ecotronics

Sustainable Electronics & Optics

Final report on ECOtronics research project carried out in Finland 2019-2022

Figure 1. Printed electronics with user interface mock-up.

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1 Introduction

Figure 2. *Printing electronics.*

ECOtronics ecosystem project's vision was to support renewal of Finnish electronics and optics industry, to increase associated export, and to support development of sustainable electronics and optics throughout their lifecycles, motivated by the need to reduce harmful electronic waste.

Sustainability was achieved by

1. **selecting highly recyclable and compostable materials,**
2. **promoting environmentally friendly manufacturing technologies to reduce the use of materials,**
3. **developing the methodology to recover the materials, and**
4. **quantifying the environmental impact of the developed solutions.**

ECOtronics consortium consisted of parallel research and company projects with a total budget of 4.2 Million Euros co-funded by Business Finland. The project schedule was 1.10.2019-31.1.2022. The research partners and their main roles were:

- **VTT Technical Research Centre of Finland Ltd. (VTT):** Project coordination; evaluation and selection of sustainable substrates, inks and adhesives; sustainable manufacturing, including printing, overmoulding and laser processing; development of organic photovoltaics (OPV) for energy source; development of thin film transistors (TFTs) with eco-design; leading demonstrator integration; life cycle assessment (LCA) studies; specification of exploitation plans; and leading dissemination efforts.
- **Tampere University (TAU):** Inkjet printability on sustainable substrates; development of supercapacitor (SC) for energy source; development of printed diodes; and development of power management system.
- **LUT University (LUT):** Evaluation and selection of cellulose based sustainable substrates; development of converting processes for intelligent packages; LCA studies; and circular economy model development, including recyclability, repulpability and deinking experiments.
- **LAB University of Applied Sciences (LAB):** development of project's visual identity and infographics; and product design for demonstrators.

Eight industrial partners were supporting the research project with their own confidential projects or by providing inkind support for the research project, and by guiding the research work in the ECOtronics Steering Group. The industrial partners were **Confidex, GE Healthcare, Green Company Effect, Iscent, New Cable Corporation, Paptic, Stora Enso and Vaisala.** The roles of all partners are presented in Figure 3.

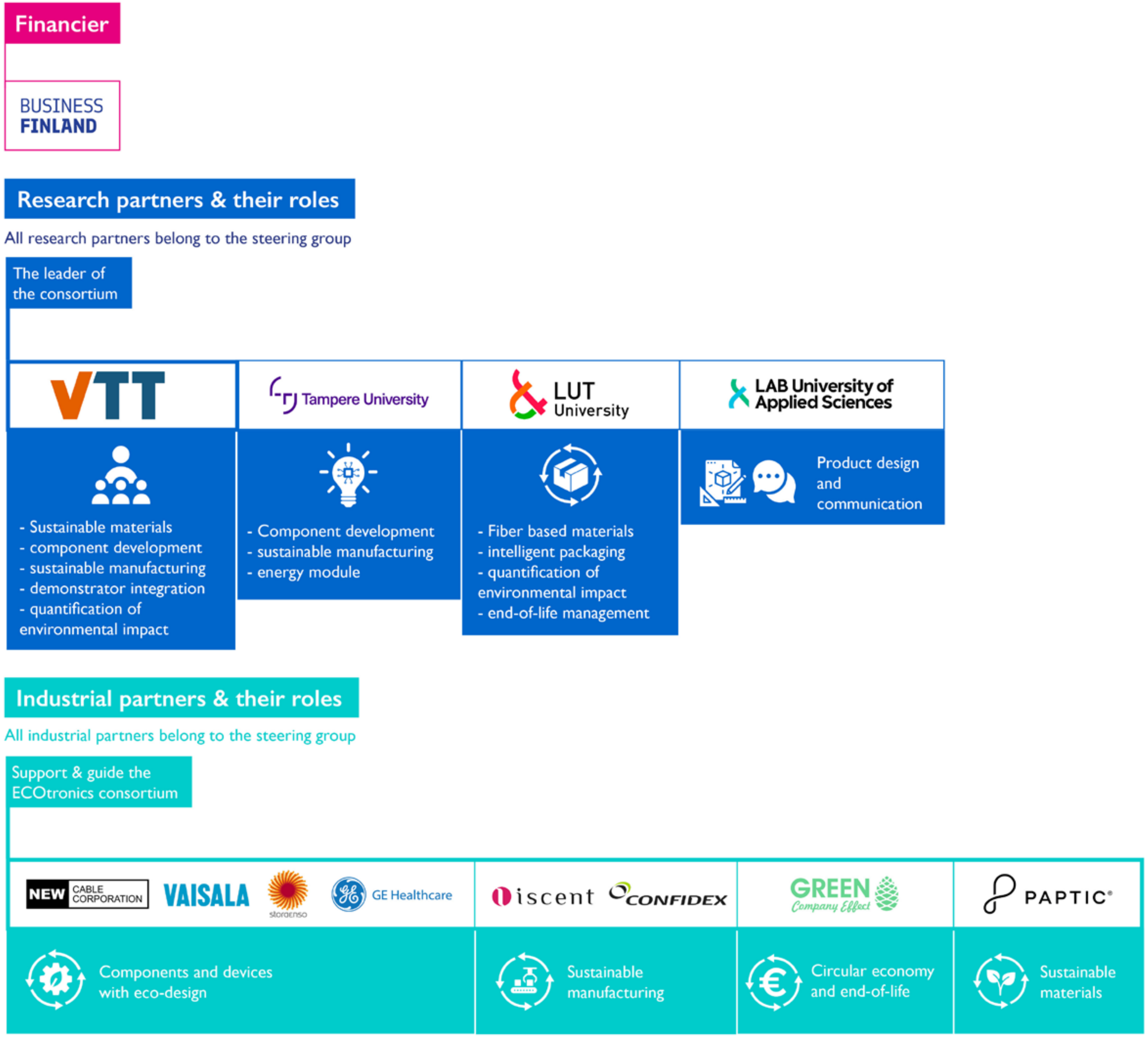


Figure 3. *ECOtronics consortium.*

The main goals of ECOtronics research project were to:

1. Improve sustainability by developing, selecting and analysing novel sustainable substrate, ink and assembly materials compatible with sustainable manufacturing, such as printing, overmoulding, hot embossing and hybrid assembly. This included environmental and economic analysis, and eco-design approaches, such as reduction in use of materials.

2. Evaluate the performance of sustainable materials and processed in two specified demonstrators:

   (i) Intelligent packaging for monitoring food quality (Smart label), and

   (ii) sensor for monitoring environmental conditions (RF circuit)

   Smart label demonstrator was designed for recycling and RF circuit for biodegradability. The demonstrators included sustainable components, such as energy module for energy autonomous sensors and printed antennas.

3. Carry out LCA to quantify environmental impact of the sustainable materials, processes, components and devices, including development of a LCA tool tailored for sustainable electronics and optics. Furthermore, define circular economy models for selected electronic domains.

ECOtronics workplan timeline

Figure 4. *ECOtronics workplan.*

4. Innovate novel electronics and optics products enabled by use of sustainable materials and processes.

5. Commit industrial companies to sustainability by supporting projects of industrial partners, by organizing events with participants outside the project consortium, by following up legislative framework, and by disseminating the project results in multiple channels.

The research work was divided into six work packages during implementation as presented in Figure 4.

This is the final report of ECOtronics research project presenting the main outcomes. The report is divided into sub-chapters about sustainable materials (chapter 2), demonstrators for intelligent packaging (chapter 3) and PCB (chapter 4), quantification of environmental impact (chapter 5), and dissemination activities (chapter 6). Chapter 3-4 about the demonstrator include reporting on relevant key technology building blocks.

2 Evaluation of sustainable materials

Figure 5. *Material examples*

In ECOtronics project one goal was to improve the sustainability of electronics and optics by developing, selecting and analysing novel sustainable materials, such as substrates, inks and adhesives, and manufacturing processes together with economic and environmental analysis of the alternative pathways of the production chain. Work Package 1 (WP1) focused on finding the best available sustainable material solutions for two demo cases presented as result of the project and for utilisation more widely within ECOtronics partners and companies using printed electronics.

2.1 Selection criteria for materials & list of materials

2.1.1 Substrates

The main selection criteria for substrate materials was to replace the fossil-based plastics typically used in printed electronics, such as polyethylene terephthalate (PET), polyimide (PI) or polyethylene naphthalene (PEN), by using materials from renewable origin. The material should also be recyclable and in some applications biodegradable. Figure 6 presents the world of substrate materials in the view of ECOtronics.

Both bioplastics and cellulose/paper based materials were considered as potential substrate for printed electronics. However, there are quite many demands or requirements for the substrate material coming from the processing (printing and assembly), compatibility with other materials in use (ink, adhesives, other layers), application performance related demands and product durability.

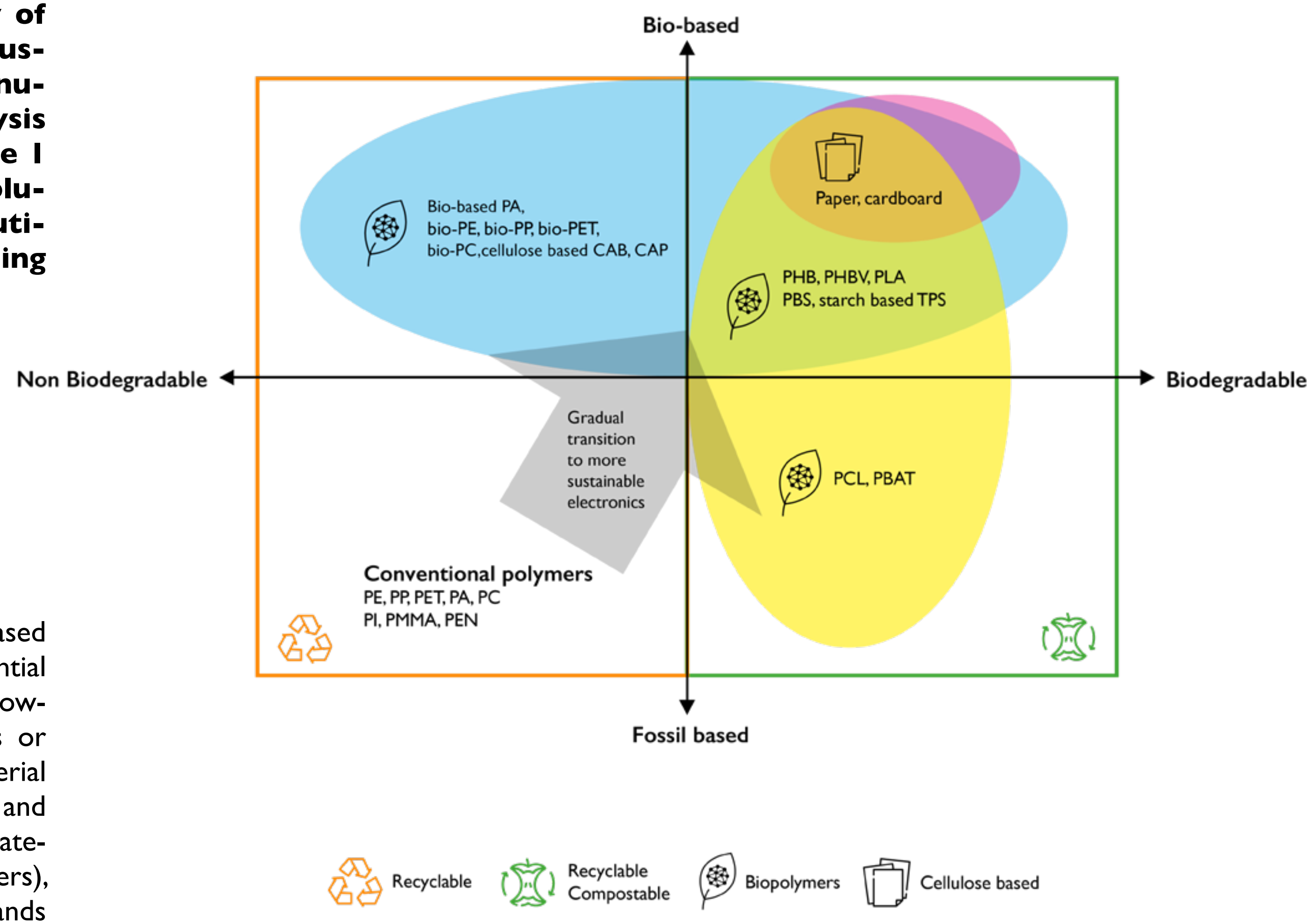


Figure 6. *Substrate material focus in sustainable electronics and ECOtronics project (KI modified chart presented by www.european-bioplastics.org)*

General requirements for substrates coming from printing process:

- substrate thickness 36-375 µm
- dimensional stability
- temperature tolerance at least up to 140°C (depending on ink, can also be lower)
- can tolerate UV curing (e.g. 200 W/cm, 365 nm or 140 W/cm, 550 nm)
- can tolerate plasma treatment
- non-conductive substrate
- chemical tolerance to typical solvents in ink: e.g. water, alcohols, MEK, pyrrolidone
- hydrophilic surface
- optimal surface energy >36 dynes/cm (OR higher than surface tension of the ink, typically 24-36 dynes/cm)
- surface roughness low enough to provide high resolution line and even thickness of ink on surface enabling high conductivity
- Substrate suitability for roll-to-roll processing

General requirements coming from assembly process:

- dimensional stability and proper strength (e.g. bending strength) in roll-to-roll process
- adhesion towards adhesives (bonding strength)
- spreading of adhesive (related to surface energies)
- temperature tolerance typicaly >80°C (depends on curing temperature)

Application related properties can be:

- coefficient of thermal expansion (CTE)
- loss tangent, permittivity
- surface resistance
- machineability (e.g. cutting, drilling)
- strength properties
- long term durability (moisture resistance, UV-resistance, heat resistance)
- biodegradation
- recyclability, existing collection logistics

Additionally there requirements concerning only cellulose/paper based substrates such as:

- surface treatment/coating on paper
- gas/oxygen permeability
- moisture absorption
- converting related properties (surface friction, strength properties)
- repulpability

Requirement concerning only bioplastics contain:

- Thermal resistance (e.g. Tg, Tmelt, HDT /Vicat)
- Crystallinity of the material
- Film strength/stability
- Transparency
- Heat sealability
- suitability for overmolding
- Bio-based and/or biodegradable

The most important properties were tested for selected bioplastics and cellulose/paper-based substrates with a focus on printed demo containing OPV and supercapacitor (SC) and that can be applied on a package surface. Substrate materials tested are presented in Figure 7.

PAPER/CELLULOSE based

Aegle® White, Kotkamills (BC)
Isla® Duo, Kotkamills (BC)
PankaSilk, Pankaboard
Berga Classic Preprint, Stora Enso
Cupforma Natura Aqua+™, Stora Enso
Foodbox, Stora Enso
NovaPress Silk, Stora Enso
Finess premium silk, UPM
Tringa®, Paptic
Powercoat® HD95, Arjowiggins (BC) ref.
(BC = barrier coated)

BIOPLASTICS

Cellidor® CP, Albis Plastics
I'm Green™ LDPE, Braskem
Eastlon Bio-PET, FKuR
Earthfirst® PLA, Plastic Suppliers Inc.
NatureFlex™ NVO, Futamura (B)
Durabio™, MCPP
PLA Luminy®, Total Corbion (B)
Melinex® PET, DuPont Teijin Films™ ref.
(B = biodegradable)

OTHER MATERIALS

KoskiPly Birch (veneer), Koskisen Oy
Biocomposite, Arctic Biomaterials Oy
(B = biodegradable)

Figure 7. *Substrate materials selected for tests in ECOtronics*

2.1.2 Inks

Second aspect in sustainable printed electronics is the use of sustainable inks. Sustainability here means doing profitable, stable business long-term in balance with, and not at the expense of 1) environmental, 2) social and 3) economical aspects. (PrintoCent 2019a)

Therefore, Printed Intelligence technologies and ECOtronics can have high impact to sustainability in general. As an example, energy-autonomous sensor nodes can impact to UM target 7 (Affordable and clean energy).

The sustainability considerations for inks are presented in Table 1 and requirements in different printing techniques in Table 2.

The printing methods selected for ECOtronics were Flexo printing, Inkjet printing and Screen printing requiring all different ink types as presented in Table 2. Besides viscosity there are issues regarding ink curing temperature, which is usually too high for some selected bioplastics and therefore some low temperature curing inks were selected and presented in Table 3.

SUSTAINABILITY CONSIDERATION	
Low-temperature annealing	Inks that require low-energy annealing, preferably in room temperature
Atmosphere	Inks that can be produced and applied in normal atmosphere, where no clean-room is required
Material consumption	Ink and material selection so that the required material consumption and material waste can be minimized.
Recycling	Materials and products should be recyclable.
Material base	Rare or harmful metals should be avoided (e.g. ITO and lead).
Volatiles	Toxic volatiles should be avoided.

Table 1. *Sustainability considerations for ink selection.*

METHOD	MINIMUM FEATURE SIZE	LAYER THICKNESS	INK VISCOSITY	ADVANTAGES	DISADVANTAGES
Screen	70-100 μm	1 – 200 μm	>1 Pa·s	-Thick layer (low sheet resistance of condutions) -Wide selection of commercial functional inks available -Moderate tooling costs -Very low printing pressure	-Limited resolution -Only for high viscous ink -Low printind speed -Screen blocking
Flexography	30-80 μm	50 nm – 8 μm	<500 mPa·s	-Sharp and well-defined edges -Good detail rendering -Cheap tooling -Low nip pressure > no damage to the underlying layers -Easily adjusted ink transfer amount	-Limited chemical resistance of the plates → Limited ink choice → Poorer registration accuracy -Difficult to achieve fine details and solid tones in a single printing pass
Inkjet	20-50 μm	20 nm – 2 μm	1 – 30 mPa·s	-Digitally controlles deposition / no need for physical printing -High resolution and registration accuracy in sheet based processing -Non-contact deposition on non-planar and fragile surfaces -Scalable to large area -Minimal ink waste	-Low viscosity ink → low solids loading, thin layers ans sensitive to surface energy variations -High resolution printing → low printing speed
Gravue	20-80 μm	20 nm – 12 μm	<200 mPa·s	-Good retail rendering -High registration accuracy -High production speed -Precise ink application	-Expensive tooling with long delivery times -Edge raggedness -Missing dots (non-transferring cells) -High nip pressure needed → can be detrimental during overprinting -Solid tones reproduces via ink spreading → rheology important to achieve uniform layer coverage
Reverse offset	~1 μm	40 nm – 150 nm	<100 mPa·s	-Extremely high resolution -High registration accuracy in sheet based processing	-Expensive tooling: printing plate (clishé) is fabricated using traditional microelectronics processes -Currently limited ink choice -Thin layers

Table 2. *Requirements in different printing techniques (PrintoCent 2019b)*

SCREEN PRINTING	FLEXO PRINTING	INKJET PRINTING	SCREEN PRINTING FOR PCB
-Solvent based Ag micro-particle ink (curing 120-150°C) -Solvent based graphite ink (curing 90-120°C)	-Water based Ag nano-particle ink (curing >80°C)	-Two solvent based Ag nanoparticle inks (curing >120°C)	-Solvent based Ag micro-particle ink (curing 120 -150°C) -Solvent based Cu nano-particle ink (curing >140°C)

Table 3. *Inks selected for ECOtronics printing tests for conductive patterns.*

2.1.3 Adhesives/assembly materials

Adhesive/assembly materials are essential part of integration of e.g. LEDs for flexible hybrid electronics. Sustainability considerations for assembly process is related both of materials in use and especially in processes. It has been estimated that about 2/3 of energy consumption in VTT's R2R assembly line (Figure 3) goes for reflow oven to cure isotropic conductive adhesive (ICA) during an assembly run

→ Reducing the curing time and temperature with alternative adhesives would make the assembly process more sustainable

→ Using low temperature adhesives would broaden the feasible material and component spectrum in the hybrid integration process

Figure 8 presents the common adhesives use in flexible electronics. However, only ICA-type adhesives were demonstrated in ECOtronics using adhesives requiring curing temperature from 50 to 80° and max 180 min curing time.

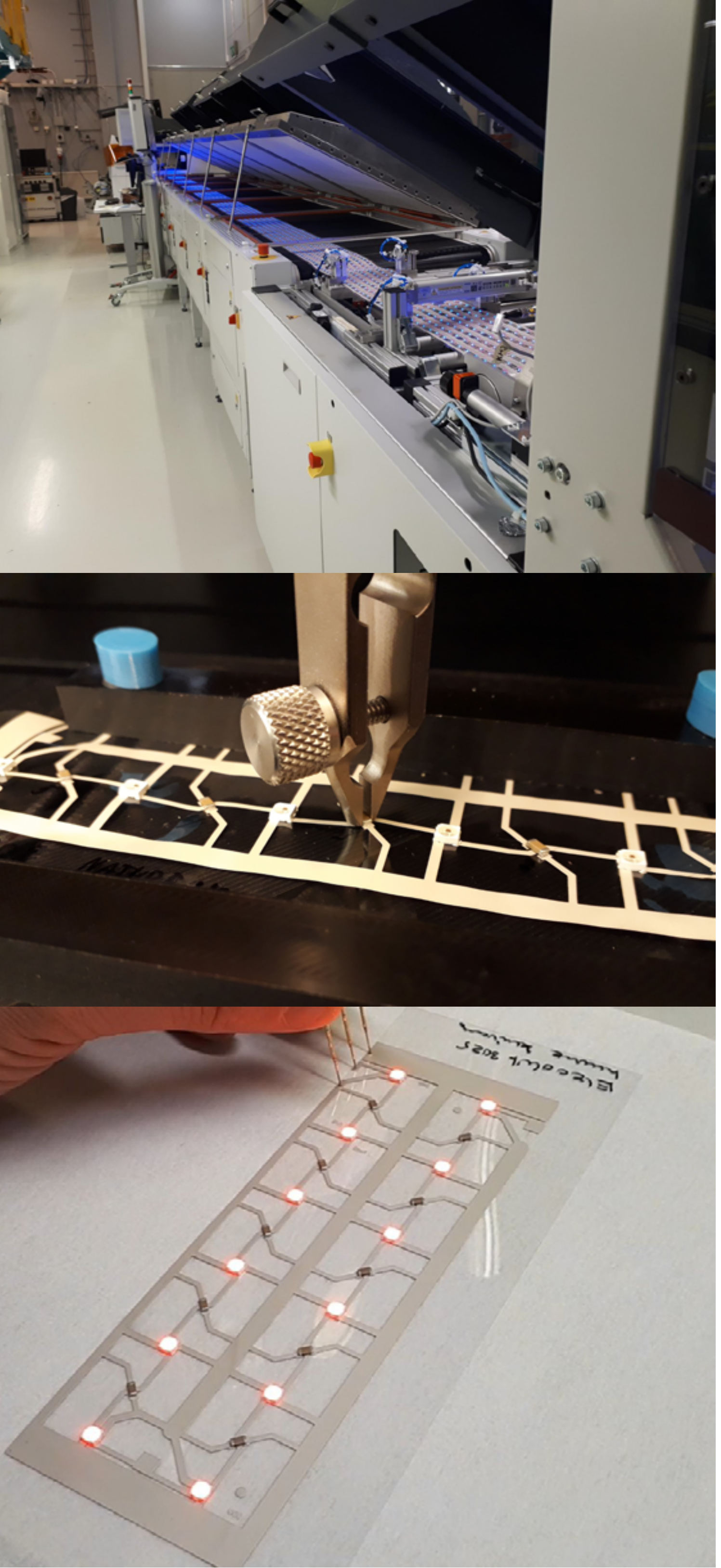


Figure 8. *VTT's assembly line, dispersing unit and integrated LEDs.*

Isotropic adhesives (ICA)

- Electrically conductive in all directions (x,y,z)
- High concentration of conductive particles
- Requires separated adhesive dots on individual interconnection pads
- Low adhesive consumption
- "Global" curing at elevated temperature

Experimental study ICA process

Anisotropic adhesives (ACA)

- Electrically conductive only in z-direction
- Low concentration of conductive particles
- Allows continous adhesive area on individual interconnection pads
- High adhesive consumption
- "Local" curing with pressure at elevated temperature (thermode)

Non-conductive adhesives (NCA)

- No electrical conductivity
- Used for enhancing mechanical bonding or structural robustness
- Applied below component (underfill), around component (side-bonding) or fully covering the component (glob-top)

2.2 Characterisation of materials: summary

2.2.1 Paper specific tests

The evaluation of cellulose/paper based substrates contained a test set showing the tensile strength, surface properties (roughness and contact angle), opacity, electromagnetic performance and suitability for typical paper recycling processed through repulping. The general outlook for test results is presented in Figure 9. The results are proportional showing the overall performance (performance index) of each test in a way that number 3 is very good result and number 1 shows poor or limited performance of the material according to the specific test result. Coated papers are containing coating at least one side of the paper and typical effect is that it is reducing the surface roughness and provides improved strength for the paper. Tringa® paper showed limited suitability for recycling due to bioplastic fibres in the structure, but it is still recyclable.

2.2.2 Bioplastic specific tests

In testing of bioplastic materials as substrate for printed electronics the main properties tested are mechanical and thermal performance. The overall performance and suitability for flexible printed electronics are presented in Figure 10 and Table 4, which opens end-of-life considerations of these substrates. The Figure 5 shows that the Bio-based LDPE film has only limited or poor mechanical strength and thermal performance having the melting point as low as 112°C, that is too low needed for a typical conductive ink curing process. The commercial PLA film Earthfirst® showed similar temperature related challenges. However, the PLA Luminy® (high heat grade) from Total-Corbion showed good temperature stability already in small scale processing and even better when the film was made in pilot-scale and oriented. Also 30% bio-based PET (BIO-PET), Durabio™ and regenerated cellulose film Natureflex NVO showed mechanical and thermal performance suitable for printed electronics. However, in Natureflex™ NVO solvent resistance and electromagnetic performance were only limited. The thermoplastic cellulose acetate propionate, Cellidor® CP, showed in general good suitability for printed electronics.

