE AA 3525 allows components to be held in place quickly after initial UV exposure. This rapid curing capability enhances assembly speed and boosts overall manufacturing efficiency. Additionally, the quick cure process significantly reduces energy consumption compared to conventional thermal curing methods, such as EPO-TEK H20E, which can take up to 30 minutes at elevated temperatures.

To bond six A4-sized sheets (assumed as the functional unit here) with the given thickness of 1 mm using LOCTITE AA 3525, the total curing time required is approximately 22 to 27 seconds. This process includes 10-15 seconds for tack-free handling, around 7 seconds for curing (extracted from the blue curve in TDS of LOCTITE AA 3525), and about 5 seconds for fixture time to achieve full bond strength. This process is much faster than heat-based systems, which can take form several minutes to hours to cure.

Compared to traditional thermal curing adhesives like EPO-TEK H20E, the use of UV light for curing with LOCTITE AA 3525 offers substantial energy savings. It eliminates the need for high-temperature ovens, reducing energy consumption.

As illustrated in 0, bonding six A4-sized sheets with EPO-TEK H20E (ICA) may require 2500 Watts to reach and maintain a temperature of 120°C over a 15-minute curing cycle. In contrast, the Zeta 7200 curing system used with LOCTITE AA 3525 requires only 155.9 Watts for brief bursts during the tack-free and fixture times. This results in over a 16-fold reduction in energy consumption, marking a substantial improvement in sustainable manufacturing processes.

The DELO DUALBOND AD345 and DELO DUALBOND IC343 are dual-curing adhesives that utilize both UV light and heat for curing, making them widely used in electronics applications. Initially, these adhesives are subject to a light fixation process using UV light with an intensity of 200 mW/cm$^2$ at a wavelength range of 365-400 nm. This phase typically lasts between 1-5 seconds, depending on factors such as adhesive thickness, material absorption, and the distance between the light source and the adhesive layer. Subsequently, full curing is achieved through exposure to a convection air heating oven preset at 100°C, taking roughly 600 seconds. This step ensures the adhesives reach their maximum bond strength. The complete curing cycle, therefore, totals around 600-605 seconds. Notably, the most significant portion of energy consumption during this process stems from reaching and maintaining the oven temperature at 100°C throughout the duration, in contrast to the initial UV curing phase, which consumes relatively less energy.

According to 0, both DELO DUALBOND AD345 and DELO DUALBOND IC343 require approximately 623.7 W of light power (for the fixation time) at an intensity of 200 mW/cm$^2$. This requirement is for the specified functional unit in this study, corresponding to the bonding of six A4-sized paper sheets. Additionally, they require 2500 Watts for a 10-minute curing process at 100°C in an air convection oven.

***Table 5.*** **Required power for curing process of four different adhesives.**

| **Parameter** | **Unit** | **EPOTEK (ICA)** | **DELO DUALBOND IC343 (ICA)** | **LOCTITE 3525 (NCA)** | **DELO DUALBOND AD345 (NCA)** |
|---|---|---|---|---|---|
| Cure time | [s] | 1800 | 1-5 (light) + 600 (heat) = 601-605 | 22-27 | 1-5 (light) + 600 (heat) = 601-605 |
| Depth of cure | [mm] | 0.1*5 (for six A4-size paper sheet) | 0.1 * 5 | 0.1 * 5 | 0.1 * 5 |
| Irradiance | [mW/cm$^2$] | N/A | 200 | 50 | 200 |
| Bonding area | [cm$^2$] | 29.7*21*5 = 3118.5 | 3118.5 | 3118.5 | 3118.5 |
| Required curing power | [Watt] | 2500.0 | 623.7 (light) + 800 (convection heat) | 155.9 | 623.7 (light) + 800 (convection heat) |