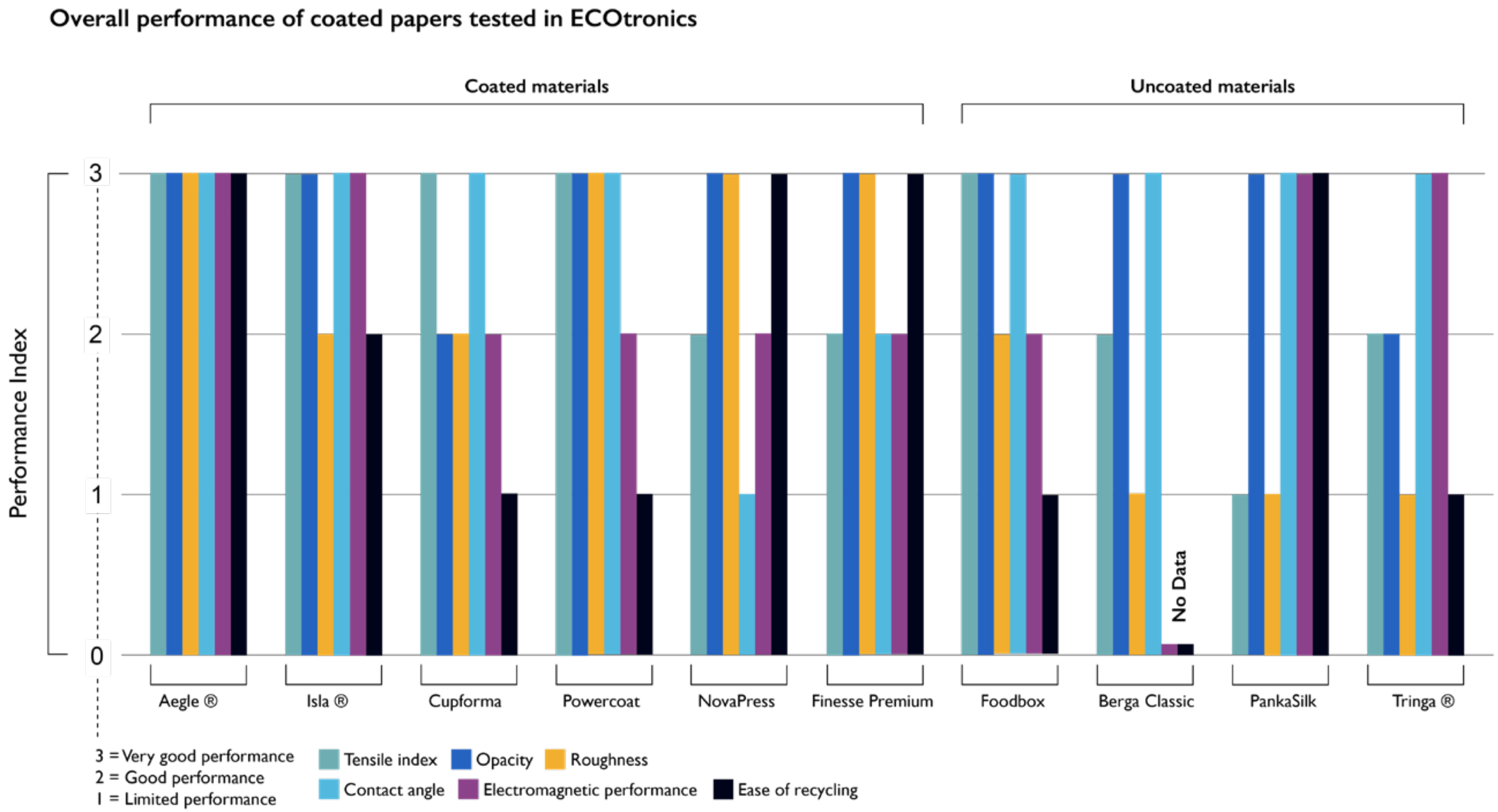


Figure 9. *Overall performance of coated papers tested in ECOtronics.*

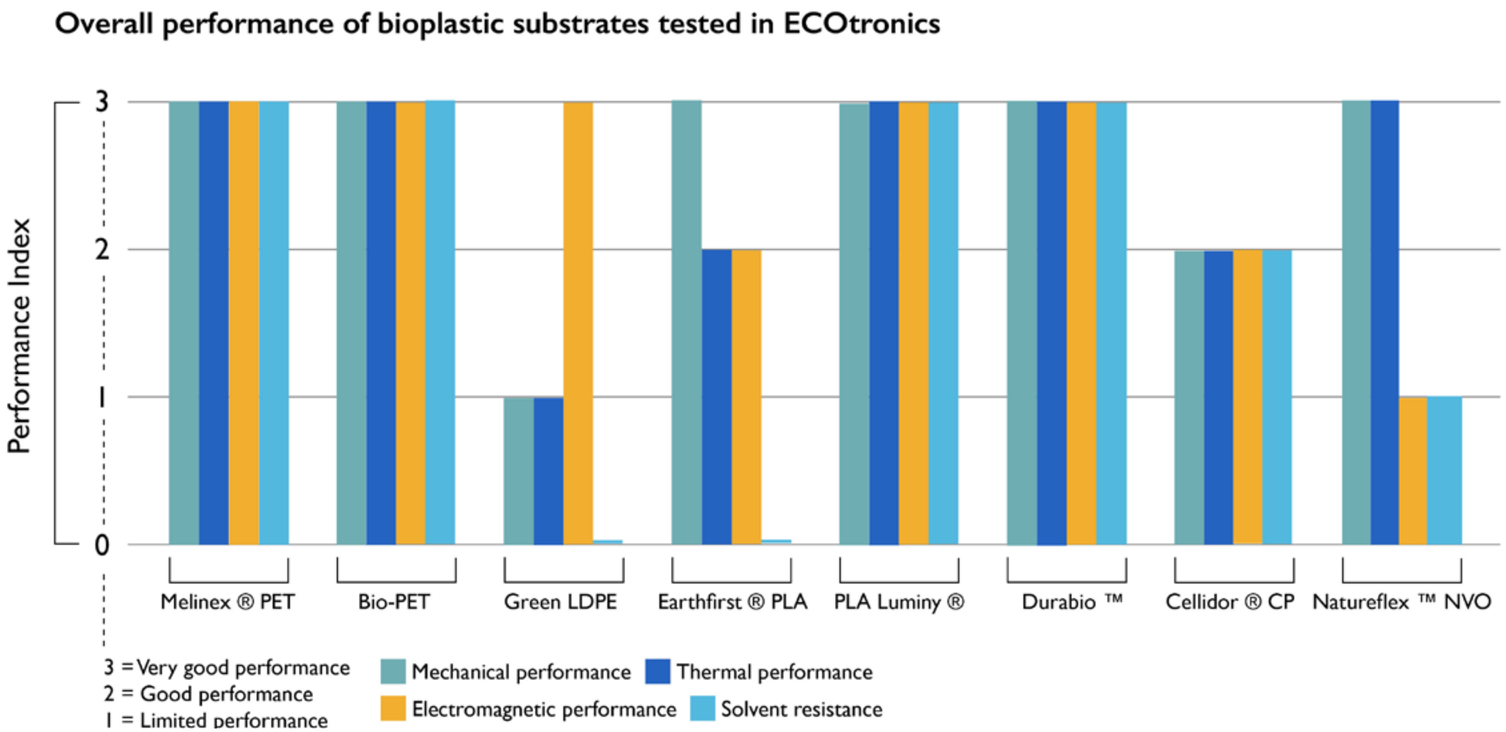


Figure 10. *Overall performance of bioplastic substrates tested in ECOtronics.*

SUBSTRATE	END OF LIFE CONSIDERATIONS AND ORIGIN
Melinex® PET	Recyclable within existing logistic, oil-based
Cellidor® CP	Recyclable in theory, wood-based
I'm Green™ LDPE	Recyclable within existing logistics, bio-based
Eastlon Bio-PET	Recyclable within exiting logistics, 30% bio-based
Earthfirst® PLA	Recyclable in theory, biodegradable, bio-based
NatureFlex™ NVO	Biodegradable, wood-based
Durabio™	Recyclable in theory, bio-based
PLA Luminy®	Recyclable in theory, biodegradable, bio-based

Table 4. *End-of-life considerations for bioplastic substrates tested in ECOtronics.*

2.3 Processability summary

2.3.1 Processing performance of substrates

Processing performance of paper-based substrates includes results from converting tests and printing methods Flexography, Inkjet printing and Screen printing presented in Figure 12. Printing test results are representing results from conductive pattern surface resistance values and thinnest printable lines and line distances. The printed pattern used in Flexography and Screen printing is presented in Figure 11 A) and pattern in Inkjet in Figure 11 B). Converting tests include results from material creasing and folding tests in automatic converting line and substrate potential for embossing.

Best overall performance in all printing processes with selected inks was obtained for Kotkamills Aegle® White, Arjowiggings Powercoat® HD95, UPM Finesse Premium silk and Novapress Silk of which Aegle® and Powercoat® were barrier coated materials. Also, bioplastic fibres containing Paptic Tringa® was showing good overall properties in Flexography and Screen printing.

In converting processes such as creasing, folding and embossing the best substrates were Kotkamills Aegle® white, Cupforma Natura Aqua+ and Foodbox from Stora Enso. Also, Paptic Tringa® showed good converting performance comparable to Pankasilk uncoated solid groundwood board.

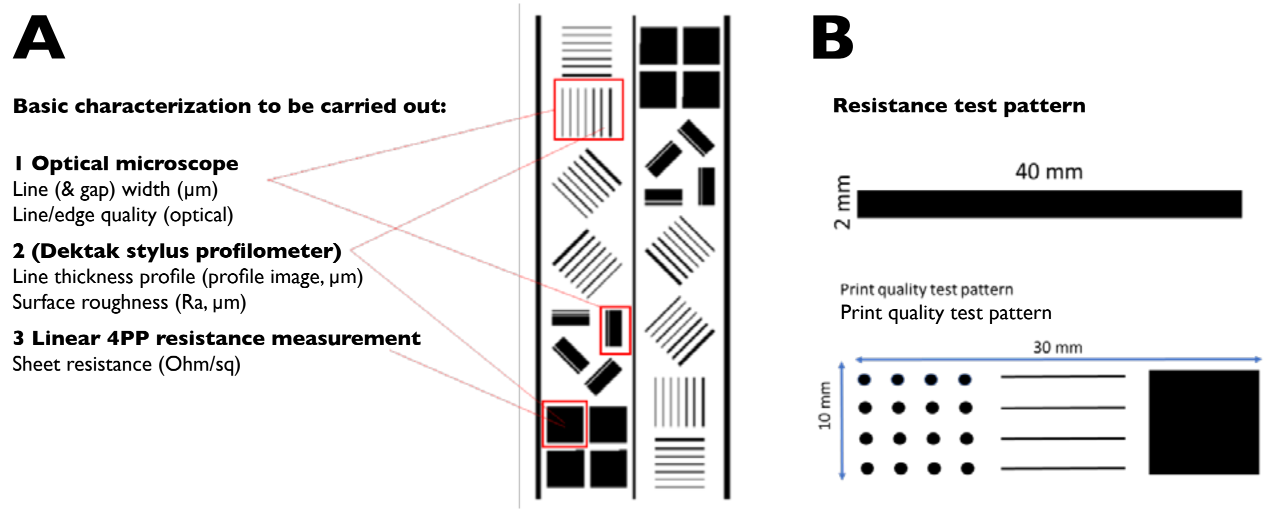


Figure 11. *Printed pattern and analytics in Flexography and Screen printing A) and Inkjet B).*

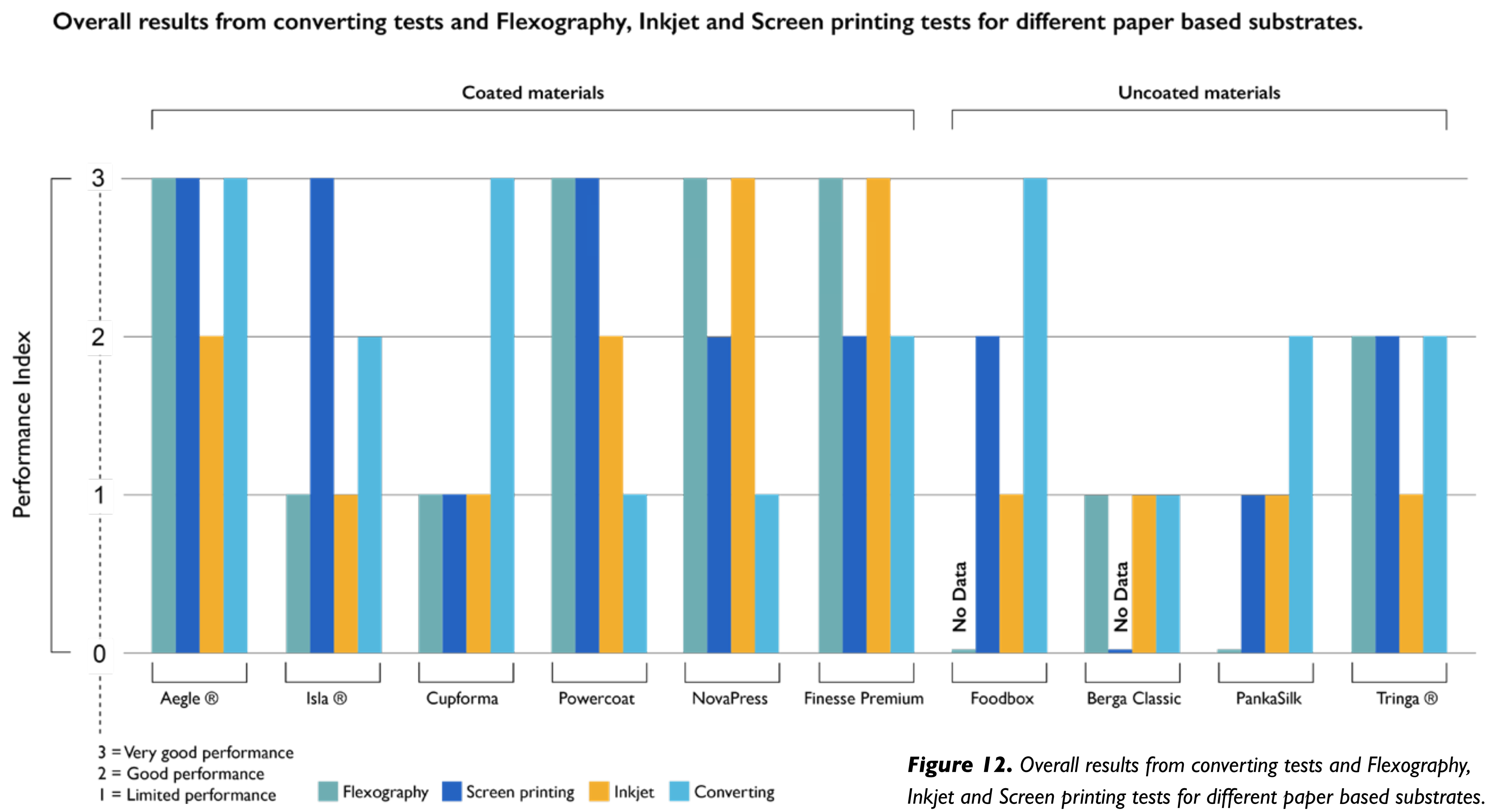


Figure 12. *Overall results from converting tests and Flexography, Inkjet and Screen printing tests for different paper based substrates.*

Overall results for bioplastic substrates in Flexography, Inkjet and Screen printing tests and substrate behaviour in overmolding and accelerated aging test are presented in Figure 13. Results from printing tests include surface resistance of printed lines and squares, information about thinnest printable line and line distance and substrate stability during printing process and during curing of the conductive ink. The result bar for each printing method is an average of those individual tested elements. Overmolding results represents substrate behaviour in injection moulding during overmolding of printed sheet with other material. Accelerated aging test showed the substrate material dimensional stability and changes in increased temperature (50,5°C) or in increased temperature and moisture (50% r.h.) or increased temperature and moisture and UV-light after 552h period.

Compared to commonly used PET material the Bio-PET, PLA Luminy® (high heat) and Natureflex® NVO showed similar results in Screen printing. PLA performed better than other bioplastics in Flexography and Bio-PET showed lowest resistance values in Inkjet printing with selected inks. Durabio™ and Cellidor® CP had some high temperature curing stability related challenges.

In overmolding PLA Luminy® (high heat) and Cellidor® CP were the best substrates comparable to reference PET.

In accelerated aging the moisture sensitive Natureflex™ NVO started to distort and did change dimension. Durabio™ and Cellidor® CP became brittle. Bio-PET and PLA Luminy® showed good stability during all aging tests.

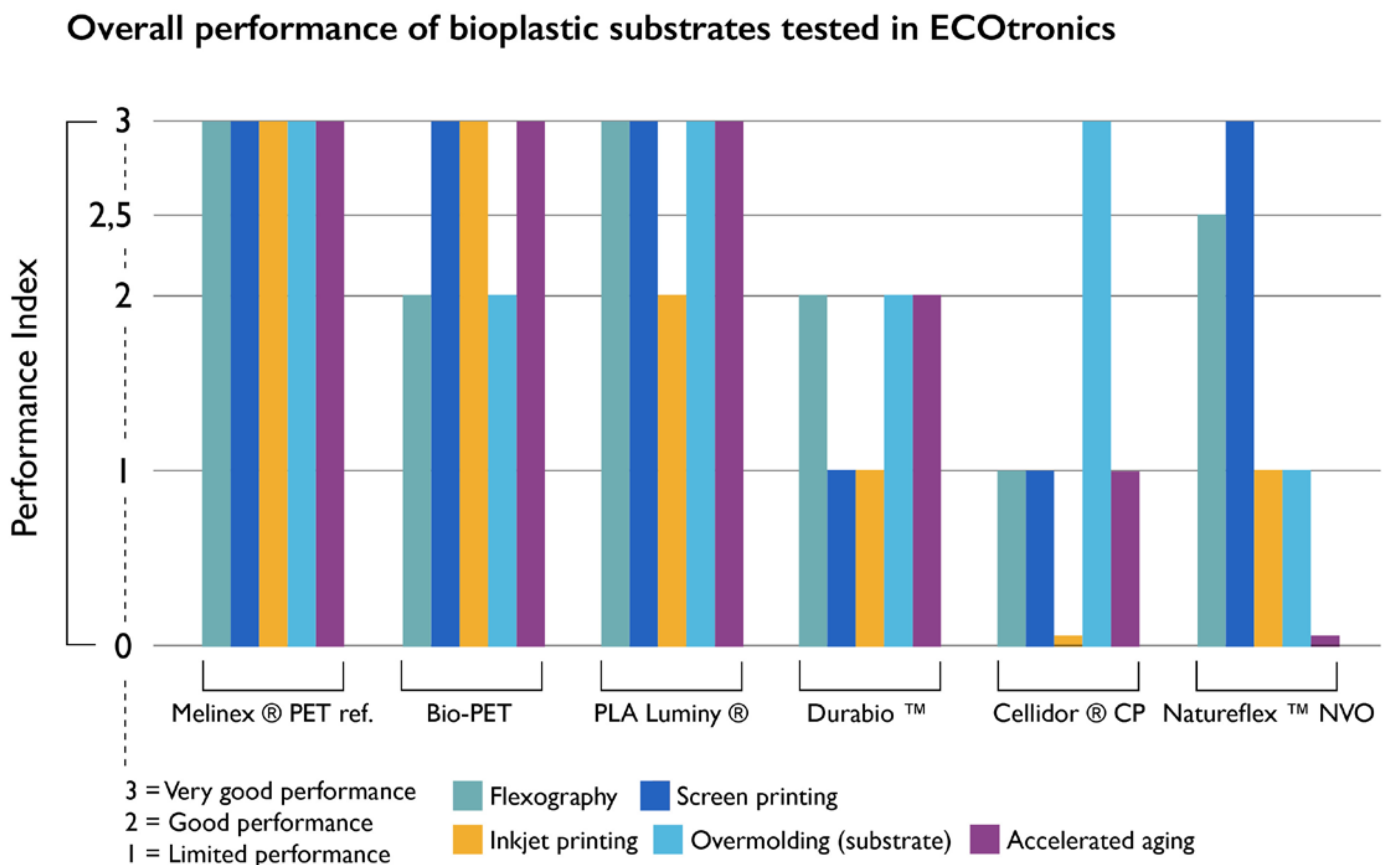


Figure 13. *Overall performance of bioplastic substrates tested in ECOtronics.*

2.3.2 Assembly tests

The assembly test process contains several steps presented in Figure 14. In the first stage A4-size plastic sheets were preheated and Screen printed with Asahi LS411-AW silver paste & 325L mesh screen and curing at 80°C for 60 min. The printed pattern is presented in Figure 15. Substrates used in test were reference PET, bio-PET, PLA Luminy®, Natureflex™ NVO and CAP (Cellidor® CP).

Low temperature isotropic conductive adhesives (ICA) used in this study were silver containing materials

Epotek H20S (curing 90 min at 80°C),
Epotek H20E (curing 180 min at 80°C),
Elecolit 3025 (curing 120 min at 50°C)
and **Delo IC343** (curing 30 min at 80°C)

as reference. The analysed properties were processability of adhesive and substrate, adhesion strength and functionality of integrated LEDs. The compiled results are presented in Figure 16. Best bio-based substrate combination with low temperature ICA was PLA Luminy® with Delo IC343. Bio-PET was performing with Delo IC343 almost as well. With reference ICA Epotek H20E turned out to be the best performing bio-based substrates.

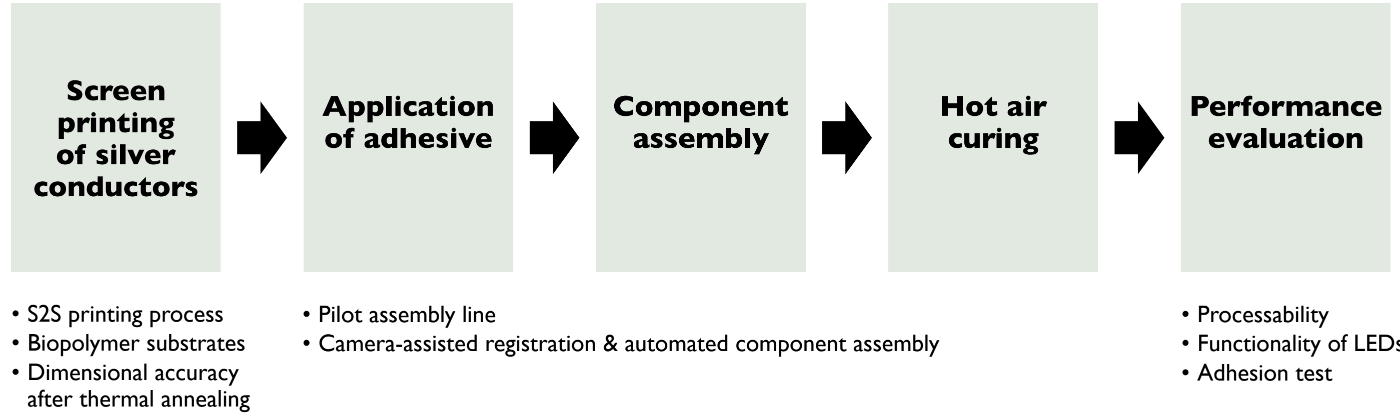


Figure 14. *Process schema for assembly test.*

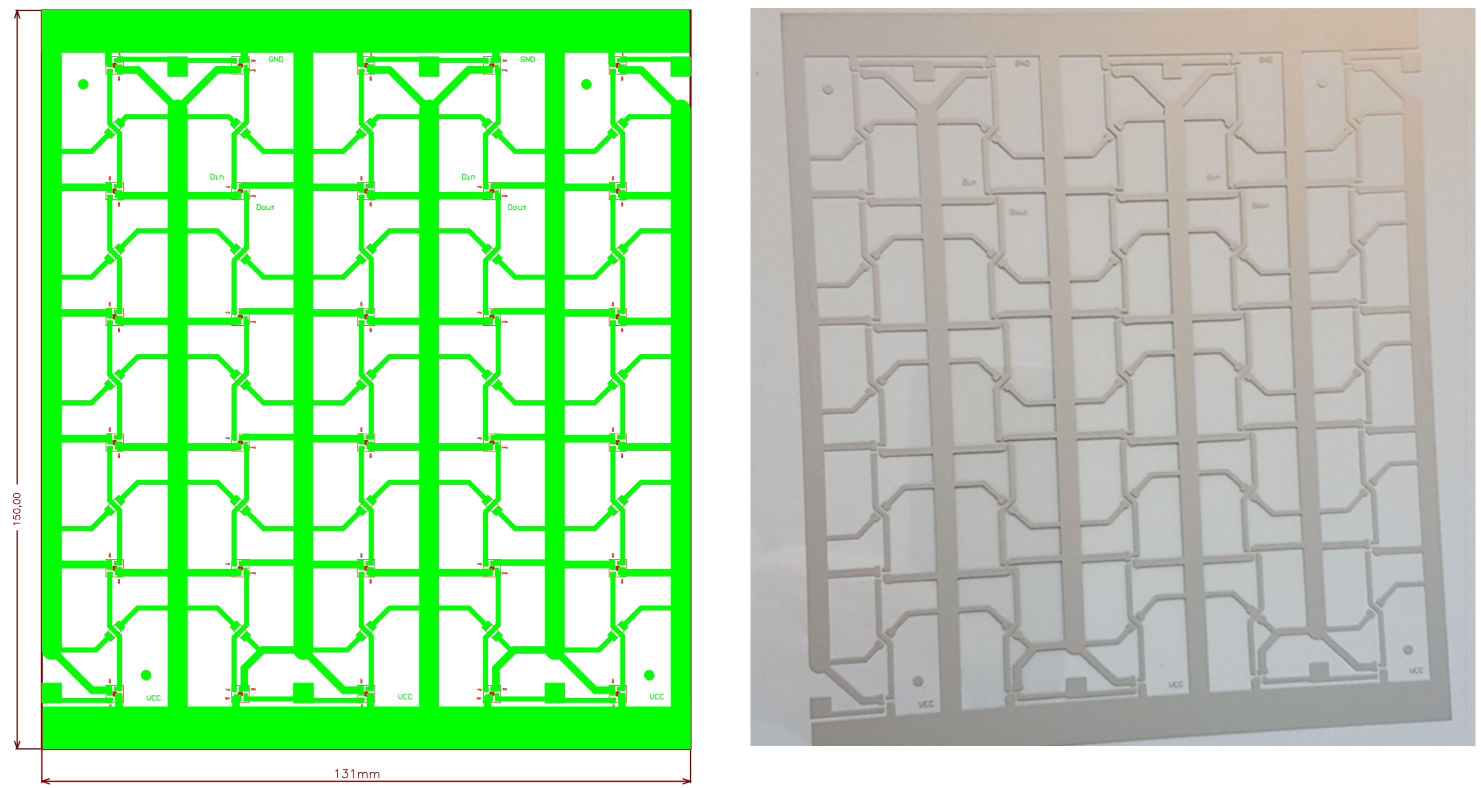


Figure 15. *Screen printed pattern for assembly test. Schematic figure in left and silver print on PET on right picture. (Pattern first presented in Luoma et al.* Oriented and annealed poly (lactic acid) films and their performance in flexible printed and hybrid electronics. *Journal of Plastic Film & Sheeting 2021)*

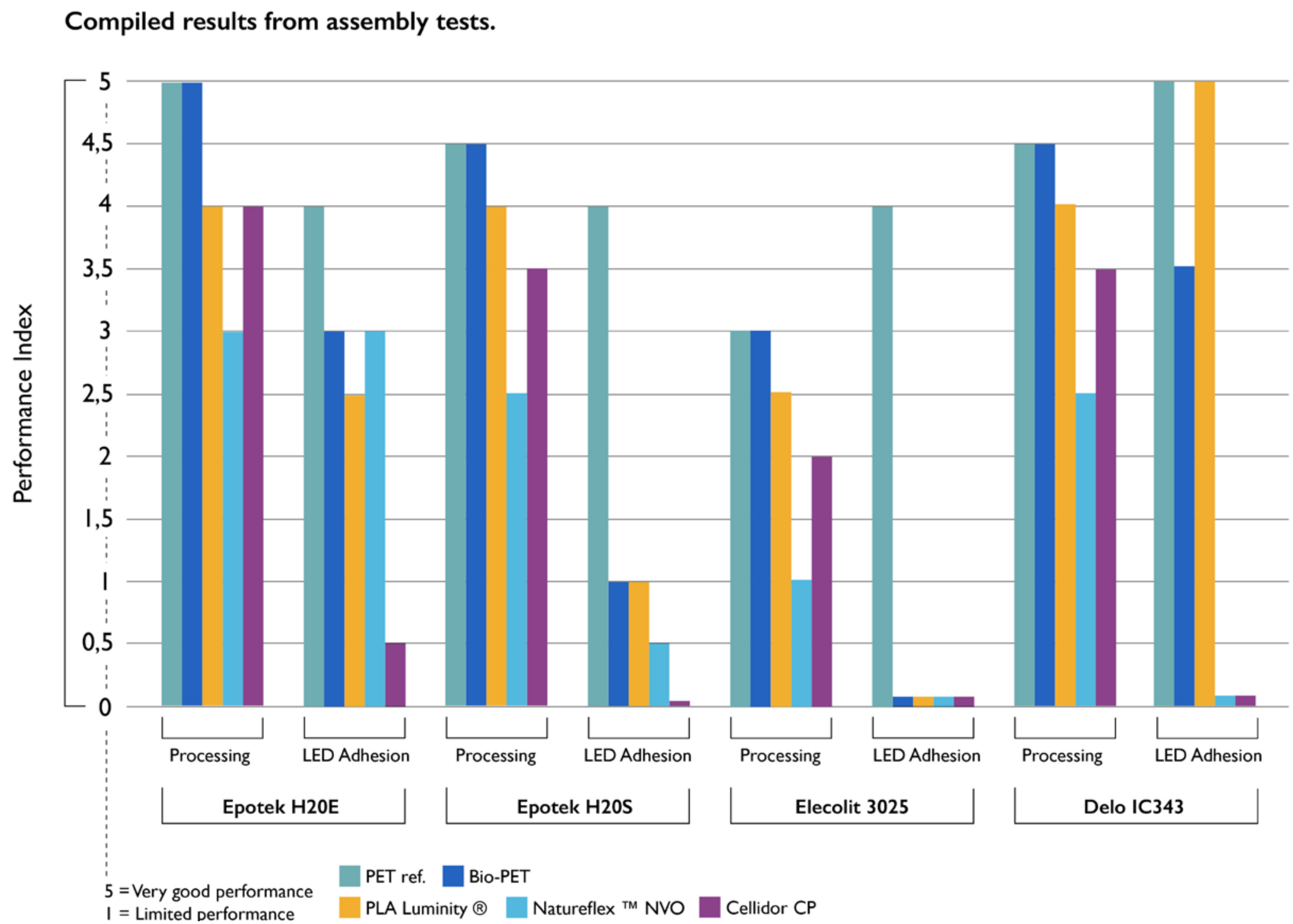


Figure 16. *Compiled results from assembly tests.*

2.3.3 Thermoforming

The primary objective of the study was to determine the thermoformability of four bio-based plastics: Polylactic Acid (PLA), Cellulose Acetate Propionate (CAP), Bio-Polyethylene Terephthalate (Bio PET) and Natureflex. LUT Packaging Technology's Variovac Primus thermoforming line was used to carry out the experiments. Due to variation in the roll width of the materials, the sheet forming unit of the Variovac machine was used to conduct the experiments.

The thermoformability of the materials was investigated by varying forming parameters and utilizing vacuum and pressure thermoforming. To assess each material's capability in terms of making the shape depth, two different mould depths (15mm and 30mm) were used. All the materials were tested with the HSB 1 RDM heat sealer device prior to thermoforming to determine the starting forming temperature. Various forming temperature, heat up time, forming time, forming pressure and vacuum settings were used in the experiments. Special attention was paid in the experiments to shortcomings in the quality of the trays, such as spring back at the bottom of the tray, spring back at the wall of the tray, wrinkles, colour marks (blurring), melting, ruptures and inadequate forming. By observing these phenomena and the general behaviour of the sample materials, optimal driving parameters were found for each sample.

The results of the study indicate that the process window in terms of forming temperature is a limiting factor in achieving the target depth with the sample materials. With the most functional sample materials, it was possible to obtain the complex shape of the mould and sufficient forming depths. By expanding the processing window and optimizing the thickness of the sample materials, the processability of other samples can be improved.

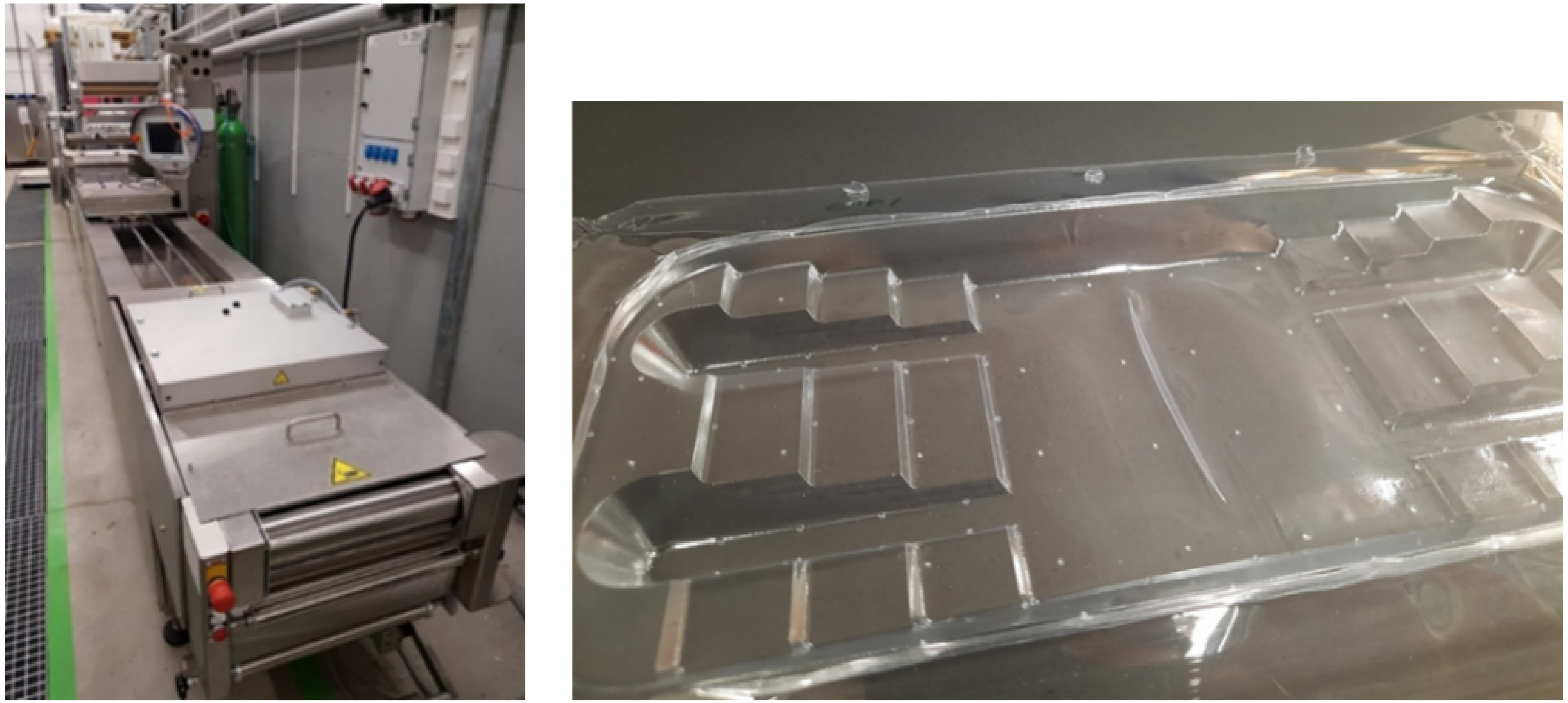


Figure 17. *Thermoforming line and thermoformed tray package.*

2.4 Development of bio-based coatings

2.4.1 Paper coating

The aim of the coating was to find suitable substrates and bio-based coating components to meet the requirements for printing, and to evaluate their effect on moisture or water repellence and repulpability. The suitability of the fiber-based substrates and bio-based coatings were tested for spray coating and was evaluated with measurements indicating for example, their water repellence or absorption. Based on these results, repulpability studies of the uncoated materials and their performance with bio-based coating, the coating tests were eventually performed on two different substrates with three bio-based coatings. For printing tests, the coat weight was selected based on the properties to meet requirements for printing.

The performance in terms of repulpability remained similar. Coating on had most impact on the strength properties, but also on surface roughness was increased with coating. Contact angle value for water was one of the requirements regarding printing and was changed from limited performance to good or very good. On Foodbox, only a contact angle performance index changed when PLA coating was used.

Based on contact angle results Aegle® White and Foodbox were selected for further testing. They were coated with PLA Landy 1005, TopScreen BW200 and Carnauba wax and tested in Flexography printing using Novacentrix PFI-722 water-based silver nanoparticle ink and using Flexiproof RK-100 lab-scale printer. Materials were oven dried, PLA in 130°C for 30 min and Carnauba wax and TopScreen BW200 in 80°C for 30 min (NOTE: the lowest curing temperature for the ink was 80°C). The result for printed patterns are presented in Figure 20 and total performance index from printing tests in Figure 21.

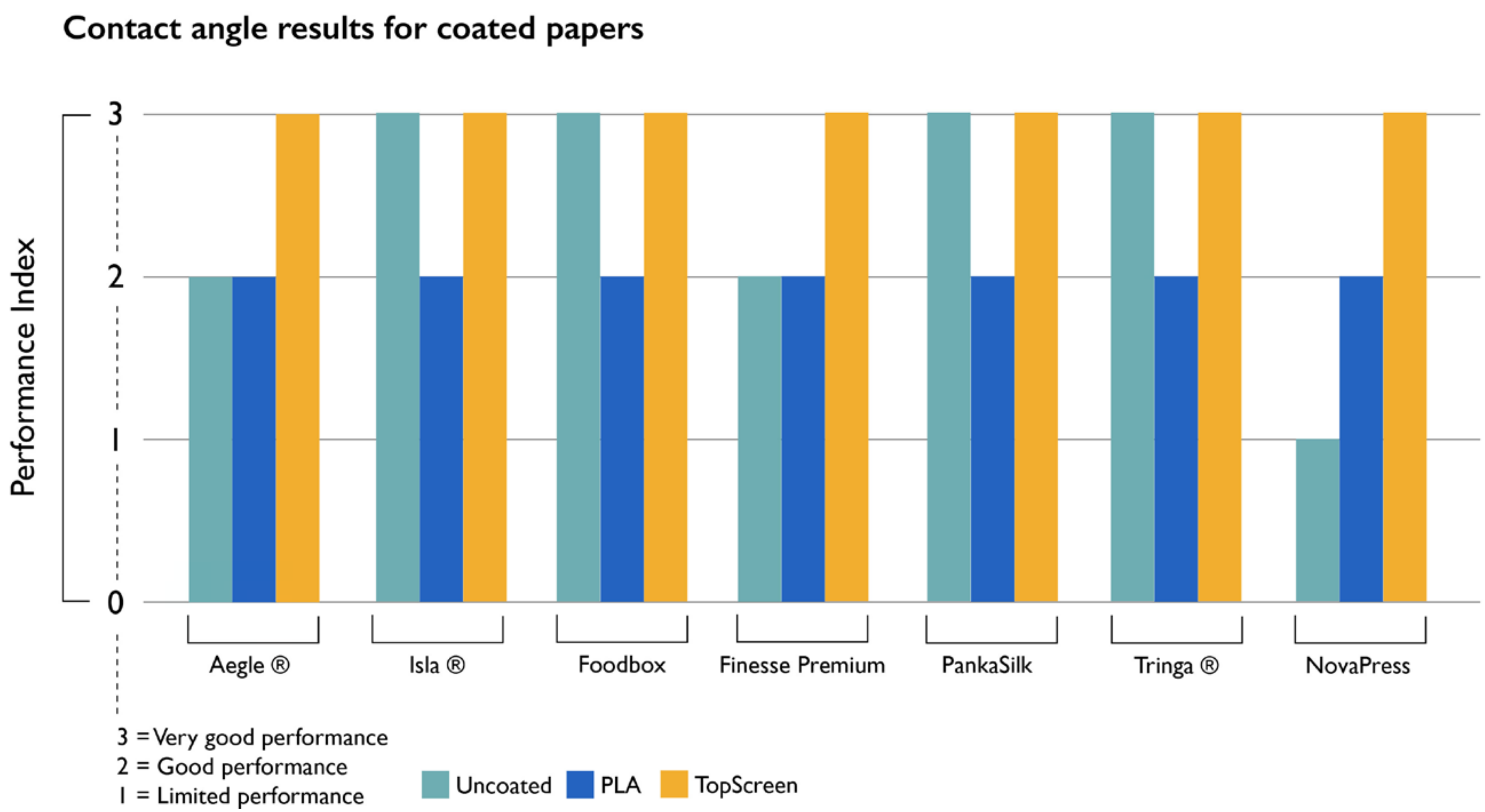
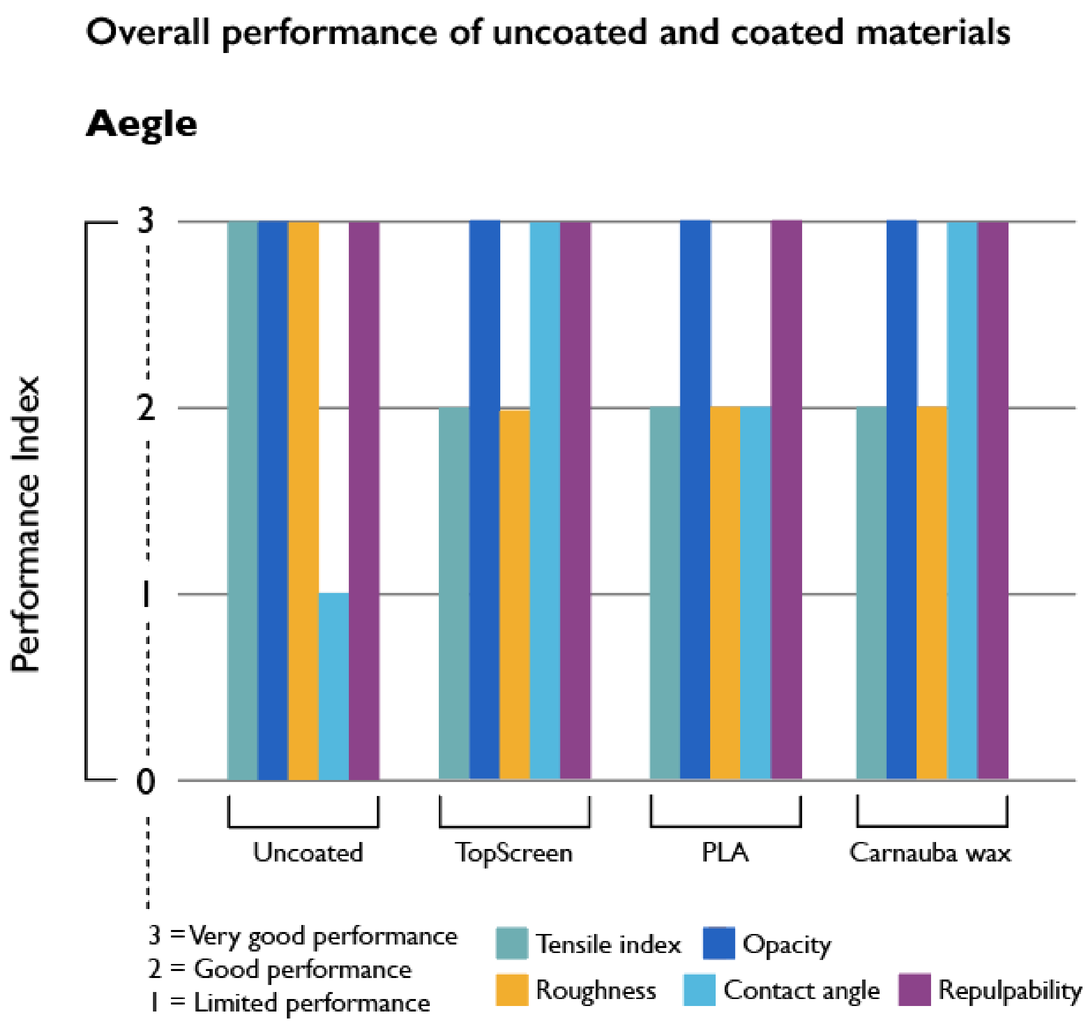


Figure 18. *Contact angle results for uncoated and bio-based coatings, PLA dispersion or TopScreen, coated papers*



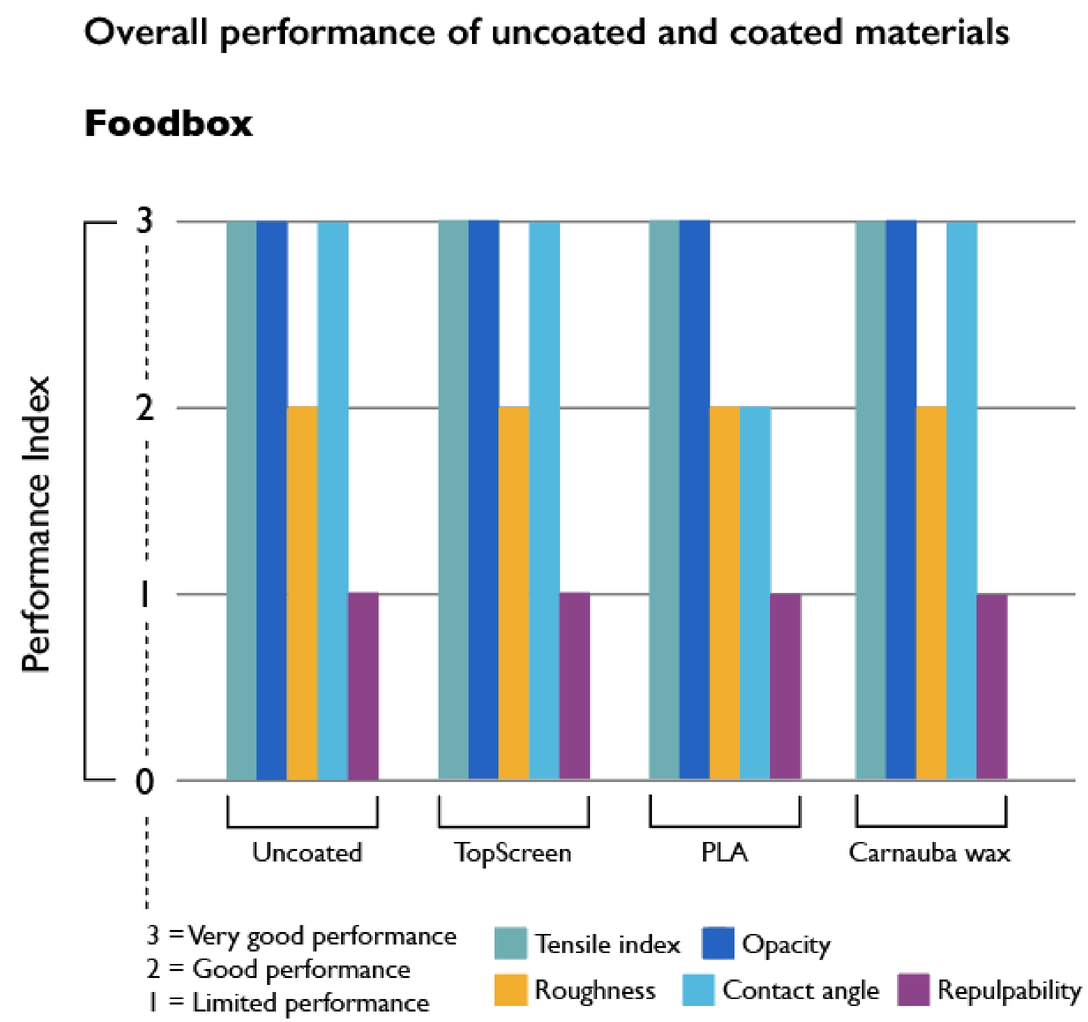


Figure 19. *Overall performance of uncoated and coated Aegle (left) and Foodbox (right) materials.*

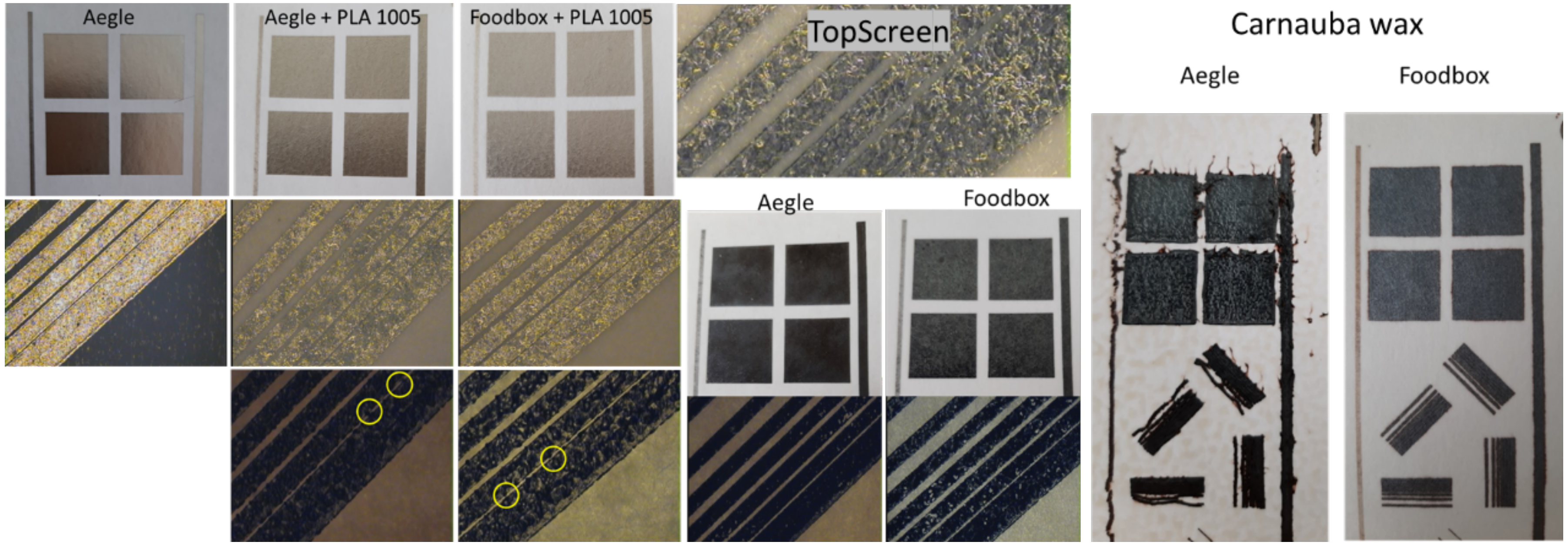


Figure 20. *Visual outlook of biobased coatings coated and Flexo printed Aegle® white and Foodbox.*