The comparative analysis of the adhesive properties in the table reveals significant variations in curing time, irradiance, and required curing power among the four adhesives: EPOTEK, DELO DUALBOND IC343, LOCTITE 3525 (NCA), and DELO DUALBOND AD345. EPOTEK stands out with the longest cure time of 1800 seconds, while LOCTITE 3525 (NCA) requires the shortest curing time of 22-27 seconds. DELO DUALBOND adhesives (IC343 and AD345) exhibit a dual phase curing process, consisting of 1-5 seconds of light exposure followed by 600 seconds of heat application, totalling 601-605 seconds. In terms of irradiance, DELO DUALBOND IC343 and AD345 adhesives require higher irradiance levels (200 mW/cm$^2$) compared to LOCTITE 3525 (50 mW/cm$^2$), while EPOTEK does not need any irradiance. The bonding area remains constant for all adhesives at 3118.5 cm$^2$. However, the required curing power varies significantly, with EPOTEK requiring 2500 Watts, which is notably higher than the other adhesives, while LOCTITE 3525 demands the least power at 155.9 Watts. This comparison underscores EPOTEK's high energy requirement and extended cure time, contrasting with the efficiency of the other adhesives, particularly LOCTITE 3525, which offers faster curing with minimal energy consumption.

A summary of 0 is illustrated in Figure 6, where the curing time and power requirements for four different adhesives are individually compared across cases 1, 2, and 3. As seen, the DELO DUALBOND adhesives may provide equivalent or enhanced performance while consuming less energy, suggesting they are a more sustainable option. However, a complete assessment would also need to include lifecycle analyses of these products to understand their overall environmental impacts, including sourcing of raw materials, production, usage, and disposal phases.

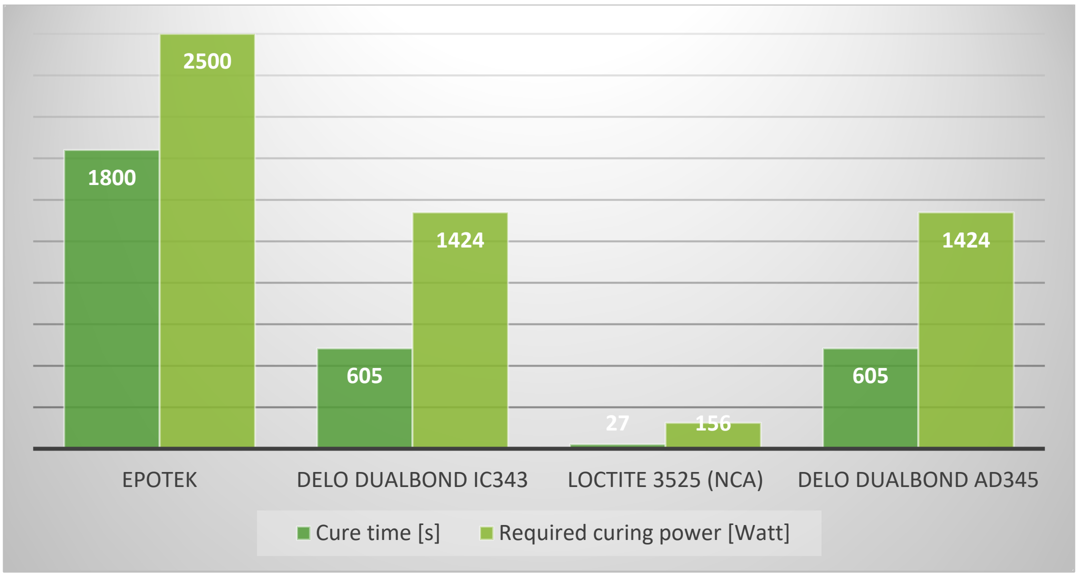


***Figure 6.*** **Comparison of the curing time and required power for four different adhesives across cases 1, 2, and 3.**

Additionally, Figure 7 compares cure time and required curing power across three cases evaluated in this study. Case 1 has a cure time of 1827 seconds and requires 2656 Watts. Moreover, Case 2 shows the most efficient performance with a reduced cure time of 632 seconds and 1580 Watts of power. Case 3 has a moderate cure time of 1210 seconds but demands the highest power at 2847 Watts.

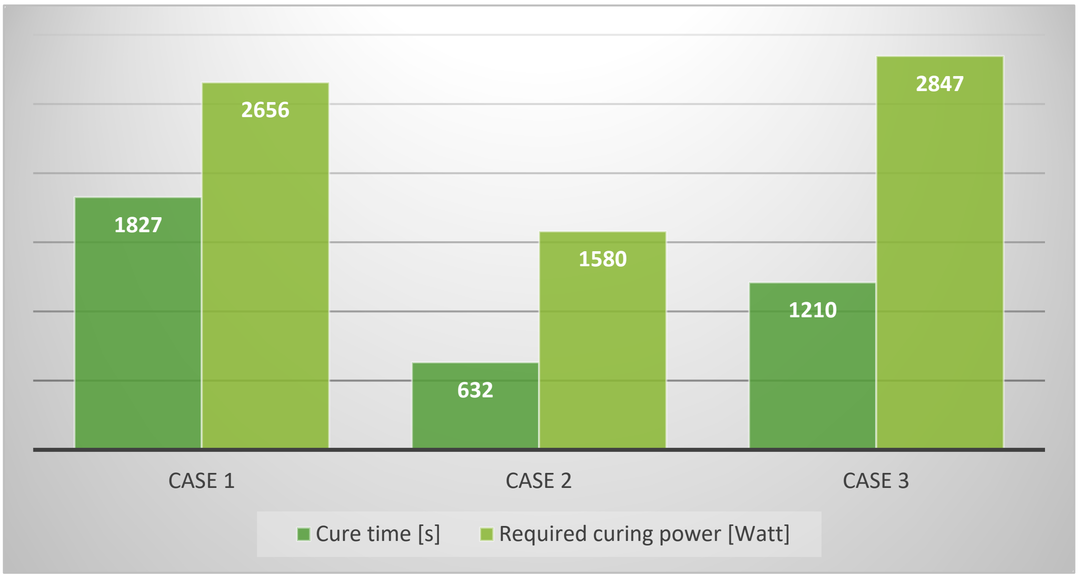


***Figure 7.*** **Comparative analysis of cure time and required curing power across three studied cases.**

Note that the performed calculation has focused only on the assembly stage so care must be taken when interpreting the results. Since many of the lifecycle stages have been discarded the results should be considered to represent only a single stage of adhesive lifetime. When making a full LCA over adhesive lifetime, the raw materials used, and the adhesive manufacturing process should also be considered as well as end-of-life. These will certainly influence the total environmental impact of the adhesives used for component assembly.

When selecting an adhesive its performance as part of a system should also be considered, and a balance between the technical performance and sustainability, but also economics, should be found.

# 4. End-of-life processes for sustainable materials

SUSTRONICS considers two main end-of-life routes for electronics: biodegradability and recyclability.

## 4.1. Biodegradability

SUSTRONICS will investigate compostability of different materials and material combinations with focus on how integration of metal circuitry on biodegradable substrates affects compostability. The work will be carried out as part of T4.4 (Process development, tests and data quantification on material recycling, biodegradation and disposal) during M12-M36. The plan for the compostability is described here. The objective is to evaluate biodegradability of substrates in industrial composting conditions and to evaluate the impact of (printed) electronics on the biodegradability of substrates.

Compostability experiments will be implemented at VTT based on two standards:

1. EN 14046 Packaging. Evaluation of the ultimate aerobic biodegradability of packaging materials under controlled composting conditions. Method by analysis of released carbon dioxide.
2. ISO 14855. Determination of the ultimate aerobic biodegradability of plastic materials under controlled Composting conditions. Method by analysis of evolved carbon dioxide. and ISO 14855).