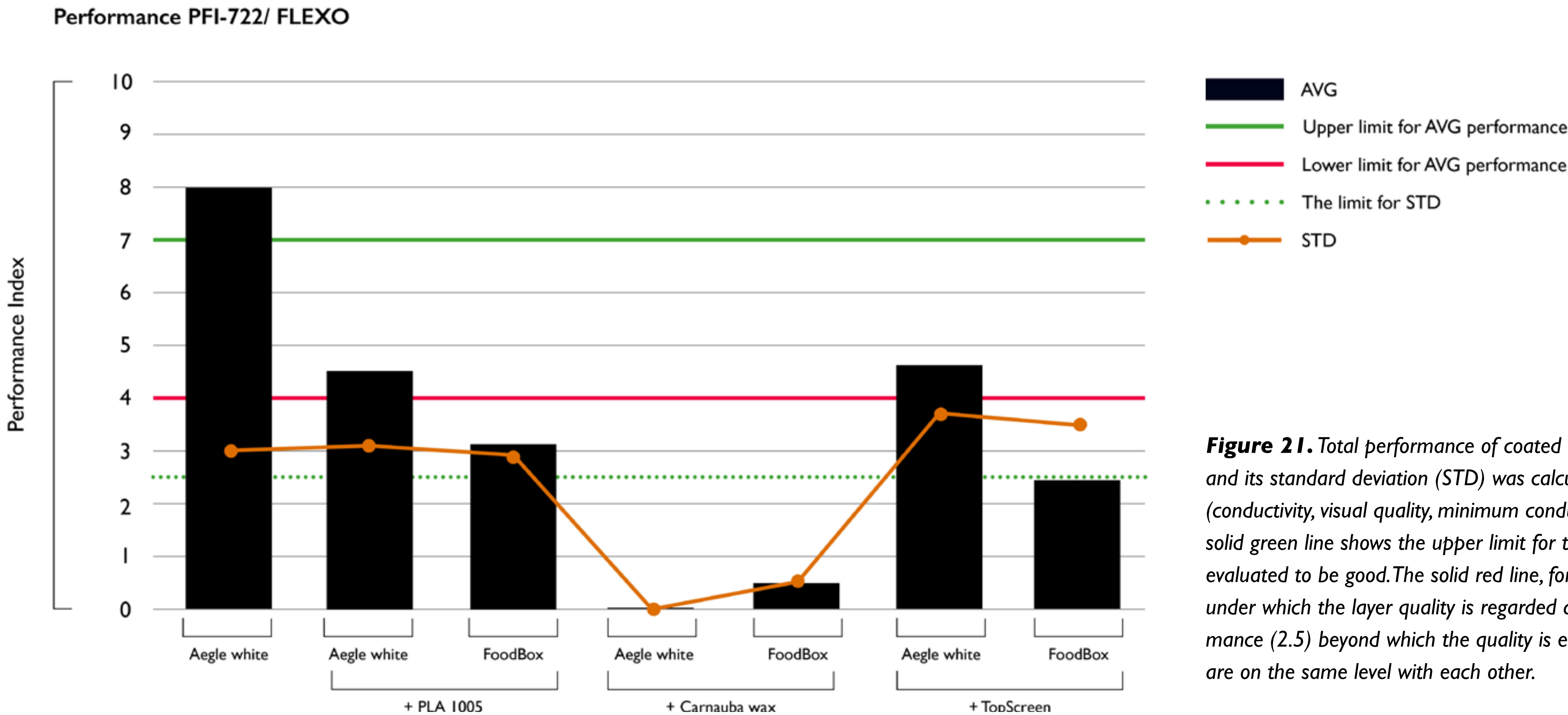


Figure 21. *Total performance of coated papers on Flexography. Average performance index (AVG) and its standard deviation (STD) was calculated from the performance indexes of each quality factor (conductivity, visual quality, minimum conductive line width, minimum gap width, and ink spreading). The solid green line shows the upper limit for the AVG performance (>7) beyond which the layer quality is evaluated to be good. The solid red line, for its part, shows the lower limit for the AVG performance (<4) under which the layer quality is regarded as poor. The dotted green line is the limit for the STD performance (2.5) beyond which the quality is evaluated to be even so that all the separate quality factors are on the same level with each other.*

2.4.2 Fire retardant coatings

One approach in ECOtronics was to find ways to develop a bio-based and potentially biodegradable printed circuit board (PCB) using printing methods instead of normally used etching of stiff boards manu-factured from thermosetting materials. As base materials, stiff PankaMax boxboard from Pankaboard Oy and veneer KoskiPly Birch from Koskinen Oy were selected. One challenge with these materials was fire retardancy typically required in FR4-type PCBs. The substrates were coated using fire retardant materials Fireproof P2 and Fireproof W1 from Kiilto Oy, Organowood Protection 01from OrganoWood AB, ZEOPOL® 33 from Evonik GmBH and Palonot film from Palonot Oy. The analyzed values were surface properties, burning properties and Screen printability of coated surfaces using solvent based microparticle silver paste Asahi LD-411AW and results presented in Figure 16. Printed patterns on substrates are presented in Figure 22.

The results indicate that the selected substrates for PCB development had as such a quite rough surface and the silver paste spread on the surface providing conductive patterns with uneven sharpness and low conductivity. Only in the case of veneer coated with Fireproof W1, the fire retardant coating was able to smooth the surface properly. As a conclusion it can be said that some additional coating is needed for a cardboard type substrate to meet the surface smoothness requirements for screen printing with the selected silver ink.

Fire retardancy requirements were met with Palonot film, which was able to provide a surface not able to catch fire in normal conditions. The other FR-coatings were also effective especially when applied in bigger amounts using roller coating.

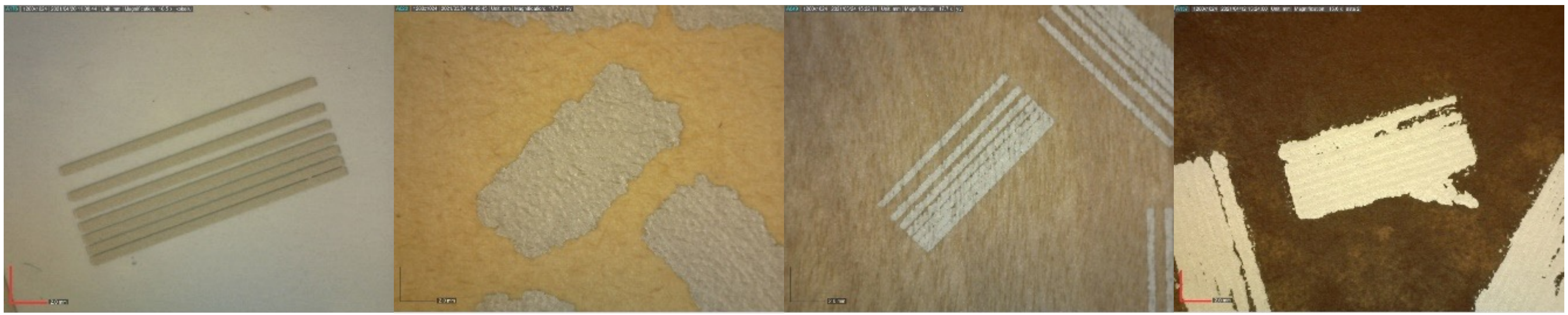


Figure 22. *Screen printed silver paste patterns on uncoated substrates for fire retardant coating. From up to down, PET ref., PankaMax, KoskiPly veneer and Palonot F1-00 coating.*

Result overview for fire retardant coated PankaMax cardboard (PB) and KoskiPly Birch veneer

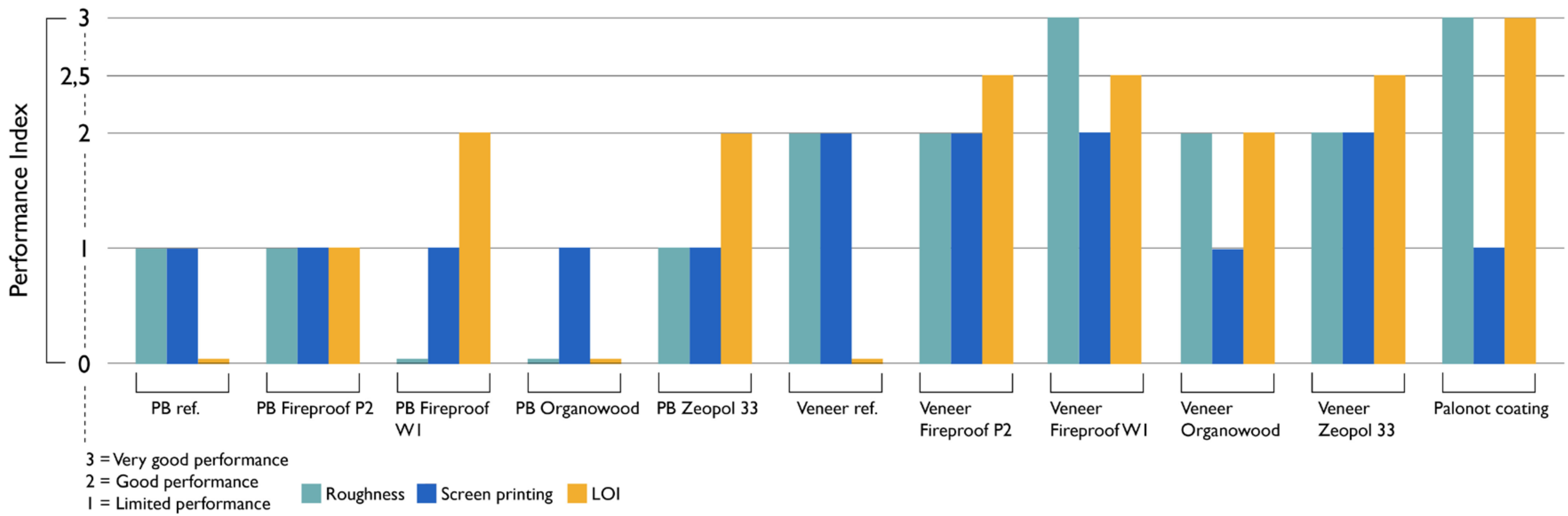


Figure 23. *Result overview for fire retardant coated PankaMax cardboard (PB) and KoskiPly Birch veneer.*

3 Demonstrator 1: Intelligent packaging for monitoring food quality

Figure 24. *Packages*

Demands for sustainable, cost-efficient on-line sensing of chemical and physical properties has increased. The measuring of physical properties such as temperature and humidity can improve the product safety and the efficiency of logistic operations. Implementation of recyclable low environmental footprint technologies are compatible for providing energy-autonomous monitoring in consumer products and their production chains, for controlling material supply chains, tracking and traceability in industrial manufacturing, or for monitoring and controlling data in healthcare sector. In the future, the versatile production chains could utilize these technologies for on-line sensing of chemical and physical properties and locations.

Demonstrator primarily targets for intelligent packaging business sector for the monitoring of the packed goods to improve product safety and to avoid product spoilage (e.g. food waste). According to estimates, almost 21 billion packages sold in 2030 will feature an electronic feature, but this cannot mean that this will represent a new source of electronic waste. Therefore our demonstrator has taken an environmental approach in order to minimize environmental impact of intelligent packaging devices.

Intelligent food package, jointly designed with research partners and end-use companies, demonstrates energy autonomous temperature logger attached to secondary packaging for monitoring quality of packed products during shipment. Intelligent packaging is a relatively new application domain and it has specific needs, such as cost-efficient, recyclable and lightweight electronics. Aim of the product design was to identify the opportunities of intelligent product packaging using new materials and production processes to improve material and production efficiency and product properties thus, the value to improve climate impacts, resource savings, functionalities, usability and wider context of use. The findings obtained from intelligent product packaging can lead into new technological openings when reflected into the potential industrial and market areas.

3.1 Specifications

The smart sensor is thin (40 μm) bare-die chip for temperature monitoring and data logging is IC optimized and embedded with NFC interface. System specifications for the demonstrator case presented in Table 5 is based on calculations where the temperature monitoring takes place in every 15 min or 30 min, and printed silver antenna for communication.

To obtain energy autonomous monitoring, energy source is rechargeable and using renewable energy i.e. printed organic solar cells for energy harvesting, supercapacitor for energy storage. This way the lifetime of the electronic features is increased compared to primary batteries. In addition, external recharging is not required during use phase due to energy harvesting capabilities. The intelligent packages are mainly use indoor environments thus the light harvesting is mainly from artificial light sources under low light conditions. 24-hour energy demand is reachable by harvesting indoor light for four to eight hours per day and by providing storage power for 16 to 20 hours per day. To fullfill the specifications of the system, component structures were experimentally optimized and layouts for the demonstrator defined. The following subsections presents this development.

PARAMETER	SYSTEM SPECIFICATIONS
U [V]	3 (2 - 3.5)
I [A]	3 μ (average)
E [J]	0.648
C[F]	0.157/0.144
Daily need	2-4 x times /h
mm x mm	86 x 54 (~credit card size)

Table 5. *System specifications for energy autonomous temperature monitoring.*

Figure 25. *The potential applications for use-case demonstrator.*

3.2 Energy module for self-powering sensor system

3.2.1 Substrate

Evaluation of bio-based substrate comprised two commercial film material, namely cellulose derived Natureflex™ NVO film and Earthfirst® PLA film and, laboratory and pilot-scale extruded Bio-PET, Durabio™, Cellidor® CP, PLA Luminy® and. DuPont Teijin Films' Melinex ST506 film was used as a reference material. Table 6 depicts the suitability of bio-based films for printed electronics in general.

Earthfirst® PLA was not compatible for printed electronics processing at 80°C or higher temperatures. In addition to Earthfirst® PLA, the solvent resistance of Natureflex™ NVO and Cellidor® CP was limited. Bio-PET and PLA Luminy® film obtained the best performance and durability against heat, humidity and solvents, providing a good optical transmission. For that reason, Bio-PET and PLA Luminy® (PLA) films were selected for component development.

FILM PROPERTIES			DURABILITY		
Substrate film	**Biodegradability**	**Optical Transmission**	**Temperature**	**Elevated T, RH & light**	**Against solvents**
PET (ref.)	No	Green	Green	Green	Green
Bio-PET	No	Green	Green	Green	Green
Durabio™	No	Green	Green	Yellow	Green
CAP (Cellidor® CP)	No	Yellow	Green	Yellow	Yellow
PLA Luminy®	Yes (industrial.)	Green	Green	Green	Green
Natureflex™ NVO	Yes	Green	Yellow	Red	Yellow
PLA Earthfirst®	Yes	Green	Red	Red	Red

Table 6. *Evaluation of bio-based films properties and durability for printed electronics processing and applications; green = compatible, yellow = partially compatible and red = non-compatible.*

3.2.2 Printed organic photovoltaics

Objective of OPV development was to meet the system requirements under specified lighting conditions by fabricating low environmental impact organic photovoltaics (OPV) for the demonstrator. In practise this means that the device fabrication from earth abundant, non-hazardous materials and fossil-based materials replacement with bio-based materials. In ECOtronics project, the material screening was based on literature and the experiments were executed with OPV device structures presented in Figure 26. Furthermore, the fabrication of thin film device structures, namely printing emphasized the eco-efficiency through the material and energy efficient manufacturing.

Flexible OPV comprise typically PET substrate with a thickness of ~100 µm. Depending on device materials, the thickness of electrodes is ranging between 0.1 to 15 µm, respectively the thickness of interlayers between 0.001 to 1 µm and photoactive layers between 0.08 to 0.2 µm. Since the substrate comprise 80 - 90% of the device already prior the device encapsulation, the replacement of fossil-PET substrate is important to reduce CO2 emissions. In addition, the replacement of sputtered ITO electrode is important to avoid use of rare materials like Indium and energy intensive processes. Furthermore, optimization of OPV for indoor use helps minimizing the solar cell area through increased power conversion efficiency.

Development of OPV structure was carried out by processing small cells on PET substrate. The work was started with screening the materials for ITO bottom electrode replacement enabling the use of bio based substrates. PEDOT:PSS was selected to the OPV stack for hole contact and hole transport material. PEDOT:PSS ink, containing only water and alcohols as a solvents, is an sustainable alternative for sputtered ITO electrode and can be patterned by gravure printing. NF3000 was selected to solar cell active material due its good performance in low light conditions, which is the working environment for intelligent package demonstrator and also due its solubility of non-halogenated solvents. OPV active material was gravure printed on top of bottom electrode. O-xylene was selected as a solvent for active material ink as it is friendlier for environment and also for user than solvents commonly used. Printed top electrode layers weren't found compatible with the other layers used among tested alternatives. Therefore standard OPV structure with thermally evaporated top electrode, Lithium Fluoride and Aluminium, were selected to ensure the performance needed to meet the system requirements.

Next the selected OPV stack was tested on PLA and Bio-PET substrates which were chosen to substrate materials replacing the PET reference material based on previous tests. Characteristics in Figure 27 show similar performance of the OPV cells on PET and PLA substrates while the performance on cell processed on Bio-PET show lower performance. Maximum power point voltages (Vmpp) and power on maximum power point (Pmpp) measured under 500 lux illumination were on PET 0.42 V / 3.5 µW on PLA 0.44 V / 3.5 µW and on Bio-PET only 0.28 V / 2.5 µW. Based on these results PLA substrate was selected to be used in further testing with OPV modules and in the demonstrator.

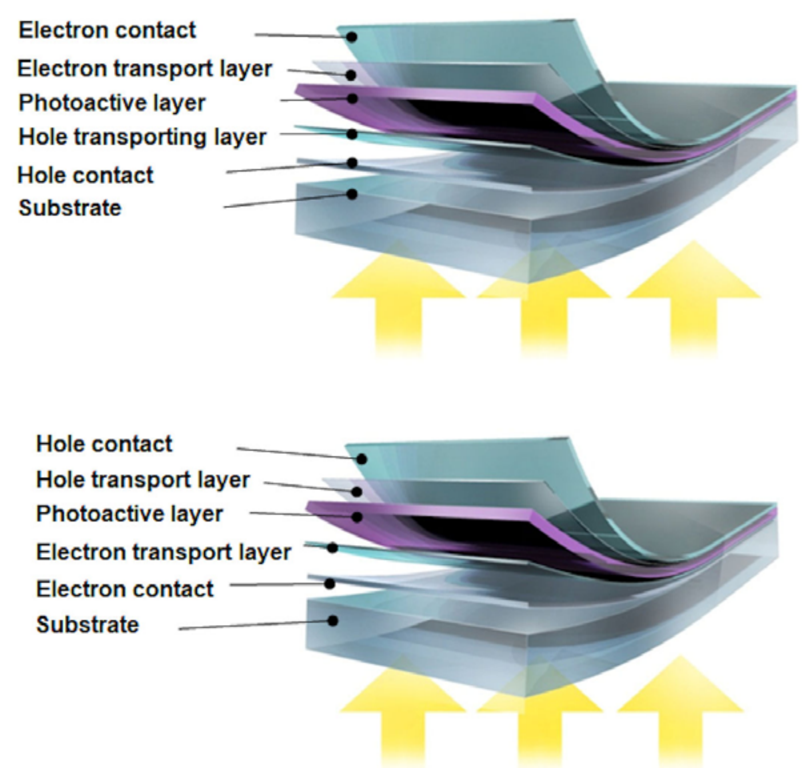


Figure 26. *Standard and inverted organic photovoltaics (OPV) device structures assessed for energy module.*

OPV modules containing eight serially connected OPV cells were processed on PLA and PET substrates. The outside dimension of the OPV module was 76 x 37 mm from which the active cell area was 1056 mm^2. Figure 28 a). Device stack used in cells was up scaled to modules. An example of the performance of OPV modules under 200, 500 and 1000 lux illumination is shown in b). Performance on PLA substrate was observed to be slightly lower than on PET, most likely due the surface roughness, but still meeting the system requirements.

In demo fabrication, OPV was printed on the same PLA substrate after silver printing of antenna and circuitry. Similar OPV performance on demo substrate was achieved than on plain PLA. However it was noted that the varying surface of PLA caused deviation on printing quality and resulted fluctuation on OPV performance especially on voltage output Figure 28 c). Average Vmpp for modules was 2.8 V and maximum 3.9 V while average Pmpp being 130 µW and maximum 177 µW. Picture of ready OPV module on PLA is shown in Figure 28 d). Encapsulation of OPV module was made using commercial PET based barrier foil and pressure sensitive adhesive. In this project the encapsulation material were not optimized, but in future using bio based or other sustainable encapsulation would degrease the environmental impact of material use.

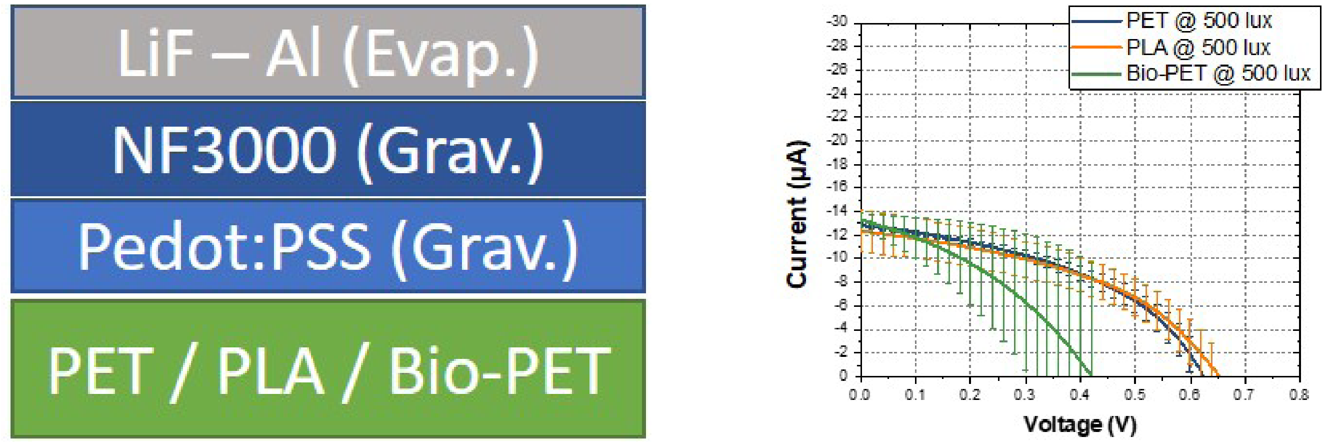


Figure 27. *OPV structure used in demonstrator 1 and IV-curves of OPV cells fabricated on PET, PLA and Bio-PET substrates*

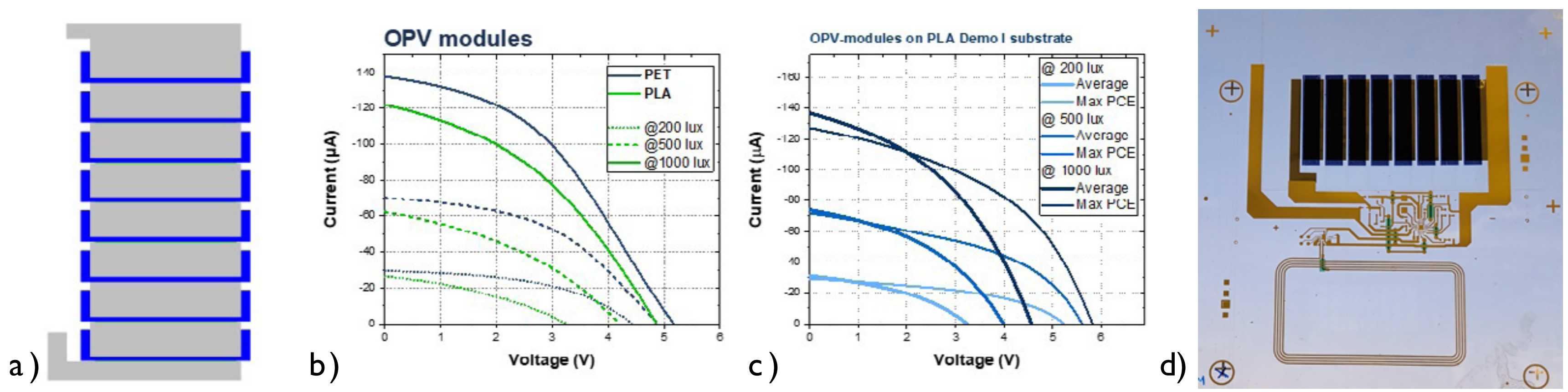


Figure 28. *a) OPV-module layout, b) IV-curves for OPV modules on PET and PLA substrates, c) IV-curves for OPV modules fabricated on the same PLA substrate with printed circuitry and antenna, d) photograph of demonstrator after printed circuitry, antenna and OPV fabrication.*

3.2.3 Printed supercapacitor

The target of the supercapacitor development work was to use environmentally friendly materials without deteriorating electrical and mechanical properties. The schematic structure of the supercapacitor used in the demonstrator is shown in Figure 29. The aqueous electrolyte used in the supercapacitors limits the voltage of one cell to about 1.2 V, thus in this case there are three cells connected in series to obtain the higher voltage level required by the demonstrator. The current collectors (Electrodag PF-407C graphite ink) and electrodes (activated carbon ink formulated at TAU) were applied with doctor blade method. As separator Dreamweaver Titanium cellulose paper was used and the face-to-face assembly was sealed with 3M 468MP adhesive. As electrolyte a solution consisting of NaCl and water (mass ratio 1:5) was used.

Already in the beginning of the project the supercapacitors did not contain toxic materials. However, some materials related work was done in the project to change the original substrate material, PET, to PLA. In this way the fossil-based material was replaced with a bio-based alternative. Based on the experiments, both PET and PLA require application of barrier material to prevent excessive electrolyte evaporation. Without the barrier material the electrolyte is evaporated from the supercapacitor in few weeks. Based on the experiments done, when barrier layer is applied, life-time of several years is expected.

In some applications it would be beneficial to combine supercapacitors with in-mold printed electronics. A set of experiments was performed to estimate how the printed supercapacitor behaves in the injection moulding process. It was found that although the supercapacitors contain water-based electrolyte, they survive the injection moulding process without clearly deteriorating electrical properties.