The methods are commonly used for plastics and packaging materials and the biodegradation is calculated based on $CO_2$ evolution. The sample is mixed with mature compost and milled or tested as pieces at 58$^{o}$C from 45 days up to 6 months. $CO_2$ is automatically measured in continuous aeration.

Two test runs will be implemented. Each test run will contain ten samples and a positive reference that is microcrystalline cellulose. The samples will contain pure substrates (4 different), and the same substrates with printed metal circuitry (silver, copper, carbon). The first test run will contain cellulose and biopolymer based substrate materials from UPM, VTT and TER that have been tested to be technically the most potential sustainable substrates for Pilot#2.2. These substrates are also biodegradable or industrially compostable. The first test run will start at ca. M18. The samples for the second test run will be decided based on the results from the first test run.

## 4.2. Recyclability

Recyclability of selected materials and components will also be studied as part of T4.4 during M12-M36. This will include mapping of current or expected end-of-life behaviour, identification of potential challenges for material recovery (as an ideal separate waste stream, or within other waste streams), and semiquantitative estimation of material recovery potential led by MIR. These finding will be used to reflect on developed technologies for improved design for end-of-life. Furthermore, recycling methodologies to meet the needs of sustainable electronic products will be developed.

Results for end-of-life experiments will be reported in D4.4 ‘End-of-life concepts and new processes for sustainable electronics’ at M30 led by MIR.

# 5. Conclusions

The main materials related to development of sustainable electronics in SUSTRONICS are substrates, inks and adhesives. The other materials reported in e.g. D1.3, such as covering, encapsulation etc. were excluded from this deliverable, but will be addressed in pilot specific LCAs. The substrates relevant to SUSTRONICS are plastics, paper, nanocellulose, biopolymers, cardboard and wood-based materials such as veneer. These all can be considered sustainable, also plastics when recycled versions are used. According to LCA cellulose based substrates have the lowest environmental impact. Biopolymers and plastics have higher environmental impacts from manufacturing.

The most important inks for SUSTRONICS are metal based ones: silver, copper and carbon. Silver is not very environmentally friendly due to its mining process, but copper and carbon are considered more sustainable. Carbon can be also bio-based and considered an abundant material. Bio-based adhesives are not available, but their sustainability can be addressed through assembly process energy consumption. However, a balance between performance and sustainability must be found. Furthermore, in the presented calculation the NCA requiring lower curing temperature was not found more sustainable due to the required longer curing time. Therefore, the sustainability of adhesives is not a straightforward question when talking about curing temperatures and times.

To benchmark different sustainable materials LCA has been used as the main methodology. It is a standardized methodology and suitable when enough LCI data is available. In this deliverable carbon footprint calculations were done for raw materials manufacturing (inks, substrates) or for energy consumption during manufacturing (adhesives). It is recommended to continue with lifecycle and pilot specific data to benchmark different lifecycle phases and how the materials perform as part of the use case scenario. This will be done for different SUSTRONICS pilots and reported in D3.3-3.4 and D4.6.

The end-of-life options in SUSTRONICS are material recycling and recovery as well as composting. These will be investigated further based on plans presented in this deliverable to be reported in D4.4. Many of the selected bio-based substrates for SUSTRONICS pilots are compostable, some even biodegradable. Therefore, it would be interesting to do a comparison between recyclability and composting for the same material. The effect of inks and adhesives on end-of-life is to be investigated, specifically their effect on composting.

# 6. References


[1] Md. N. Uddin, K. Arifa, and E. Asmatulu, "Methodologies of e-waste recycling and its major impacts on human health and the environment," *International Journal of Environment and Waste Management*, vol. 27, no. 2, p. 159, 2021, doi: 10.1504/IJEWM.2021.112949.