The series connected supercapacitor modules designed for demonstrator were characterized with methods based on IEC 62391 standard. In addition, cyclic voltammetry measurements were done. Examples of cyclic voltammetry and constant current charge/discharge characterization results are shown in Figure 30.

In the case of series connected supercapacitor it is important to minimize the variation in the electrical properties of each individual cell to avoid overcharging of the cells, which results to short lifetime. During the project the precision of ink application as well as assembling accuracy were clearly improved. This resulted to narrower distribution of capacitance, equivalent series resistance and leakage current values.

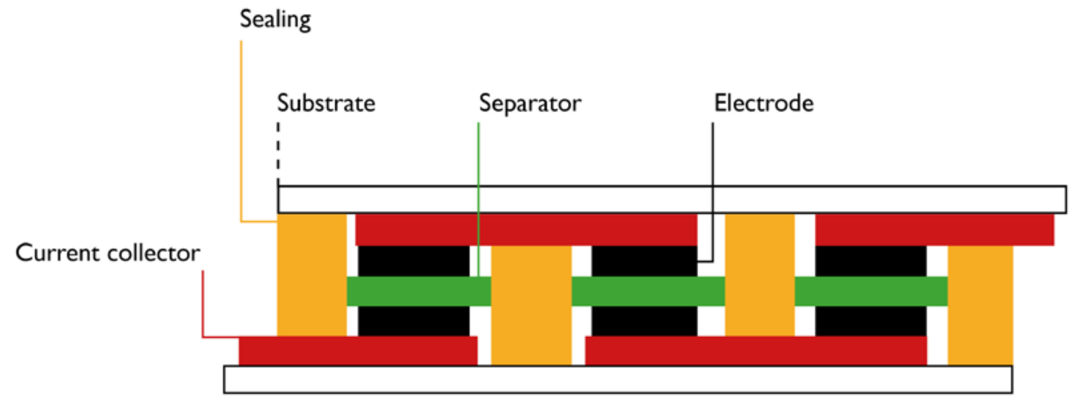


Figure 29. *Schematic cross-section of the supercapacitor module consisting of three cells.*

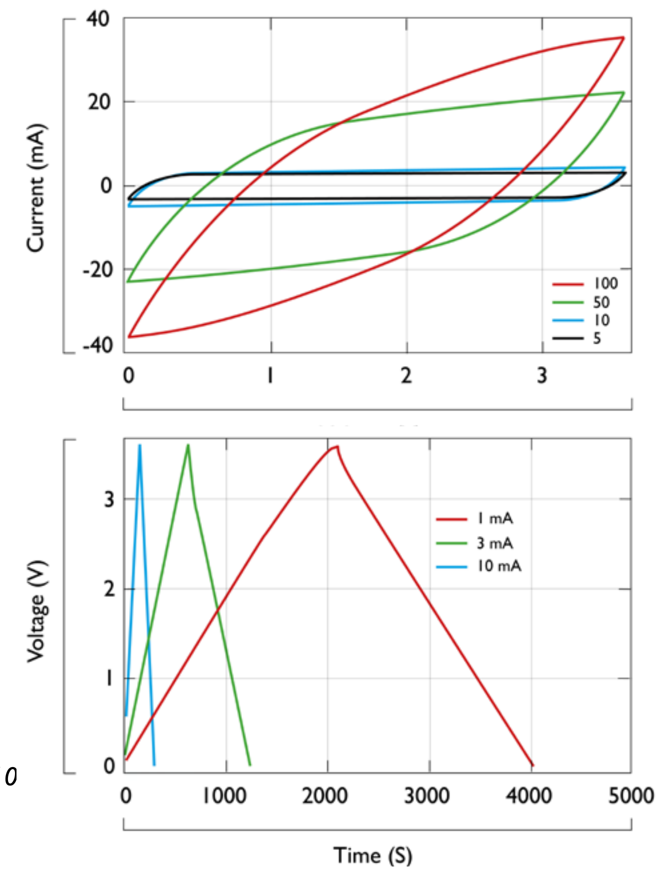


Figure 30. *Cyclic voltammetry (scan rates 5-10 mV/s) and constant current measurements of a supercapacitor module.*

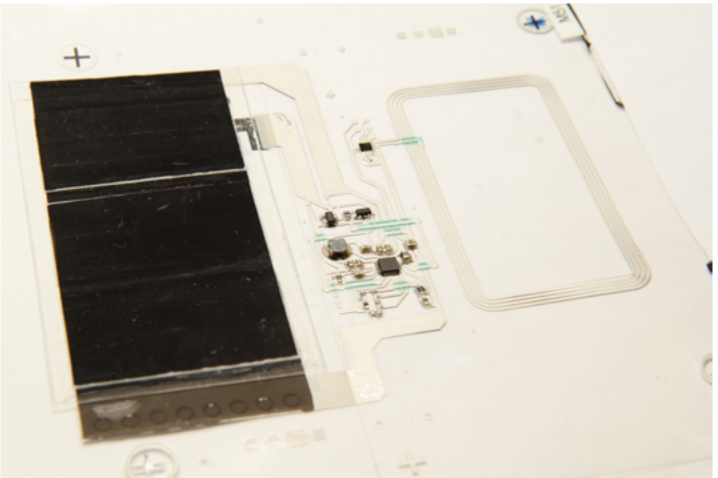


Figure 31. *SC printed on top of OPV on demonstrator 1*

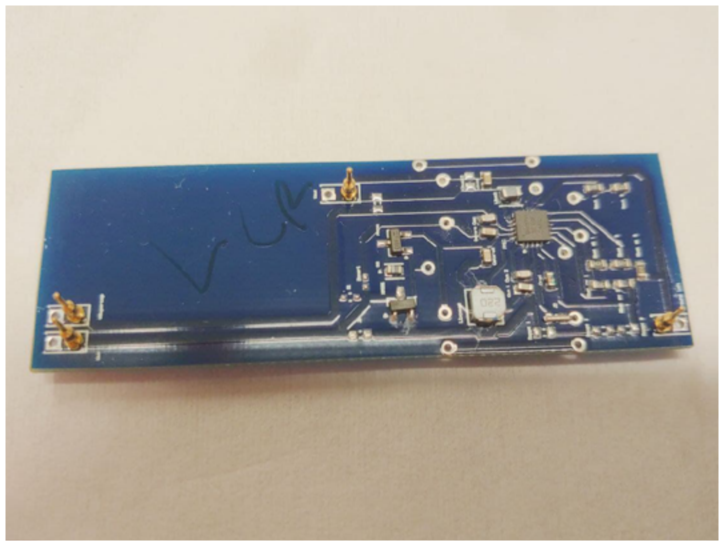


Figure 32. *PMIC circuit on FR4*

3.2.4 Power management circuit

Power management circuit is important getting energy harvested by OPV to the smart chip and supercapacitor energy storage. Plan was to use simple two diode over voltage protection or use commercial power management integrated circuit (PMIC). First two diodes over voltage protection were designed with low leakage Schottky diode and Zener diode to set desired max charging voltage of 3.6V for supercapacitor.

For PMIC power management first part was to study datasheets of different manufacturers. Operational parameters of the smart sensors are in Table 1. Supercapacitor (SC) voltage range is 0-3.6 V and OPV maximum power point is around 2V. Minimal quiescent current and good efficiency was required from PMIC. Minimal component passive component count was also desired, but all PMIC circuits had similar component counts. Desired topology of PMIC operation was boost or buck-boost as maximum power point (MPP) of OPV is lower than operational range of SC. PMIC evaluation boards from e-Peas, Analog devices, ST microelectronics and Texas Instruments were ordered for further study.

Evaluation board behavior with OPV and SC were tested for charging and output efficiency, quiescent current and stability of maximum power point tracking (MPPT) in varying light levels. e-Peas AEM10941, or ST SPV1050 was not providing good MPPT, therefore selection was between Analog Device ADP5090/91 or TI BQ25570. Although output regulation was not deemed necessary TI circuit has high efficiency buck output regulator which was selected as the other parameters with AD circuit were similar. In evaluation board testing it was noted that all circuits used inefficient charge pumps, when SC voltage was under their operational voltage. For TI BQ25570 this was 1.8 V and bypass transistor bridge was designed to work until SC achieved 2 V. This is mostly important for the first charging of the device as PMIC will cut out output when SC voltage falls below this voltage. Final printed PMIC has 18 passive components and two transistors.

PMIC circuit and smart sensor fit in same 22x70 mm area between antenna and printed SC. During the testing 100 lx standard fluorescent tube office lighting was able to run circuit and charge SC at the same time. This was very good performance as indoor lighting is often more intensive. Lowering the driving voltage of the smart label significantly reduced its energy consumption. This means that using the buck converter of the PMIC reduced overall power consumption. With 1.8 V output PMIC and full 3.6 V SC could drive the sensor for around two days. With typical indoor lighting PMIC would charge to operation conditions in couple of hours.

Diode over voltage protection could not charge the SC to full, as OPV current falls quickly after MPP and maximum achievable SC voltage is around 3 V depending on light level. 3 V SC would run smart sensor for around 23 h in dark. Charging time to 3 V would be around 30 h as charging current is very small after 2.5 V, but with good OPV sample with high MPP voltage higher charge could be achieved. This is a lot worse performance than PMIC, but the PMIC circuit has over ten times the material costs of this simple design.

3.3 Development of printed thin film transistors and diodes

To envision fully printed/flexible efficient energy harvesting module, printed thin-film transistors (TFTs) or diodes could be used to implement the supercapacitor loading and DC-DC conversion circuits. The TFTs could also be considered for circuitry to regulate the supercapacitor DC output V. One possible circuit to implement DC-DC conversion would be a diode-based Dickson charge pump, which needs a clock signal to operate. The clock-signal could be implemented by using a ring-oscillator circuit with several printed TFTs. The clock frequency is affected by the unity-gain frequency of the TFTs (f_T), which can be estimated based on the TFT device geometry (channel length L and gate-to-source overlap L_{g-s}) and electrical parameters (operation voltage V_g-V_t and saturation mobility μ_{sat}) as

$$f_t = \frac{\mu_{sat}(V_g - V_t)}{2\pi L(L + L_{gs})}$$

It can be estimated using the equation that improvements in L from 70 – 90 µm to 5 – 10 µm and L_{g-s} from 5 – 10 µm to 2 – 5 µm range could lead to increase in the unity-gain frequency from 4 – 45 kHz to 200 – 6800 kHz when neglecting other effects arising from the short device channels. Besides the increased operation frequency, by decreasing the TFT device size, the footprint of the flexible circuit would decrease, which would result in lower environmental impact of the final product. For example, for a circuit containing 1000 TFTs with width length ratio of 10, conventional printing (e.g. inkjet) with L = 100 µm leads to ~30 mm^2 area whereas high-resolution printing with L = 1 µm would require only ~0.3 mm^2 area. This was the impetus for the developments at VTT to focus on the miniaturisation of printed metal oxide TFTs. The research work was performed together with Academy of Finland-project FLEXRAD (PI Leppäniemi), which focuses on high-resolution-printed metal oxide TFTs for radiation and photosensor applications.

VTT's new 8''-compatible sheet-fed high-resolution printing system with automated overlay alignment system shown in Figure 34 (a) was installed in September 2020. The system is used for the TFT development in FLEXRAD/Ecotronics-projects. The system is based on reverse-offset printing (ROP) method whose three main steps are shown in Figure 34 (b). The system was run in during late 2020 and all supporting processes were established in-house at VTT, namely PDMS blanket, printing plate and glass slit fabrication processes, in internal VTT projects. At highest, the system has demonstrated printing resolution of ~0.5 µm for isolated lines and ~1µm for line/space structures. Overlay alignment was tested in a related EU-project (Hi-Accuracy) using alignment test patterns shown in Figure 34 (c). The histograms in Figure 34 (d) show the amount of at the overlay alignment error inside one sample is at ~2 µm level with the cross-direction (CD) being more accurate than the machine direction (MD).

Metal oxide TFTs were fabricated in FLEXRAD / Ecotronics-projects using VTT's ROP-based lift-off method shown in Figure 33, which has been earlier shown to enable the patterning of Al source/drain electrodes that provide good charge injection to the n-type oxide semiconductor. New dedicated printing plates were designed and fabricated for all the layers of the TFT stack, namely gate electrodes, gate dielectric, semiconductor and source/drain-electrodes. All layers have been successfully patterned using ROP-printed polymer resist layers during the FLEXRAD/Ecotronics-projects. The results of the TFT fabrication using ROP and their characterization will be published in a scientific journal publication later.

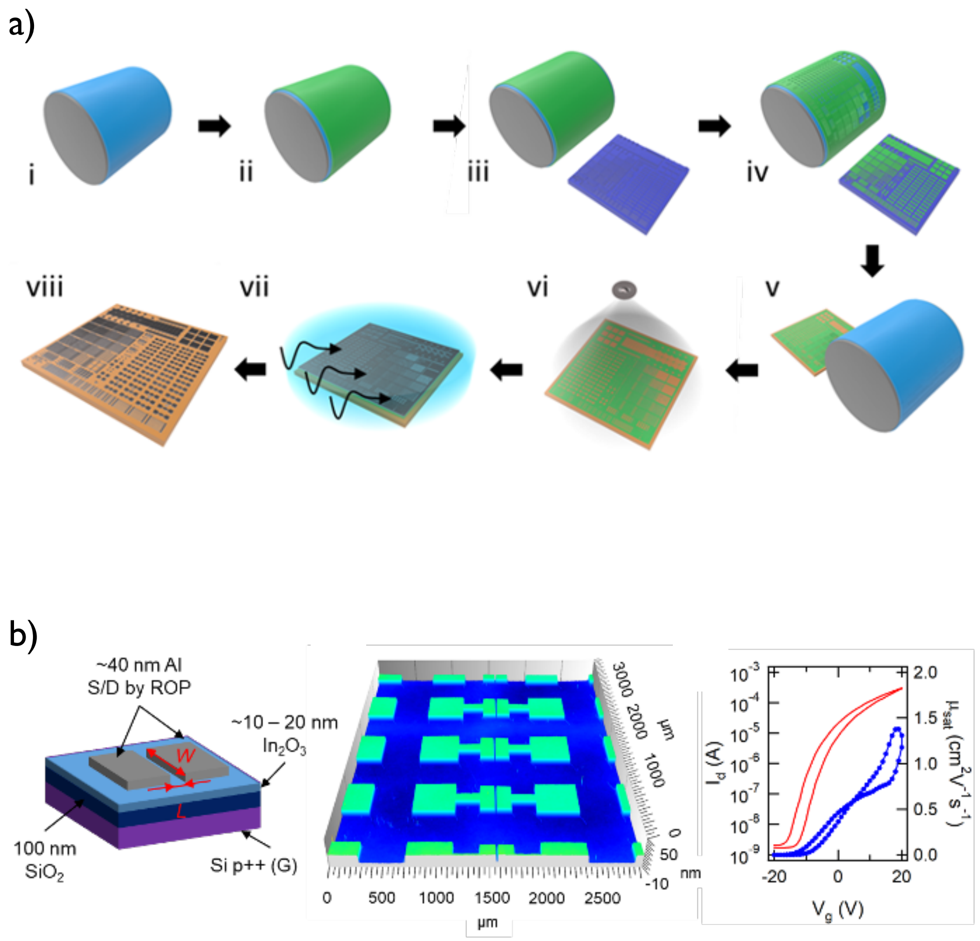


Figure 33. *(a) Steps of ROP-based lift-off method used to fabricate high-resolution metal oxide TFTs in the project. (b) Schematic image, 3D microscope image and electrical characteristics of metal oxide TFT with ROP-patterned Al source/drain-electrodes. Figures from Sneck et al. "Reverse-Offset Printing of Polymer Resist Ink for Micrometer-Level Patterning of Metal and Metal-Oxide Layers" in ACS Applied Materials and Interfaces, vol. 13, pp 41782 – 41790 (2021).*

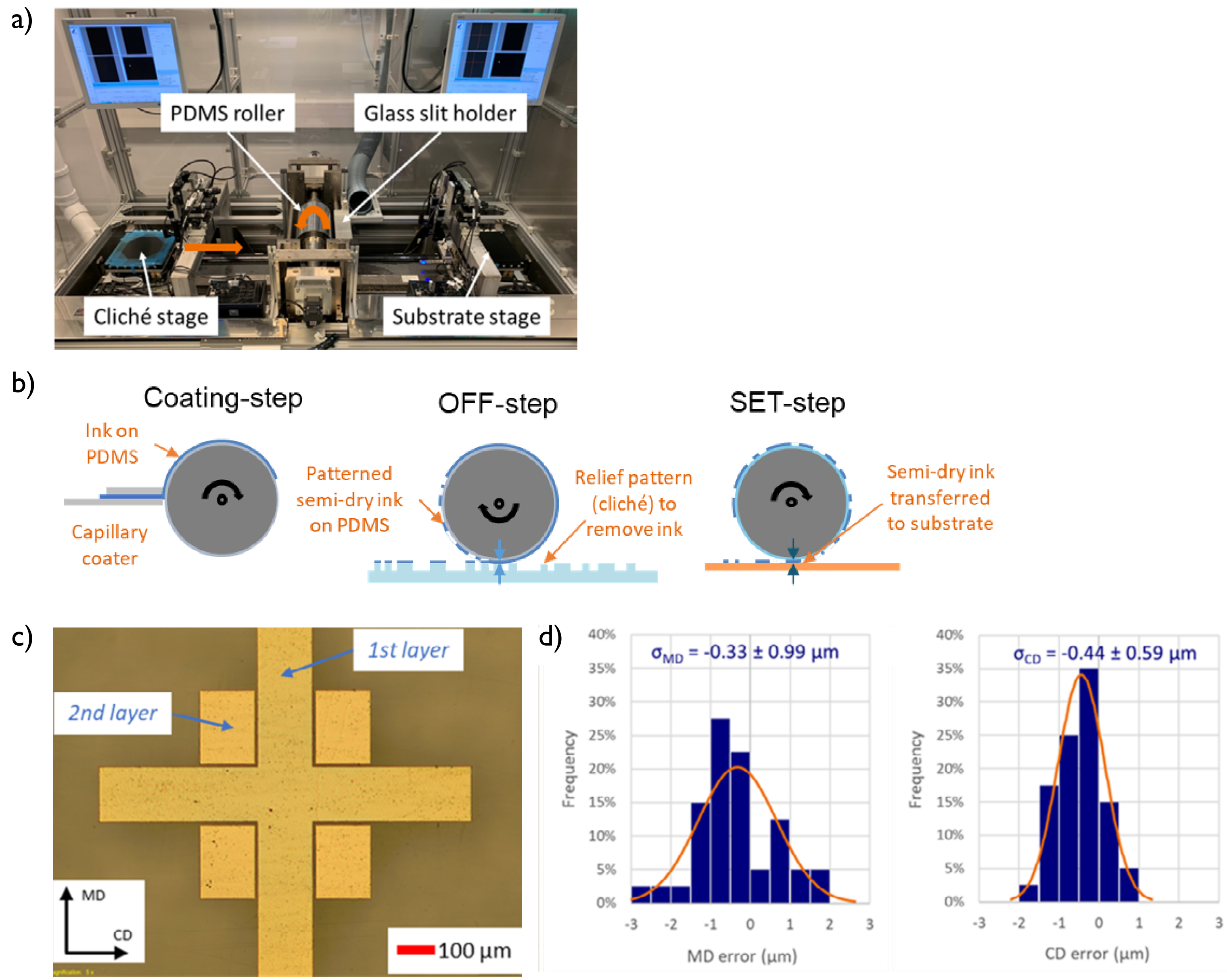


Figure 34. *(a) VTT's new high-resolution reverse-offset printing system with automated overlay alignment system. (b) The three steps of the reverse-offset printing process. (d) Overlay alignment accuracy tests of VTT's reverse-offset printing system. The alignment error is measured for 40 locations inside one sample and data shown for machine direction (MD) and cross-direction (CD). The data shown in the histograms indicates that the alignment is at ~2 µm level and CD is more accurate. Figures from Alastalo et al. "Taking accuracy of printed electronics beyond 1 µm" in OPE-Journal issue 37 (2021).*

3.3.1 Diode development

The aim of the work is to develop a thin-film low turn-on voltage (V_T < 1 V) diode to prevent discharge of supercapacitors through OPV. Compared to Si-based SMD diodes, the turn-on voltage of the solution processed thin-film diodes are, in general, considerable higher.

In this work, a solution processable p-type organic semiconductor named IDTBT has been used based on its reported performance including high intrinsic mobilities, a low transition voltage and a high forward current density. The initial architecture of the diode had three vertically stacked layers, that is an anode layer with a high work function metal, a semiconductor layer, and a cathode layer with a low work function metal compared to the HOMO level of the semiconductor. Ag, Au, and Al has been tested for the anode and cathode electrodes. To improve the carrier injection, a PFTP SAM layer has been grown on top of the anode electrode. In addition, MoO_3 has been tested as a high work function modification electrode to realize a better Ohmic contact between the anode and the SC. After several optimization round, however, the performance of this kind of diode did not met the target requirements.

Therefore, a reverse structure was investigated, i.e., the cathode electrodes are placed at the bottom, while the anode electrodes are fabricated on top as shown in Figure 35. Together with a new pair shadow masks to ensure an optimal diode area/size, the fabricated diodes achieved a higher yield and repeatability. Secondly, 1-2 Dichlorobenzene were used as the new solvent for IDTBT to achieve a better uniform thin-film layer. Thirdly, both the bottom cathode Al electrode and MoO3 layer were treated with UV-ozone. The UV-ozone on Al likely leads to a thin layer of Al oxides which helps the wetting of IDTBT on top; the UV-ozone on MoO3 improved the efficiency of the carrier injection, hence, a higher forward current density. Figure 11 shows the IV characteristics of the IDTBT diodes fabricated on Sio2 wafer and polyimide substrates.

The diodes showed overall good performance measured in air conditions. The forward and reverse current densities are 19 mA/cm^2 at 2V, 34 μA/cm^2 at -2V for the wafer sample and 2.6 mA/cm^2 at 2V, 0.37 μA/cm^2 at -2V for the PI sample, respectively. The resulting DC rectification of the wafer sample is 5.6×10^2, while the PI sample yields an excellent 7×10^3. The turn on voltage is close to the targeted 1 V goal.

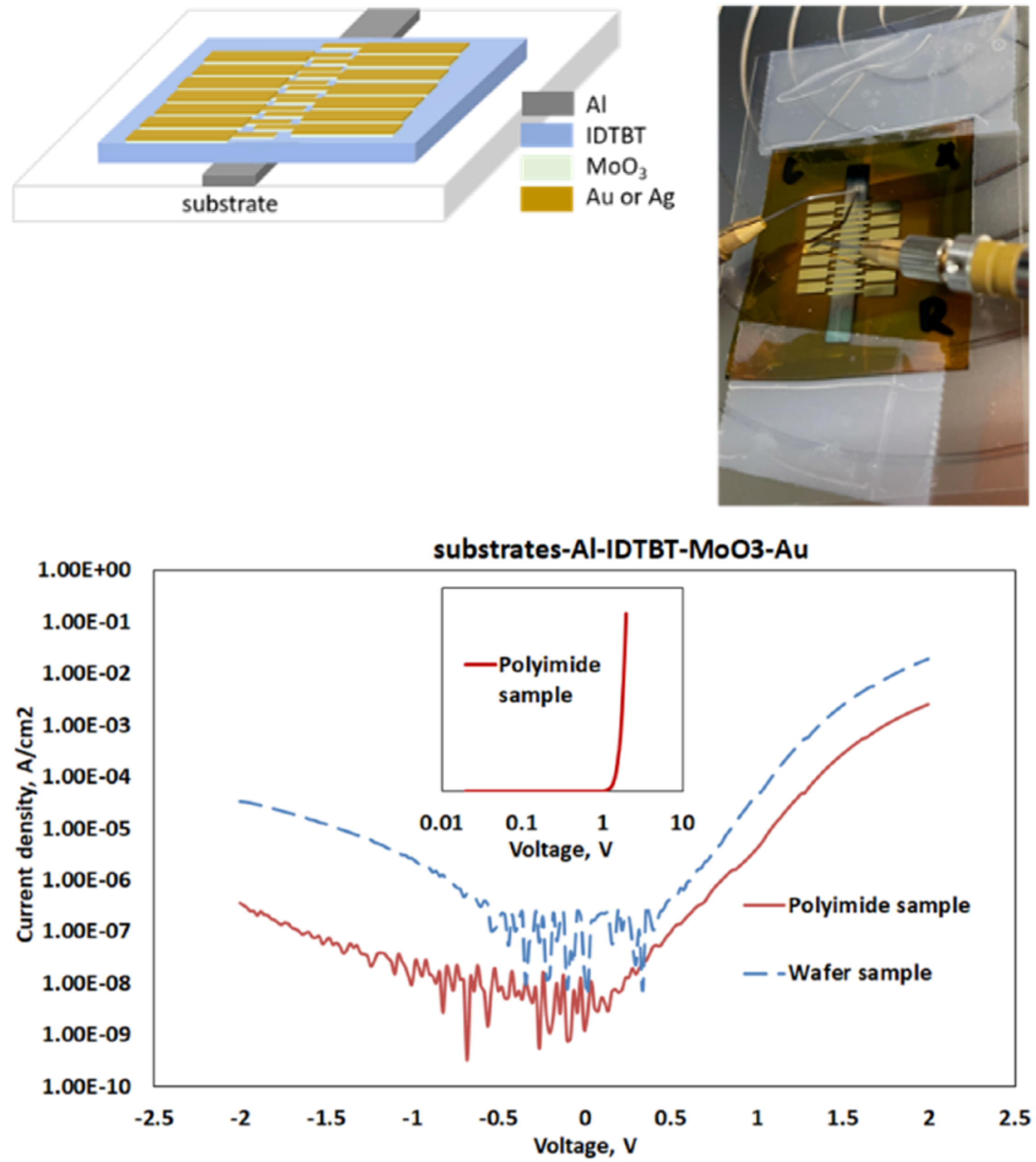


Figure 35. *Final diode structure (top left). A photo of diodes on polyimide bottom (top right). I-log(V) characteristics of the diodes on polyimide and wafer, insert log(I)-V of the PI sample (bottom).*

3.4 Product design

The product design for the intelligent package was divided into the design of the label, package and user interfaces. The intelligent package was fabricated for demonstrator use and, the user interface was developed in mock-up versions. The user interface comprises the roles of a merchant, a consumer and a smart shopper.

3.4.1 The smart label

The Institute of Design and Fine Arts of LAB University of Applied Sciences (later LAB) had the main responsibility of the product design of the intelligent package demonstrator, but there has been a close collaboration between all research partners while executing the task. ECOtronics team came across during the project that electronics and optics would be easiest to manufacture on a label. It would have taken more studies and tests if electronics would have been printed directly on the package. The label gives an opportunity for different recycling options

1. label recycling with the package and
2. label recycling separately.

The first brief was to visualize the label. Five trainees from LAB produced visualizations of the smart label. The work included visualizations of the layers which made it easier for all to understand what will be included in the smart label. They also visualized the scenario of the lifecycle of the smart label, from manufacturing to disposal and a first draft of the layout. During autumn 2020, the project team discussed which product the smart label would be best to use. It was decided that the best way to introduce the smart label would be on groceries because smart label gives extra value with the temperature logger and groceries are familiar to everyone. The design trainees produced beautiful concept pictures of how the smart label would look like at different food packages.

At this stage it was too early to design the final layout of the smart label. The development process of the components was still running, and researchers couldn't specify the size of the components or even the layout. Lively conversations were held about the layout of the components. The LAB team wanted to have as small label as possible to it to be suitable for food packages. The future scenarios were created to show how the development of electronics could proceed and could it be possible to have a different layout for the components and save space in the near future.

In autumn 2021 the final dimensions and layout of the components were ready and the finishing touches for the smart label were made. The smart label includes the OPV that harvests the light, the size of the OPV and the size of the antenna were the defining factors of the size of the smart label and the graphics. The final dimensions for the label are 120 mm x 98 mm. The main features for the smart label were to have the ECOtronics logomark, QR-code that leads to the mobile application and in this case to the ECOtronics website with information of the demonstrators and the information of the smart label.

Figure 36. *3D-modelling of microwave meal with smart label*

A

B

C

Figure 37. *Future scenario, how label size could change smaller with component development.*

Figure 38. *The development of the smart label.*

3.4.2 User interface

The smart label produces information and one of the key factors is to design how the information is received. At the early spring 2021 it was suggested that LAB student could create a mock-up of an application that would make visible the data that sensors are collecting. The proposal was supported. Two design students began brainstorming of what is the best platform for the application, what features should it have and what is the target group. After brainstorming and ideation, it was obvious that there must be two user interfaces. Customers and merchants need to receive different information, for example, the customer might only need to see that the product is in good condition, but the merchant is interested to see in what stage the temperature has gone too high, at the transport or at the store.

Mobile application was considered as the best platform for the mock-up. The mobile application enabled the use of QR-code so it is quick way to guide people to test the mock-up and read more about the project while presenting it at fairs. It was also thought that mobile application would be easy to use for the store staff and they would have the information at their hands all the time.

The mock-up introduces several other features than just a temperature logging. The following ideas were created as an inspiration to manufacturers. The customer can read more information about the product for example carbon footprint and information of the intelligent package. The most important information for consumer is the recycling instructions. The merchant has an inventory list and a map showing the disposable products. The most important feature, the temperature log, is the first option in the merchant's version, at the navigation bar. The screen opens to the temperature curve and at the top of the screen, the user can move easily to the point where the temperature has gone too high if this has happened.

Figure 39. *User interface mock-ups. On the left: the customer's interface. On the right: the merchant's user interface. User interfaces were created according to the needs of the target groups. Screenshots of the mock-up created with Figma-software.*

3.4.3 Package design

The package design process started in spring 2021 and was finalized in November 2021. LAB team received the brief that the package should be easy to manufacture. The graphics should be designed for general food package and the package should have some wow-effect, so it will stand out from other packages. After sketching and analyzing the options three packages were presented to the ECOtronics team. Two of them went to the second round and after some guidance from LAB experts, the packages were modified to work as a set by changing the forms. A discussion of primary and secondary packages inspired the trainees to think if they could create bigger and smaller packages, so the bigger package could be used as a primary or a secondary package. The thinking and testing paid off and design trainees were able to create a nice set of packages.

The process included the design of the structures for the packages because the packages were designed as unique pieces. The ECOtronics team had expressed the wish that the package should have a minimum number of adhesive surfaces. This was thought from the ecological and the manufacturing point of view. The first versions of packages had multiple adhesive surfaces but after iteration rounds, the adhesive surfaces were able to cut to a minimum. During the process, the use of the packages was tested with quick paper prototypes and with the real cardboard provided by LUT University. These tests enabled the team to see how the package functions in real life and helped to notice the needed modifications.

The graphics of the packages were created to present general food packages. Two different patterns were created. The icon pattern includes visualizations of different food items for example blueberry, fish, and carrot. The pattern perfectly fulfills the wish for a general food package. The second pattern is geometrical and the idea behind this pattern was to create three-dimensional effect that catches the eye. The geometrical pattern is versatile because it can be used for different products which also fills the brief of a general food package. The colours of the packages were thought to follow the visual appearance of the ECOtronics project.

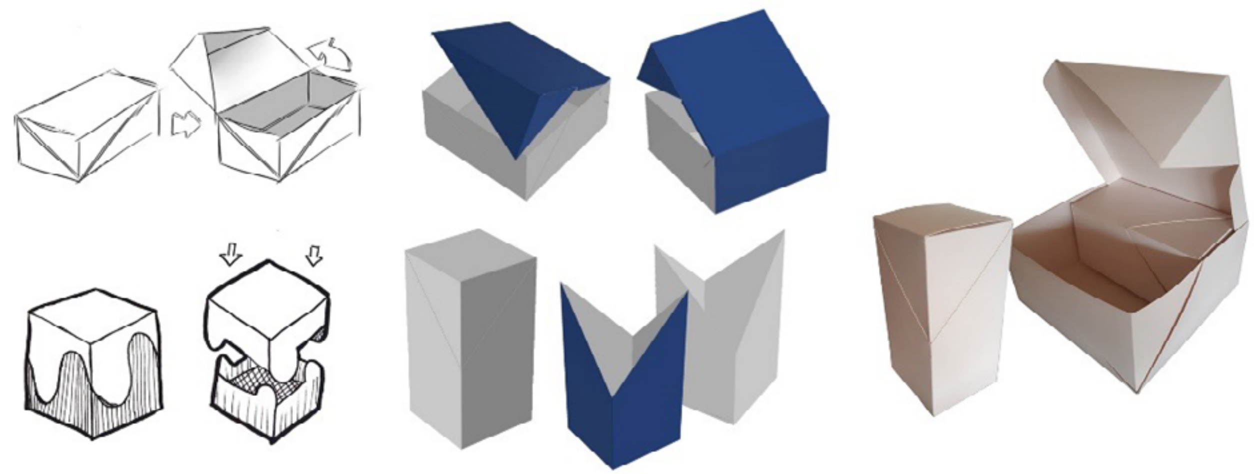


Figure 40. *Development process of the package*

Figure 41. *The design image of the final package with smart label and graphics*

3.5 Fabrication and testing of smart label and package

The smart label and associated package design was optimized for the best performance, functionality and appearance. In addition, scenarios and concepts specified use case. The design of the secondary package comprised mechanically embossed area for the label to protect it from wear during the use. The labels for the packages were fabricated according to process flow described in Figure 42.

Bio-based PLA and commercial fossil-PET (as a reference) films were chosen as base substrates for the labels. Silver and dielectric were screen printed for the antenna and circuitry. After that OPV was gravure printed next to the antenna and, the supercapacitor (SC) screen printed on top of OPV. Surface mount devices (SMD) were assembled with isotropic conductive adhesive (ICA) after the printing. The printed graphics film on bio-based substrate covered the label. The graphics film was designed to provide the information for the user and comprising embossed feature for authentication. The label structure is presented in Figure 43.

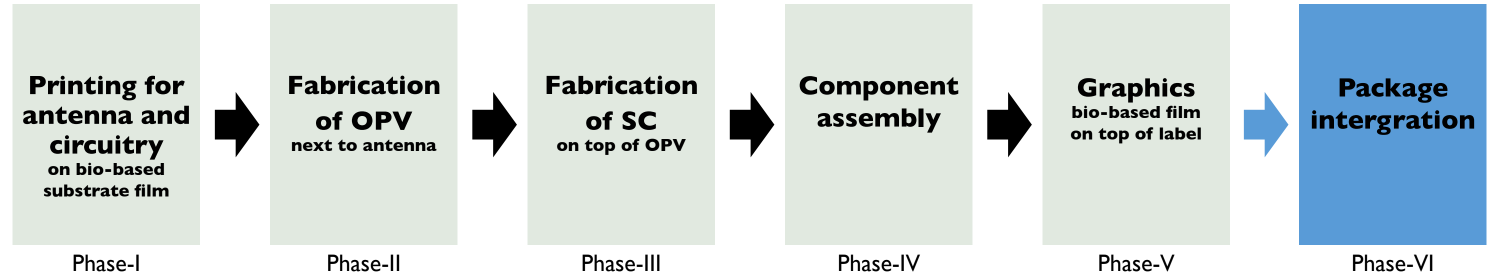


Figure 42. *Fabrication flow for the intelligent package demonstrator.*

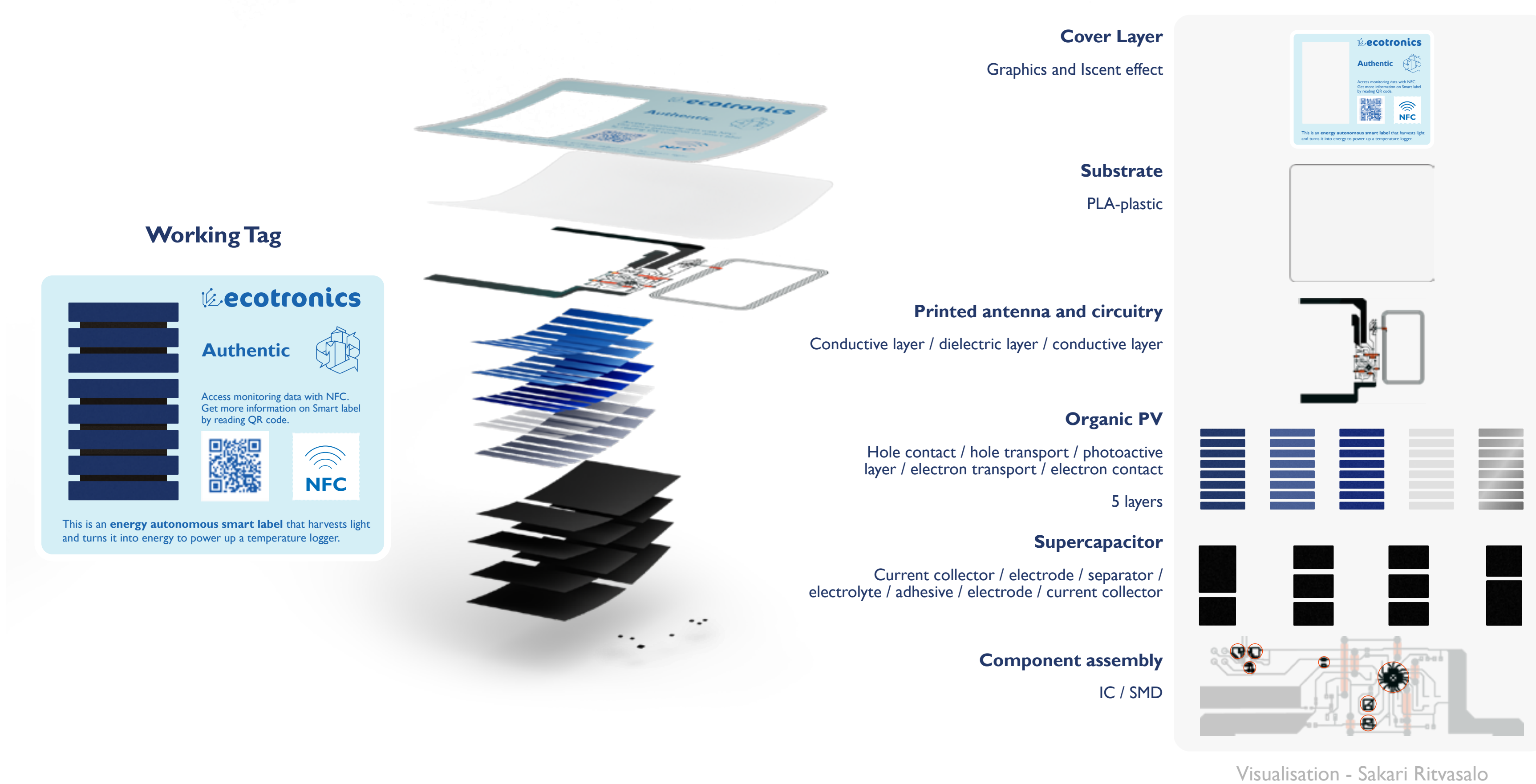


Figure 43. *The structure of the smart label.*

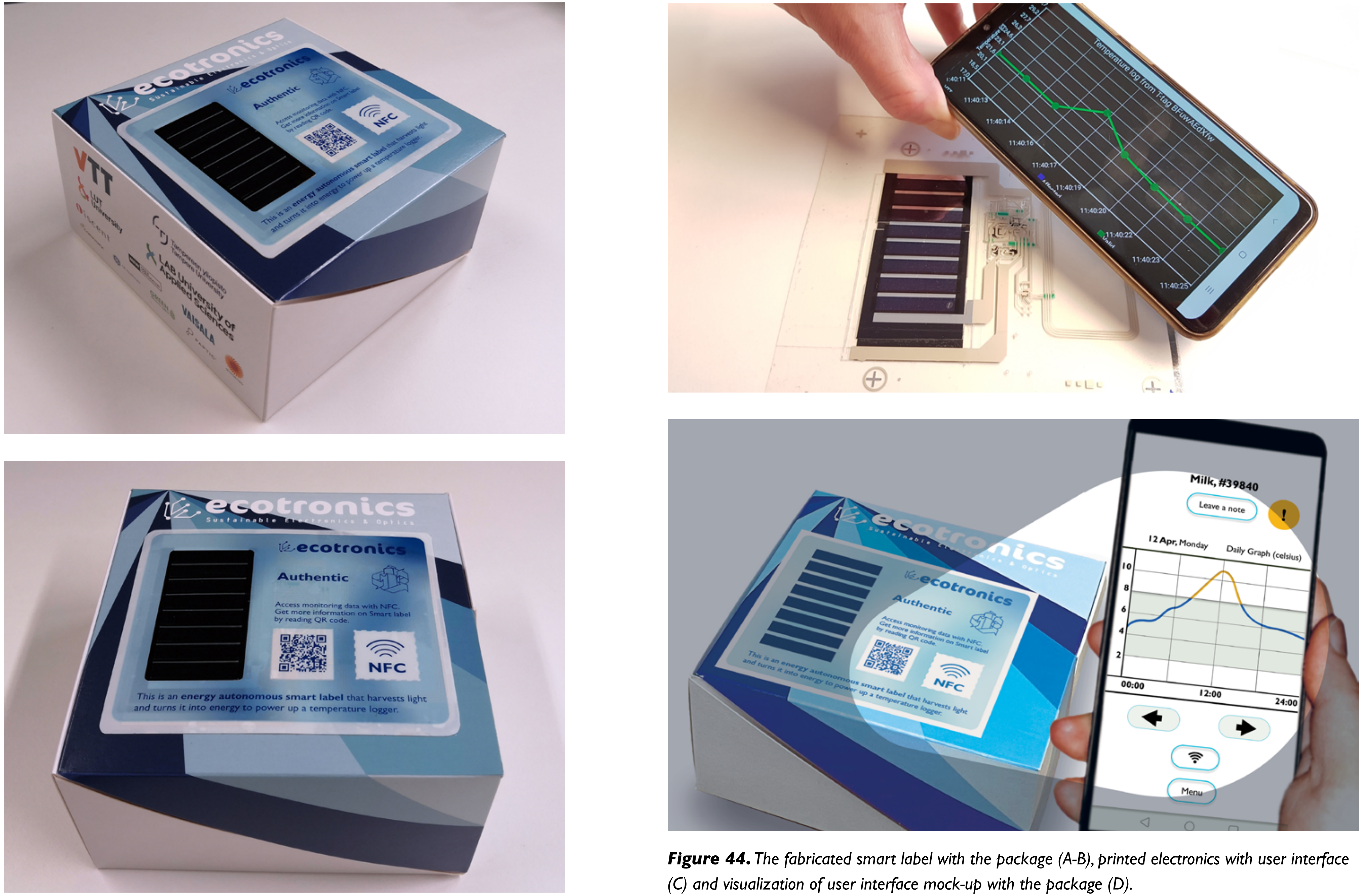


Figure 44. *The fabricated smart label with the package (A-B), printed electronics with user interface (C) and visualization of user interface mock-up with the package (D).*

3.5.1 Package production

During the first half of the project, LUT Packaging Technology developed various demonstrator packages for converting experiments. The functionality of demo-packages in production and end use was ensured in co-operation between LAB and LUT.

The most promising package designs were evaluated by preparing mock-up sample packages (Figure 45a.), which were manufactured with a digital sample cutter. The design of the chosen demo-package could be fine-tuned efficiently by preparing samples of the material used in the actual production (Aegle White 290). A similar method was utilized in the evaluation and design of print graphics.

The paperboard sheets were printed digitally with multicolour printing (CMYK) and water-based protective varnish (medium gloss). The package blank and die cutting tools for the flatbed diecutter were designed simultaneously. Industrial quality die cutting tools were manufactured for LUT Packaging Technology's flatbed diecutter and the blanks of the demonstrator packages were cut and creased as a small series production (Figure 45b.).

Functional features were formed on the top surface (lid) of the demonstrator package with a laboratory scale mechanical embossing device (Figure 45c.). The device was developed and manufactured during the project by LUT Packaging Technology for modification of sample material surfaces. The embossing toolset was designed and manufactured by precision machining from aluminum to create a protective frame around the smart label. The pressing force and tool temperature were optimized for the digitally printed paperboard material.

In the final assembly (Figure 45d.), the demonstrator packages were folded and assembled manually using hot glue. Last step in the production chain was to apply the smart label to the embossed frame on the lid of the demonstrator package.

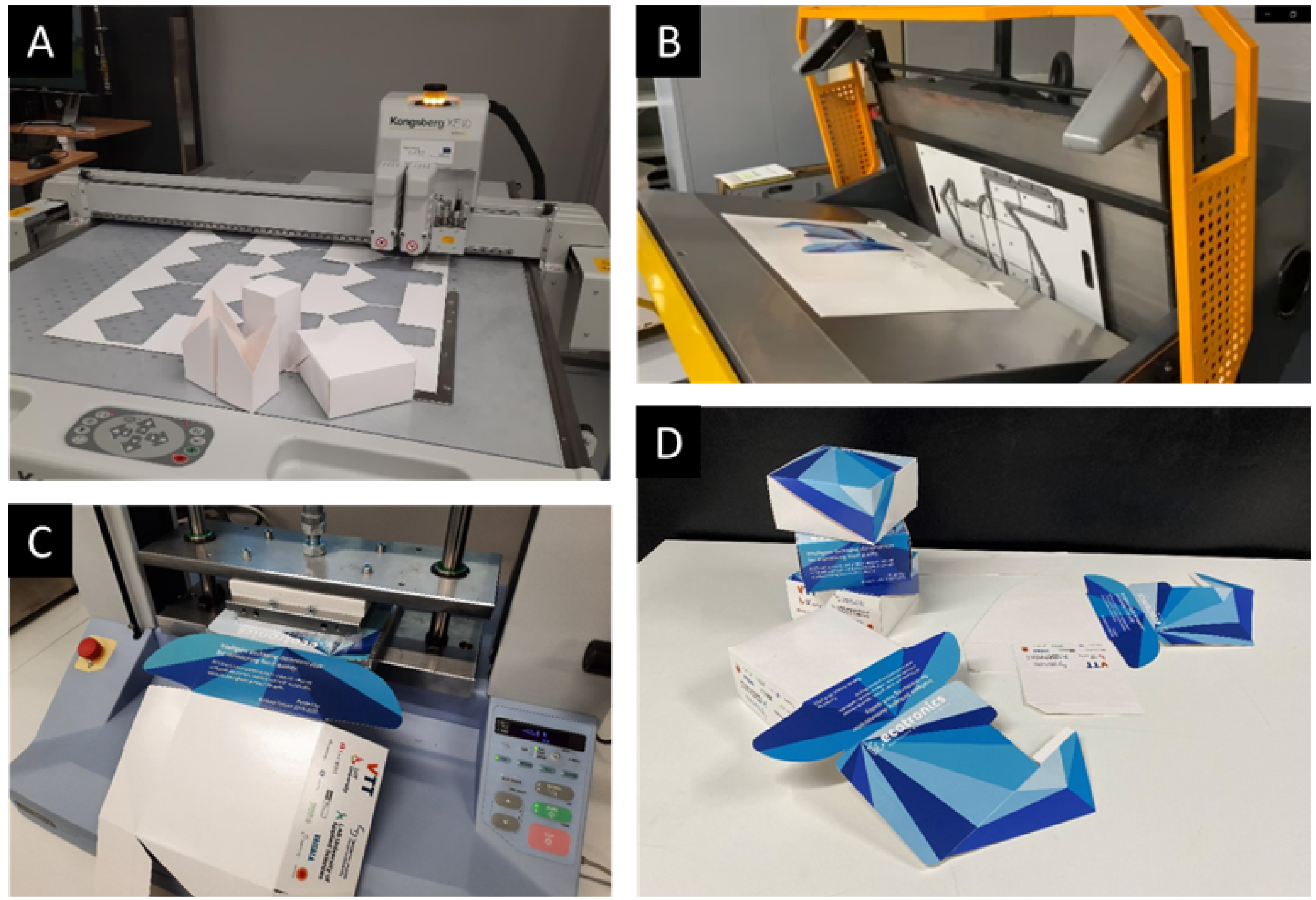


Figure 45. *Stages in the production of demonstrator packages in LUT Packaging Technology: testing of prototypes (A), die cutting of printed blanks (B), embossing of package lids for smart label placement (C) and final assembly of demonstrator packages.*

3.6 End of life

Intelligent packaging, or smart labels at large, represent a specific type of electronic products. This is explained by their primary function and application. Smart labels are meant to be attached to other products, such as packaging. Therefore, such labels will undergo the specific end-of-life (EoL) routes of the packaging they are attached to, such as metal, glass, plastic, and cardboard. The recycling processes of such packaging vary significantly, therefore combinations of various substrates and conductive materials (printing inks) were analyzed in this project with regard to the various recycling processes (Figure 46).

Mixed waste. Mixed waste can have various EoL routes with incineration and landfilling being the most common ones. In Finland, mixed waste is mainly incinerated. During incineration of smart labels, the substrates would oxidize generating energy which can then be recovered, so it can be considered as energy recovery of substrates. Metals, such as silver inks, could potentially be recovered from ashes if suitable technologies are applied. As of now, non-ferrous metals recovery from ash is not commonly practiced, thus recovery of metals is seen challenging and possible in the future.

Plastic waste recycling. In Finland, there is an operating system for separate plastic packaging waste collection. Plastic waste is mechanically recycled. During the process, plastic is separated by its polymer, then crushed, washed, and extruded. Smart labels can be separated most effectively during the washing process before extrusion. Evidence was found that printed electronics on plastics might still end up in the extrusion process, where the metals can possibly block the sieve used to remove impurities. The rejects from washing and extrusion are then sent to energy recovery. Metals and substrates other than plastic can only be potentially recovered from the rejects, but such solutions are only being developed and are not currently available.

Glass waste recycling. Separately collected glass is recycled in Finland. Glass recycling has several treatment stages during which impurities are removed: such as screening, magnetic separation, eddy current separation and optical sorting. To avoid disturbance to the glass recycling process, smart labels should be glued to the glass packaging in a similar way to traditional paper labels. Rejects from recycling are incinerated with a possibility for non-ferrous metals recovery from the reject of eddy current separator.

Metals recycling. Separately collected metals are recycled in Finland. The metals are first separated into ferrous and non-ferrous fractions. Ferrous metals are sent to smelters where substrates would be incinerated during the process, which can be considered energy recovery. Copper and silver would then become a part of alloys, whereas aluminium would end up in slag. During copper and aluminium recycling, there is possibility to recover all metals analysed.

Cardboard recycling. During cardboard or paper recycling, separately collected waste is shredded and mixed with water to separate fibers from each other. Impurities present in the cardboard would then be separated and removed with process water or as rejects. In this project, experiments were conducted on repulpubility and deinking of certain substrates to see the possibilities to recover wood fibres and inks.