[2] L. Hakola, M. Smolander, I. Orko, L. Sokka, and M. Välimäki, "Development of a Qualitative Tool for Sustainability Assessment and Application of the Tool to Benchmark Electronic Smart Labels," *Circ.Econ.Sust.*, vol. 4, no. 1, pp. 97–122, Mar. 2024, doi: 10.1007/s43615-023-00280-3.

[3] Y. Ko *et al.*, "Cutting Edge Use of Conductive Patterns in Nanocellulose-Based Green Electronics," *Advanced Functional Materials*, vol. 33, no. 37, p. 2302785, 2023, doi: 10.1002/adfm.202302785.

[4] "Generation of electronic waste per capita worldwide in 2022, by region," Generation of electronic waste per capita worldwide in 2022, by region (in kilograms) [Graph], United Nations Institute for Training and Research, March 19, 2024. [Online]. Available: https://www.statista.com/statistics/499932/per-capita-ewaste-generation-worldwide-by-region/.

[5] F. O. Leitão, T. de Sousa Martins, P. Guarnieri, and O. Ouro-Salim, "Transition from linear to circular economy of electrical and electronic equipment: A review," *Business Strategy & Development*, vol. 6, no. 3, pp. 430–446, 2023, doi: 10.1002/bsd2.249.

[6] K. Immonen *et al.*, "Potential of Commercial Wood-Based Materials as PCB Substrate," *Materials*, vol. 15, no. 7, Art. no. 7, Jan. 2022, doi: 10.3390/ma15072679.

[7] C. F. Soon *et al.*, "Advancements in Biodegradable Printed Circuit Boards: Review of Material Properties, Fabrication Methods, Applications and Challenges," *Int. J. Precis. Eng. Manuf.*, May 2024, doi: 10.1007/s12541-024-01027-2.

[8] J. Zhu, H. Wen, H. Zhang, P. Huang, L. Liu, and H. Hu, "Recent advances in biodegradable electronics- from fundament to the next-generation multi-functional, medical and environmental device," *Sustainable Materials and Technologies*, vol. 35, p. e00530, Apr. 2023, doi: 10.1016/j.susmat.2022.e00530.

[9] K. Church, "Printed Circuit Structures, the Evolution of Printed Circuit Boards".

[10] M. N. Nassajfar, I. Deviatkin, V. Leminen, and M. Horttanainen, "Alternative Materials for Printed Circuit Board Production: An Environmental Perspective," *Sustainability*, vol. 13, no. 21, Art. no. 21, Jan. 2021, doi: 10.3390/su132112126.

[11] J. Wang *et al.*, "Development Status and Trends of Several Major Flexible Printed Electronics," *Lecture Notes in Electrical Engineering*, vol. 754 LNEE, pp. 358–365, 2021, doi: 10.1007/978-981-16-0503-1_53.

[12] K. Thiyagarajan, S. G. Rahul, G. K. Rajini, D. Maji, and A. Chandrasekhar, "Conductive Nanomaterials for Printed and Flexible Electronics Application," in *Nanotechnology in Electronics*, 1st ed., V. P.M., A. Semkin, R. Balakrishnan, and S. Lazovič, Eds., Wiley, 2023, pp. 207–239. doi: 10.1002/9783527824229.ch7.

[13] M. Keskinen, "End-of-life options for printed electronics," in *Waste Electrical and Electronic Equipment (WEEE) Handbook*, Elsevier, 2012, pp. 352–364. doi: 10.1533/9780857096333.3.352.

[14] M. Naji Nassajfar *et al.*, "The effect of conductive ink alternation on the sustainability and functioning of printed electronics," *Flexible and Printed Electronics*, vol. 8, no. 2, 2023, doi: 10.1088/2058-8585/acd650.

[15] P. Maisch *et al.*, *Inkjet printing of semitransparent electrodes for photovoltaic applications*. 2016. doi: 10.1117/12.2236968.