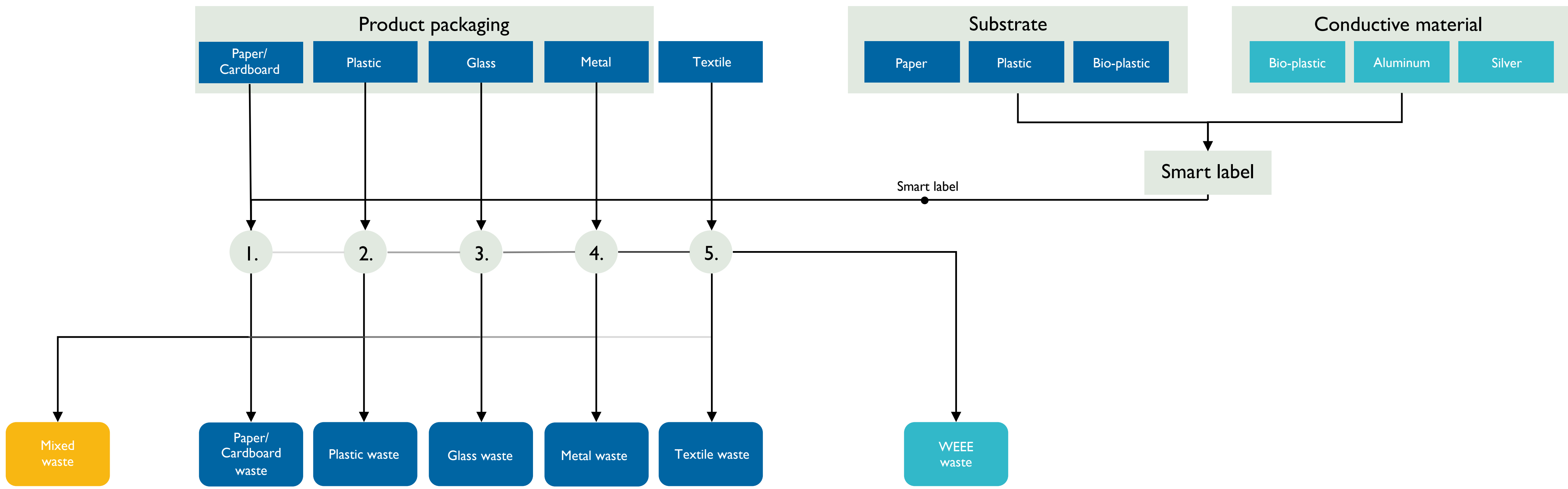


Figure 46. *End-of-life options for various packaging and products with smart labels made of alternative substrates and conducive materials*

3.6.1 Repulpubility and deinking of fibre-based substrates

In the project, several substrates were tested for their repulpubility. Out of the ten tested substrates, six substrates (Aegle While, Isla Duo, Pankasilk 360, Pankasilk 290, Finess Premium silk, and Novapress) had the share of rejects below 15% meaning that these materials can be recycled during paper or cardboard recycling. The remaining four materials had the share of rejects above 15% which makes them inapplicable for paper recycling processes.

Apart from repulpubility tests, two materials (Figure 47) were tested for their deinking properties, which shows how well the inks are removed from the fibres. The tests were conducted along with waste office paper as a reference for comparability. The deinking experiments showed that inks were generally removed from the surface of the fibers, while a part of them still remained.

The visual examination of the fibres after deinking experiments (accept in Figure 48) showed that inks were mostly removed, while not as good as in the case of waste office paper. Furthermore, it was noticed that the inks tended to accumulate on one side of the sheet formed out of recycled fibres. This accumulation can be explained by a higher density of silver inks used in the printing process as compared to conventional inks used in office printing. Presence of silver inks in accept might cause problems if the paper is used in electronics again since it can cause short circuit or other operational problems in the products.

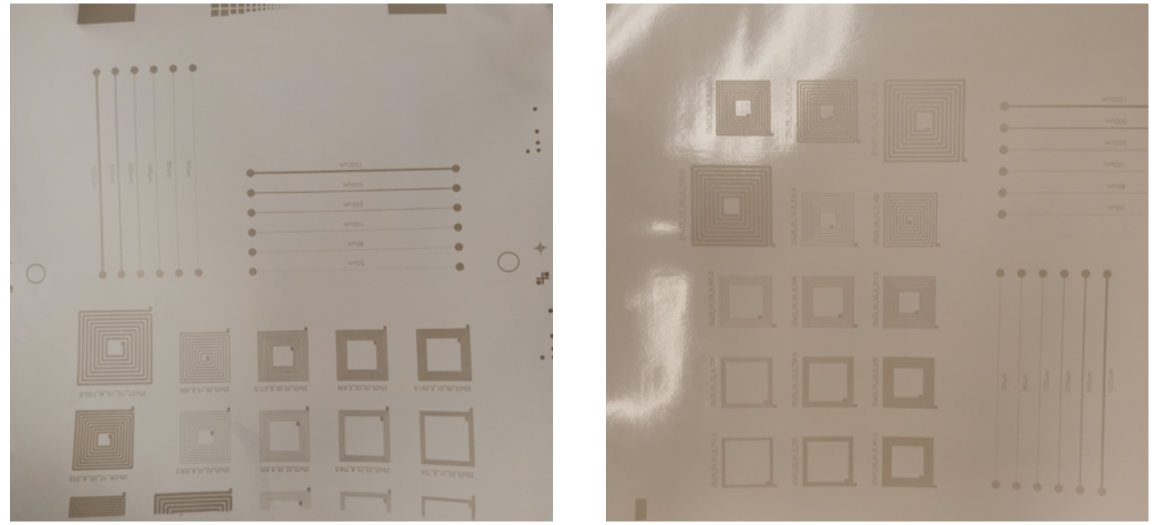


Figure 47. *Materials tested for deinking properties.*

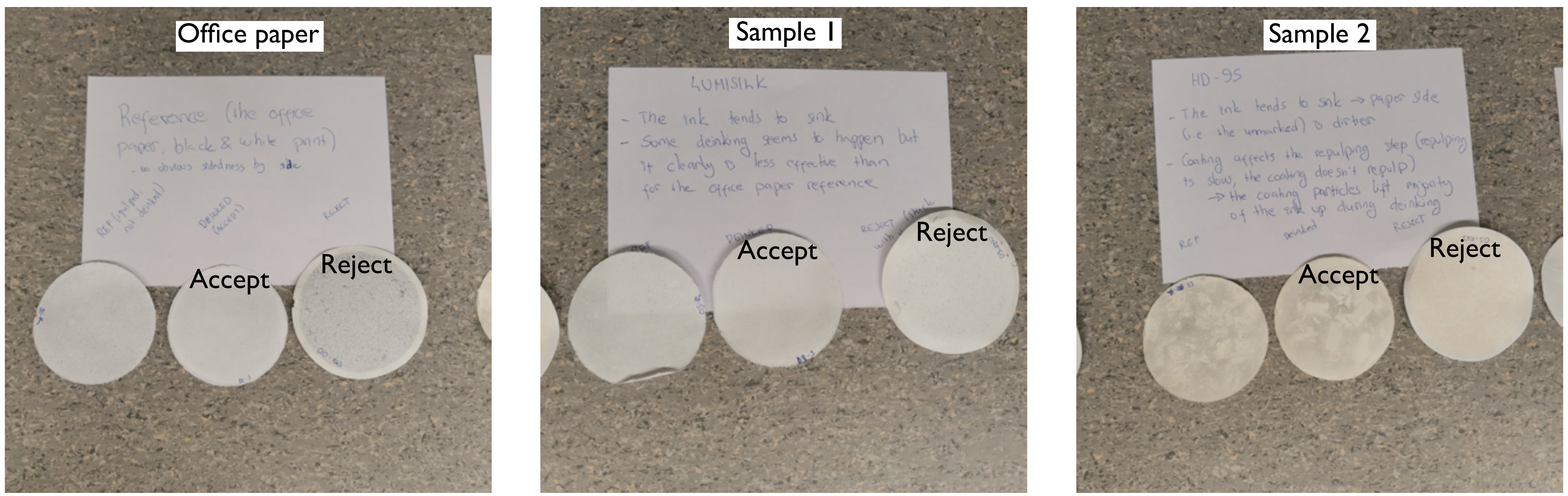


Figure 48. *Obtained recycled fibres after deinking (accept) and reject from the process.*

3.7 Life cycle assessment

In order to analyse the potential environmental aspects related to Demonstrator I, a life cycle assessment (LCA) was conducted. It should be emphasised that only the smart label (i.e. Phases I-V) was included in the assessment. In the assessment, the main focus was on the raw materials used for the production of the smart label as the most concise information was available on them. Printing of the product was assessed through data from the literature. Also recovery and disposal of the final product were included in the analysis. As the label is relatively small, and the materials used in it are very small in quantity, it was assumed that it would in waste incineration as part of the impurities originating from the recycled packages.

In the analysis, raw materials were divided in the five different production phases. Bio-based film in Phases I and V was assumed to be PLA made of corn (Benavides et al. 2019). Data on environmental impacts related to the production of the raw materials and energy used for Demo I were mainly taken from Ecoinvent and Gabi LCA databases. The use of the product, and its potential environmental impacts were only assessed qualitatively (see below).

Based on the results on the raw materials used, most, over 50%, of the greenhouse gas emissions originated from Phase I, from the production of the silver paste used in the antenna fabrication (Figure 49). Also production of PLA had a large contribution to the total emissions. The contribution of Phases II and III was around 15% with the other phases having minor role. Based on the results, it is evident that the potential replacement of silver with e.g. copper would reduce the impacts considerably (see also Chapter 4 on Demonstrator product II).

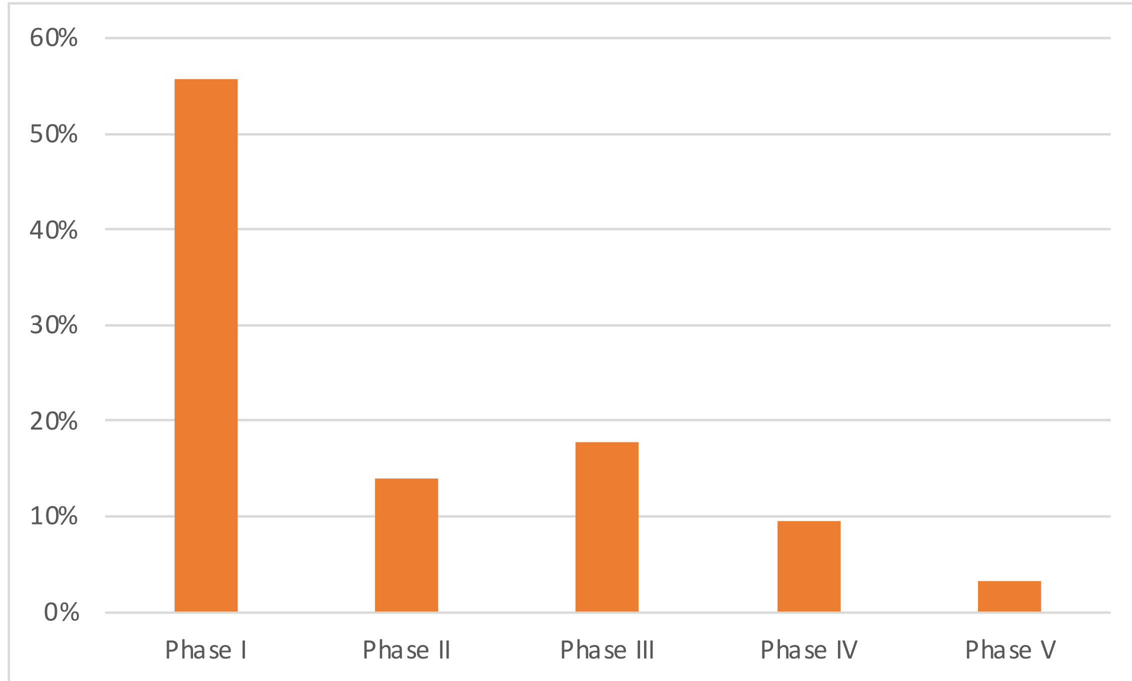


Figure 49. *Contribution of the different phases of the product to the total greenhouse gas emissions.*

The potential impact of intelligent packaging on food wastage was not studied quantitatively. However, based on other studies, some aspects can be raised. According to FAO, the global amount of food wastage is assumed to be 1.6 billion tonnes per year (FAO 2013). Of this, editable parts amount to 1.3 billion tonnes. In Finland, according to Luke (2014), the annual amount of wasted food is approximately 500 million kilograms[1]. Of this, households waste about 120-160 million kilograms, which is about 20-25 kg per person. According to FAO (2013), most of the carbon footprint of food waste is caused by cereals (34%), meat and vegetables (both causing 21% of the total).

Along with consumer behaviour, one of the main reasons for food loss and waste in high- or medium-income countries is the lack of coordination between different actors in the food supply chain (Heising et al. 2017). Presently, food trader or consumer is primarily informed about the quality of the product through fixed "best before" or "use by" dates given in the packages. It does not give information of the particular state of each package or the way the product has been treated during the production chain. According to Heising et al. (2017), if the conditions of a product during the supply chain have been optimal, its quality can still acceptable after the expiry date on the package.

The present approach with the "best before" and "use by" dates needs to conservative in order to ensure safety of every product. The "dynamic" monitoring system that intelligent packaging enables could potentially be very useful in providing information on the actual condition of a particular product (Poyatos-Racionero et al. 2018) and thereby enabling reduced food wastage. Yet, before wide-scale adoption of intelligent sensors in packages is possible, standardised and comprehensive tests on their reliability need to be adopted (Dodero et al. 2021) Furthermore, legislative changes are required in order to enable moving from the present system to the so-called dynamic monitoring system.

While it is important to pay attention to reduction of packaging and electronic waste, it should be noted that the amount of bio waste produced annually is many times higher than production of plastic waste. For example, the amount of separately collected municipal biodegradable waste produced in Finland in 2020 was ca. 494 000 tonnes while the amount of plastic waste was about 93 000 tonnes (Statistics Finland 2021). Thus, even though packaging carries an environmental load, and producing intelligent packaging even increases that, it can be compensated through the environmental savings from reduced food wastage.

1 https://www.luke.fi/ruokajate-kiertoon/

4 Demonstrator-II: Sensor for monitoring environmental conditions

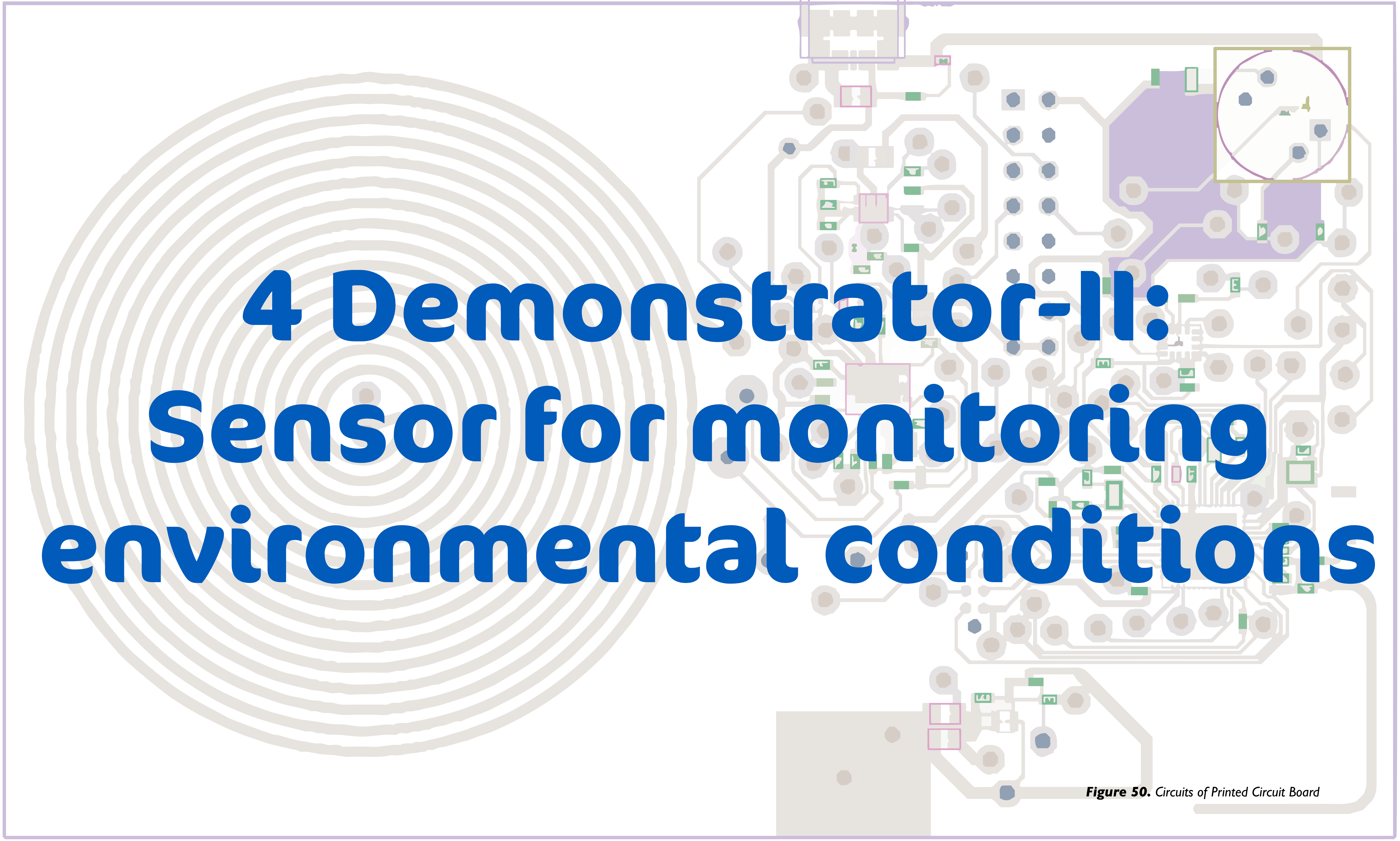
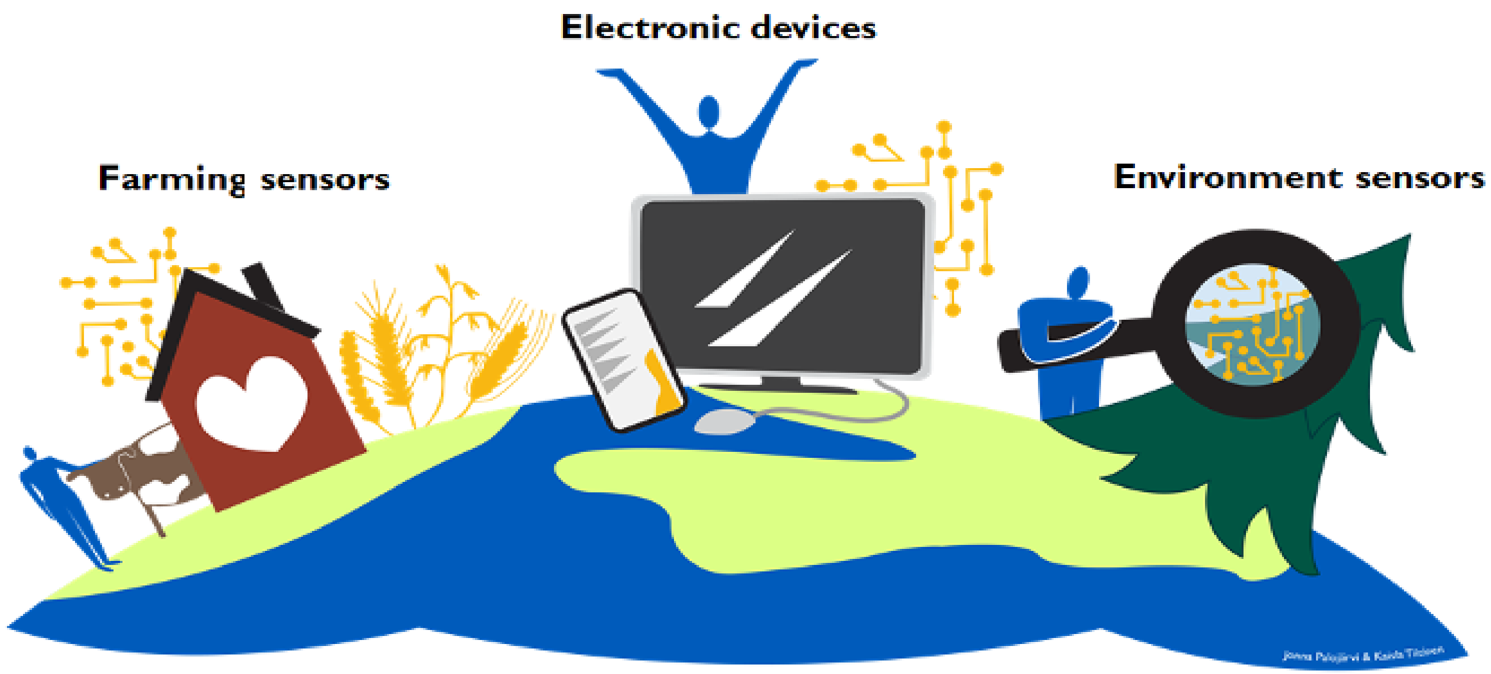


Figure 50. *Circuits of Printed Circuit Board*

4.1 Demonstrator-II: Sensor for monitoring environmental conditions

Demands for sustainable, cost-efficient on-line sensing of chemical and physical properties has increased. By measuring the properties such as temperature, humidity or presence of specific gases or toxic materials in various environments can improve the safety and efficiency of various societal and economical operations. Implementation of described, low environmental footprint technologies are compatible for providing monitoring e.g. in crop quality or weather conditions or detection of leakages and wastes in factories or environment could utilize these technologies. ECOtronics demonstrator case present opportunities in practice utilizing the opportunities of using new materials and production processes to improve material and production efficiency or product-specific properties thus, the value may improve climate impacts, resource savings, functionalities, usability and wider context of use.

Sustainability of electronics is influenced by the product materials, manufacturing processes and end-of-life. ECOtronics demonstrator for environmental sensing evaluates these aspects.



4.1.1 Specifications

Key objective in the fabrication of demonstrator for environmental sensing is the replacement of substrate. Environmental sensing applications comprise wide range of use and are providing vital information about earth and climate. The main problem is that may not be collected for recycling after their use thus, sustainable alternatives is needed. In practise this means that substrates would need to biodegradable and device materials non-hazardous for the nature. ECOtronics environmental sensing demonstrator is designed to comprise temperature and proximity sensor and, Bluetooth Low Energy Mode communication (2.4 GHz).

Objective of a PCB for the demonstrator is to have following key properties:

- Biodegradability, preferably home compostability
- Replacement for FR4 in various applications at least up to 2.5 GHz
- Four layers
- Plated through vias
- ~0.15 mm line and space
- Dielectric loss and permittivity roughly equal to typical FR4
- Preferably lead-free reflow process compatibility

4.1.2 Materials and manufacturing processes

Printed circuit board (PCB) manufacturing copper etching is the most used method. The copper etching is a central process step and, it is a well-established and widely used method. It is used to create the traces on the printed circuit board by removing the excess copper from the copper laminate, only by leaving the required material on it. There are several approaches for etching, also various process flows have been used. Figure 51a presents one example of a simplified process flow adapted from Printed Circuit Boards: Design, Fabrication and Assembly (Author: R.S. Khandbur, Publisher: McGraw-Hill 2006).

PCB manufacturing by using a screen-printing process forms an additive method where the printed material is directly deposited to the substrate and, the printed feature forms a desired pattern. Printing methods, like as a screen or stencil printing have been used in the fabrication of large area applications, for instance in keyboard backplanes. Figure 51b presents an example by Huttunen et al. (Multilayer plastic substrate for electronics, 2018 7th Electronic System-Integration Technology Conference (ESTC)). The described process flow comprises a separate dielectric substrate and, inserted between two double-side printed substrates in the lay-up step. Furthermore, the lamination using elevated temperature, pressure and partial vacuum, depending on substrates adhesives may also be used.

PCB process sets requirements for the substrates. The standard etching process is well-established and widely used, providing good performance. The standard substrate material for PCB manufacturing is a typically fiberglass-reinforced laminate, commonly known as FR4 which has many good properties, such as rigidity, thermal stability, non-flammability.

The printing is energy and material efficient and, it suits for large-area applications Many plastic substrates are also compatible for printing processes. Furthermore, plastic substrates can provide also other benefits, for instance flexibility or biodegradability although, a fire retardant-material layer might be needed. Silver has been typically used for printing the conductive traces but the replacement of silver with copper has increased the interest both ecologically and economically.