[16] M. Zhuldybina *et al.*, "Towards fully green printed device with environmental perspectives," *Flex. Print. Electron.*, vol. 8, no. 3, p. 035018, Sep. 2023, doi: 10.1088/2058-8585/acf8d6.

[17] Y. Qin, X. Ouyang, Y. Lv, W. Liu, Q. Liu, and S. Wang, “A Review of Carbon-Based Conductive Inks and Their Printing Technologies for Integrated Circuits,” *Coatings*, vol. 13, no. 10, Art. no. 10, Oct. 2023, doi: 10.3390/coatings13101769.

[18] X. Zeng *et al.*, “Copper inks for printed electronics: a review,” *Nanoscale*, vol. 14, no. 43, pp. 16003–16032, 2022, doi: 10.1039/D2NR03990G.

[19] Y. Zhang *et al.*, “Methods for fabrication of flexible hybrid electronics,” in *Hybrid Memory Devices and Printed Circuits 2017*, E. J. List-Kratochvil, Ed., San Diego, United States: SPIE, Aug. 2017, p. 12. doi: 10.1117/12.2275561.

[20] M. Smolander, K. Vehmas, and L. Hakola, “Functional inks and indicators for Smart Tag based intelligent packaging applications,” *Journal of Applied Packaging Research*.

[21] J. Wiklund *et al.*, “A Review on Printed Electronics: Fabrication Methods, Inks, Substrates, Applications and Environmental Impacts,” *Journal of Manufacturing and Materials Processing*, vol. 5, no. 3, p. 89, Aug. 2021, doi: 10.3390/jmmp5030089.

[22] Y. Khan, A. Thielens, S. Muin, J. Ting, C. Baumbauer, and A. C. Arias, “A New Frontier of Printed Electronics: Flexible Hybrid Electronics,” *Advanced Materials*, vol. 32, no. 15, p. 1905279, 2020, doi: 10.1002/adma.201905279.

[23] M. Naji Nassajfar *et al.*, “The effect of conductive ink alternation on the sustainability and functioning of printed electronics,” *Flexible and Printed Electronics*, vol. 8, no. 2, 2023, doi: 10.1088/2058-8585/acd650.

[24] C. Aliaga, H. Zhang, A. Dobon, M. Hortal, and D. Beneventi, “The influence of printed electronics on the recyclability of paper: A case study for smart envelopes in courier and postal services,” *Waste Management*, vol. 38, no. 1, pp. 41–48, 2015, doi: 10.1016/j.wasman.2015.01.005.

[25] M. Naji Nassajfar *et al.*, “The effect of conductive ink alternation on the sustainability and functioning of printed electronics,” *Flex. Print. Electron.*, vol. 8, no. 2, p. 025015, Jun. 2023, doi: 10.1088/2058-8585/acd650.

[26] A. Morão and F. de Bie, “Life Cycle Impact Assessment of Polylactic Acid (PLA) Produced from Sugarcane in Thailand,” *J Polym Environ*, vol. 27, no. 11, pp. 2523–2539, Nov. 2019, doi: 10.1007/s10924-019-01525-9.

[27] P. Pawelzik *et al.*, “Critical aspects in the life cycle assessment (LCA) of bio-based materials – Reviewing methodologies and deriving recommendations,” *Resources, Conservation and Recycling*, vol. 73, pp. 211–228, Apr. 2013, doi: 10.1016/j.resconrec.2013.02.006.

[28] D. Lu and C. P. Wong, Eds., *Materials for Advanced Packaging*. Cham: Springer International Publishing, 2017. doi: 10.1007/978-3-319-45098-8.

[29] T. Happonen, A. Korhonen, T. Kololuoma, and K. Rönkä, “Adhesive bonding strength for printed and hybrid electronics: 23rd European Microelectronics and Packaging Conference & Exhibition, EMPC 2021,” *2021 23rd European Microelectronics and Packaging Conference & Exhibition (EMPC)*, Sep. 2021, doi: 10.23919/EMPC53418.2021.9585000.