Fabrication stages in PCB manufacturing by

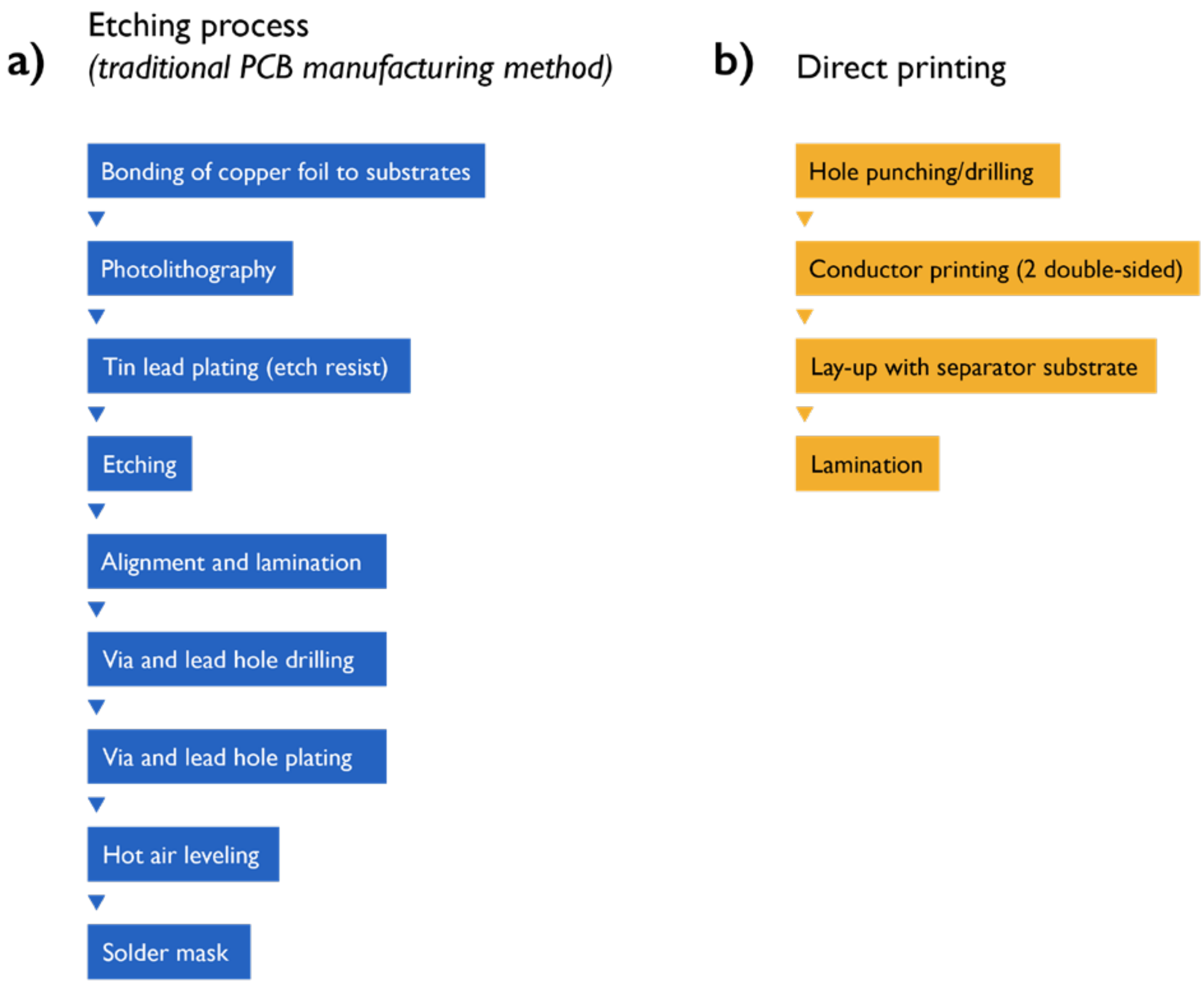


Figure 51. *Fabrication stages in PCB manufacturing by a.) etching process (traditional PCB manufacturing method) and b.) direct printing.*

4.1.3 Fabrication and testing

The fabrication of the test structures and demonstrator antenna was carried out using an EKRA E2 screen printer. A screen mesh type of 325-24 (mesh count, lpi-wire diameter, µm), squeegee hardness and angle of 75 ShA/45°, and printing speed of 40 mm/s were used. The conductor ink was a microparticle silver paste from Asahi (LS-411AW). The printed samples were oven dried at 150 °C for 20 min.

In addition to the screen printed silver antenna, the antenna structure was also fabricated using a screen printable copper nanoparticle ink (Copprint LF-360), which was sintered using a heat press at 140 °C for 120 s. The demonstrators comprised the screen printed silver antenna, the electrical performance of screen printed copper was comparable to screen printed silver thus, it can be considered as a potential alternative. Figure 52 shows the printed and heat-press sintered copper antenna on the biocomposite substrate.

Microstrips utilized double-sided printing where the bottom side was completely covered with the ink forming a continuous ground plane. The layout for the microstrips can be seen in Figure 52 and Figure 53. The coplanar waveguide was printed on a single side of the biocomposite substrate without a ground plane. The layout is shown in Figure 54.

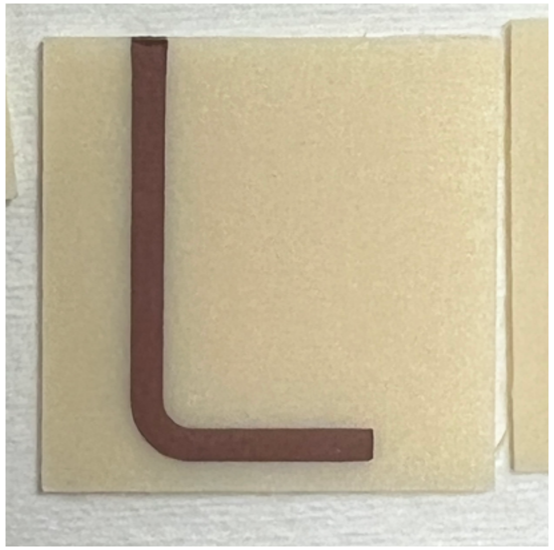


Figure 52. *Printed and heat-press sintered copper antenna on biocomposite substrate.*

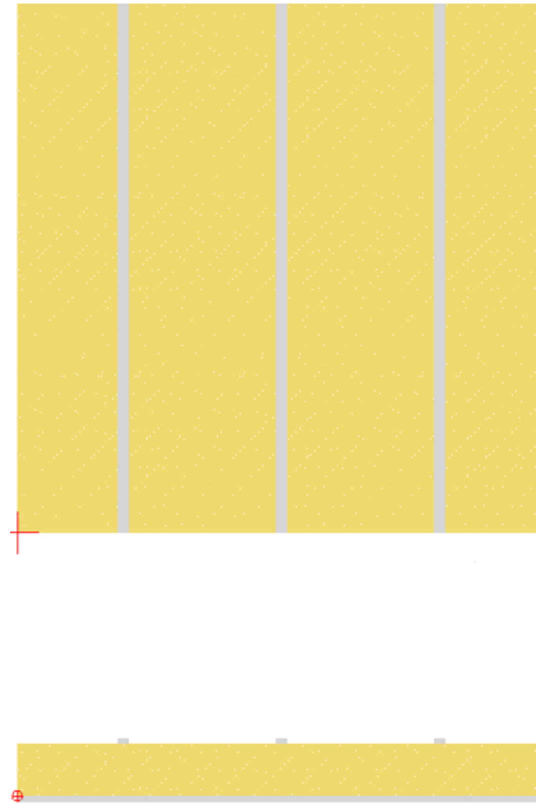


Figure 53. *100 mm Long Microstrip Layouts from Above and Cross Sections. The bottom side is completely covered with the ink. The depiction of the cross section is not to scale.*

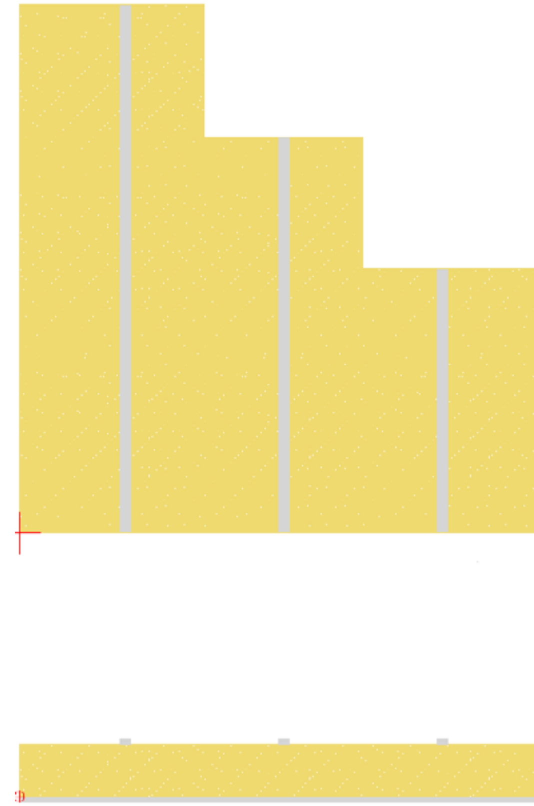


Figure 54. *Layout of the 100 mm, 76 mm and 33 mm Long Microstrips. The bottom side is completely covered with the ink. The depiction of the cross section is not to scale.*

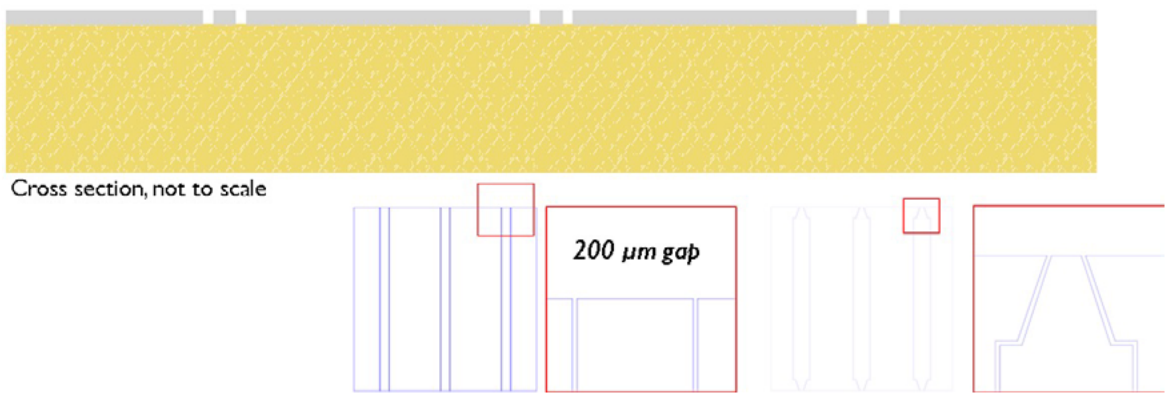


Figure 55. *Layout, Cross Section and End Detail of a Coplanar Waveguide Structure.*

Transmission Line Tests

Edge-launch SMA connectors were secured on the transmission line samples with cyanoacrylate and electrical connections from the transmission lines to the connectors were made with Epotec H20E electrically conductive adhesive. Figure 56 shows transmission line samples printed on biocomposite substrate equipped with SMA connectors.

The S-parameters S21 and S11 were measured with a vector network analyzer in the frequency span between 2 GHz and 3 GHz. Typical measurement results can be seen in Figure 56 and Figure 57.

The S-Parameter measurements show that all the measured transmission lines performed reasonably well in the neighbourhood of the 2.5 GHz target frequency. The return loss for the 33 mm microstrips was 0.5 dB higher than the return loss for the SMA F-to-F adapter which was measured for reference purposes. The reflection coefficient was generally below -15 dB so a reasonably close match to 50 Ohms was obtained over a wide range of frequency.

Coplanar waveguide, 300 µm gap

Microsrip

Edge-launch SMA connectors were secured to the test structure subrates using cyanoacrylate.

Electrically conductive epoxy Epotek H20E was used to make the electrical connections.

Figure 56. *Edge-Launch Connectors on Transmission Lines.*

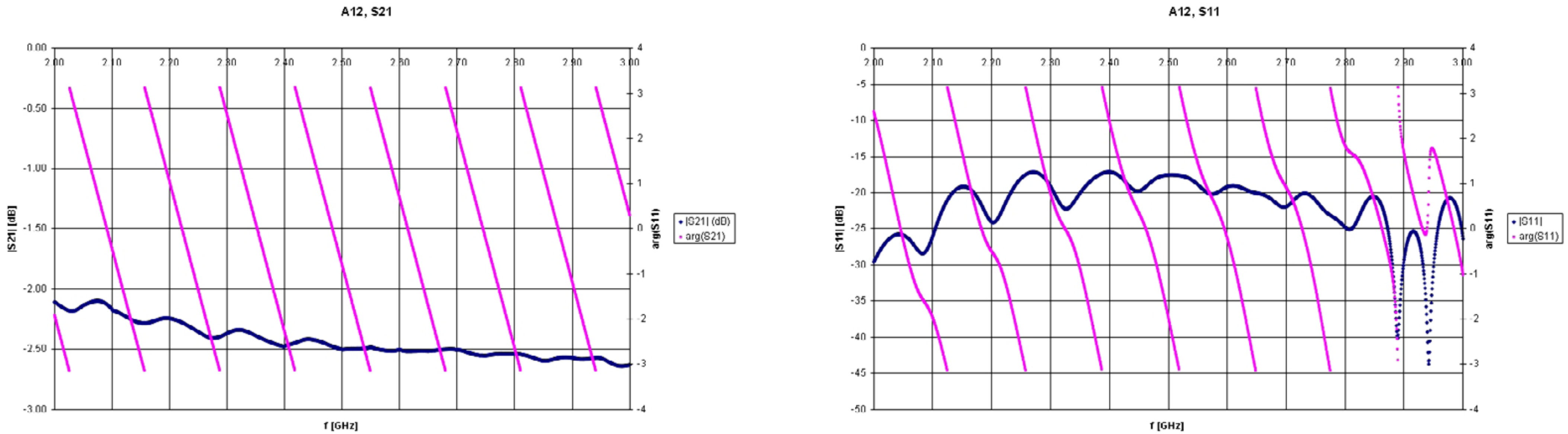


Figure 57. *Typical S-Parameter Measurement Results for a 100 mm Long Microstrip.*

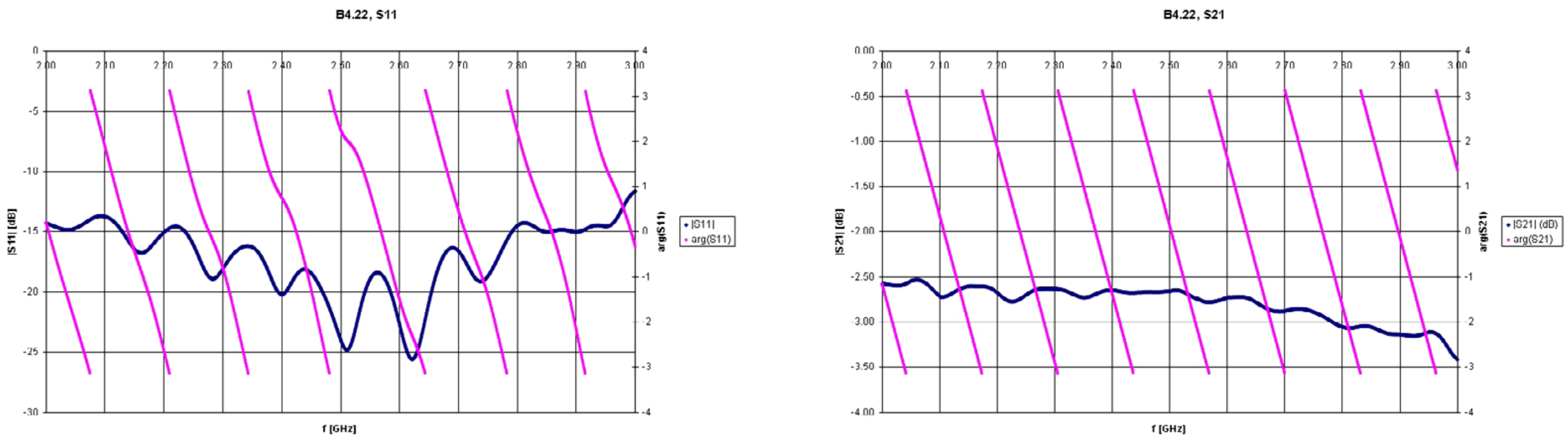
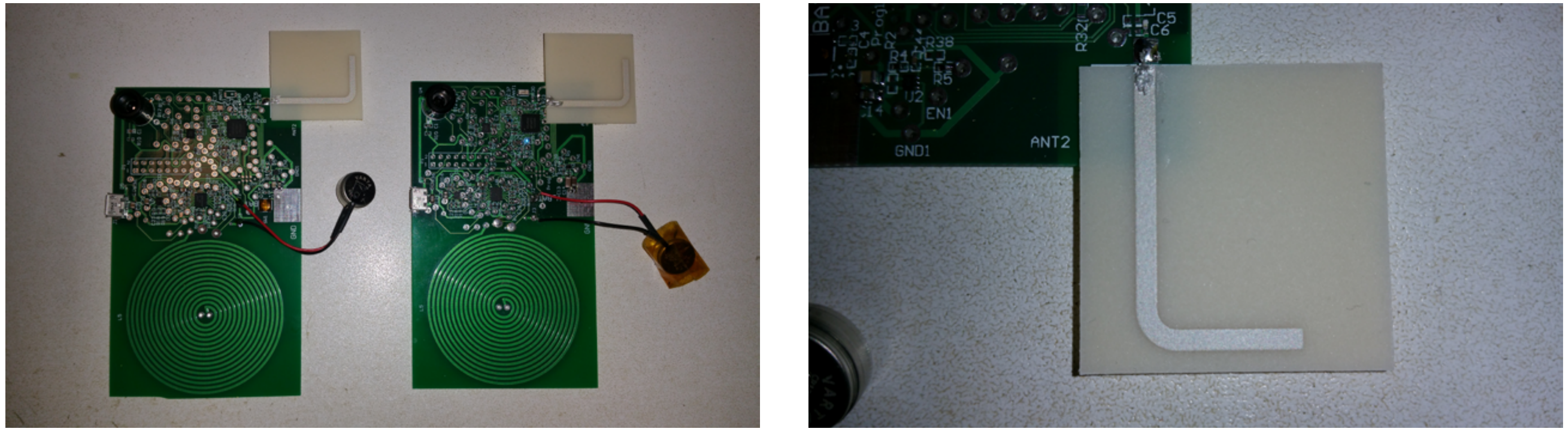


Figure 58. *Typical S-Parameter Measurement Results for a 100 mm Long Coplanar Waveguide with a 0.3 mm Gap.*

The printed antennas were glued partially on top of the FR4 electronics boards as can be seen in Figure 58. Precision antenna measurements for Demonstrator II were not performed in this project. The functionality of the ECOtronics antenna was determined in normal use scenarios and compared to FR4 and chip antennas. The antennas were not individually tuned and the tests were performed in normal indoor spaces instead of in an anechoic chamber. No quantitative analysis of the antenna performance was performed.

Advertising, connecting to the mobile terminal and measurement data transfer was successful and robust at distances greater than five meters. The ECOtronics antenna performed as well as or better than the FR4 antenna and the chip antenna. Small differences in functional antenna performance were likely due to differences in matching of the antennas to the feed.

A small Android app was developed for data readout. The app has a graphical display for the measurement results and controls starting stopping of the measurements. The collected measurement results can also be sent to cloud storage.



The antenna was glued on top of the FR4 PCB using cyanoacrylate. The electrical connection to the antenna lead was made with a copper wire and Epotek H20E epoxy

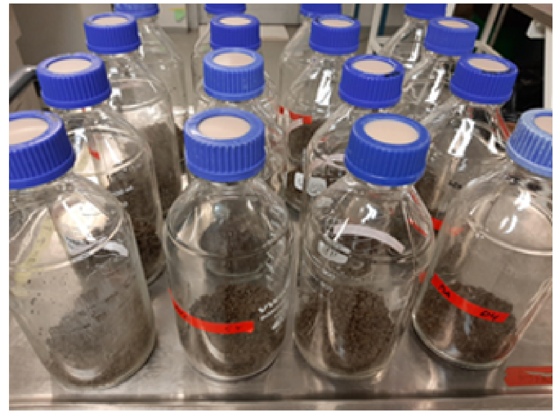
Figure 59. *Antennas Printed on biocomposite substrates glued to the FR4 PCB.*

An Android app was developed for wireless data readout. The app included graphical display for the measurement results. 6-axis inertial measurement data could be streamed to a mobile device at approximately 10 samples per second. 32 x 24 pixel 8-bit thermal IR image could be streamed to the mobile terminal at approximately 12 frames per second

Figure 60. *Android App for Data Readout on the Mobile Terminal.*

4.1.4 Biodegradability tests

Biodegradability is important in materials and products those end of life is either focused for composting or ending to nature for example in the form of environmental monitoring devices. The development of those applications started with confirmation of biodegradability of substrate materials used as base for printed device. Tested materials were veneer, board and thermoplastic biocomposite. Tests applied were biodegradation in soil and marine conditions. Biodegradation in soil was performed according to ISO 17556 by placing the sample in soil and measuring the amount of carbon dioxide evolved during the 226 day test in temperature +20°C. The test set-up and results are presented in Figure 61. The aerobic biodegradation in marine conditions were tested according to ISO 23977-1 by using sea water from the Baltic sea with added nutrients and incubating the samples in 20°C for 176 days. The results are presented in Figure 62. The results showed that compared to microcrystalline cellulose veneer, cardboard and thermoplastic biocomposite biodegraded only partly. It has been shown that lignin containing samples show reduced biodegradability in test based on complete mineralization to CO_2 (Vikman et al., 2002)[1] and this could have influenced the biodegradability results of veneer. Biocomposite showed better biodegradability in soil compared to marine environment. One reason for this could be that microbial diversity in soil environment is more optimal for cellulose-based samples compared to marine environment.



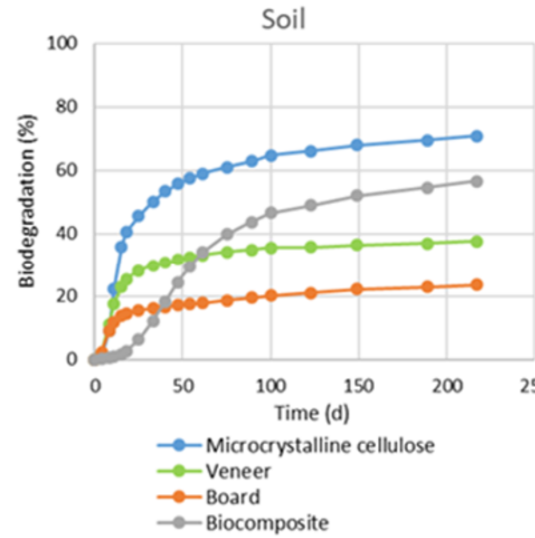


Figure 61. *Test set-up for soil biodegradation test (left picture) and test results for substrates veneer, cardboard and biocomposite with microcellulose reference (right picture).*

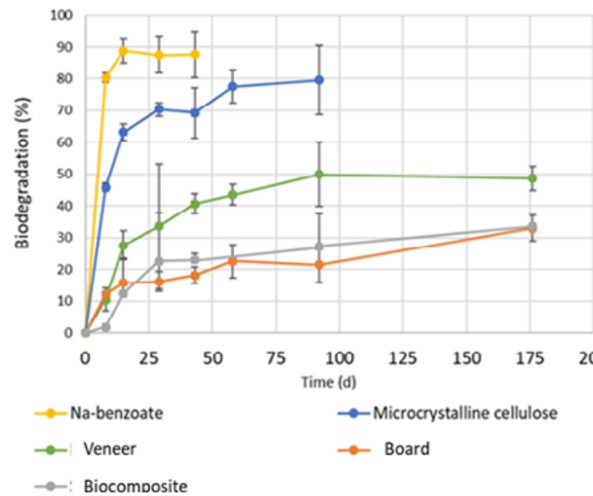


Figure 62. *Marine biodegradation test (left picture) and test results for substrates veneer, cardboard and biocomposite with microcellulose reference (right picture).*

1 Vikman, M., Karjomaa, S., Kapanen, A., Wallenius, K, Itävaara, M. (2002). The influence of lignin content and temperature on the biodegradation of lignocellulose in composting condition, Appl. Biotechnol. Microbiol. 59, 519-598

4.1.5 Life cycle assessment

The LCA for the Demonstrator II was conducted using the bill of materials for the demonstrator together with the data from ecoinvent and Gabi databases. The methodology for calculating the LCA followed that described in the study by Naji et al. (2021)[2]. The specifications of the studied demonstrator are presented in Figure 63. As can be seen, the main board is nearly 7 times larger than the antenna board. Furthermore, the main board has 4 layers. Therefore, the impact from the main board is expected to be higher than that of the antenna board. Apart from the boards, there are also electric components on the main board. In this study, almost 100 components were included in the analysis. The components studied were capacitors, ICs, LED indicators, battery, and resistors, to name some.

In this report, only the global warming potential (GWP) was included showing the potential impact on climate change. The function of the studied product system was to manufacture the demonstrator described above, while the functional unit was one finished demonstrator. The study was conducted as cradle-to-gate excluding the use and the end-of-life (EoL) phases from the analysis, yet the implications of having biodegradable or bioerodible materials in products ending up in nature were discussed. Four scenarios were studied as shown in Table 7. The main scenario (S1) represents the actual demonstrator, whereas other scenarios show hypothetical cases using different production methods and materials.

SCENARIO	MAIN BOARD	ANTENNA BOARD
S1	FR4 + etched Cu	Biocomposite + printed Ag
S2	FR4 + etched Cu	Biocomposite + printed Cu
S3	Biocomposite + etched Cu	Biocomposite + printed Cu
S4	Biocomposite + printed Cu	Biocomposite + printed Cu

Table 7. *Scenarios modelled.*

MAIN BOARD					ANTENNA BOARD				
	Material	**Value**	**Unit**	**Thickness**		**Material**	**Value**	**Unit**	**Thickness**
Substrate	FR4	6000	mm^2	1600 µm	**Substrate**	Biocomposite	900	mm^2	1600 µm
Ink	Cu (etched) (4 layers)	7441	mm^2	35 µm	**Ink**	Cu (printed)	81,4	mm^2	10 µm
	Coverage (per layer)	31	%			Coverage	9	%	
	Cu (printed)	7441	mm^2	10 µm					
	Ag (pinted)	7441	mm^2	10 µm		Ag (printed)	81,4	mm^2	10 µm
Electricity	Etching	20	kWh/m^2		**Electricity**	Printing	0,26	kWh/m^2	

Figure 63. *Specifications of the boards used in the Demonstrator II.*

2 Nassajfar, M. N. et al. (2021) 'Alternative Materials for Printed Circuit Board Production: An Environmental Perspective', Sustainability 2021, Vol. 13, Page 12126, 13(21), p. 12126. doi: 10.3390/SU132112126.

The results of the LCA study (Figure 64) showed that manufacturing one Demonstrator II has the impact of 0,49 kg CO_2-eq. The impact is equivalent to driving a small petrol-fueled passenger car of EUR-5 standard including gasoline production for almost 4 kilometers. When analyzing the baseline scenario S1, one can see that the impact was dominated with ICs and LEDs which contribute 85% of the total impact on climate change. A closer analysis of the impact of the alternative production methods and materials is possible through the results in Figure 65. The results showed that the impact of switching from silver to copper in the antenna board manufacturing reduced its impact by 28%, which however was only 1% reduction when considering both boards (S1 vs. S2). It can be concluded that on a large scale, switching from silver to copper would bring significant reduction potential to printed electronics. When FR4 was replaced with biocomposite on the main board, the impact of that board was reduced by 21% which was almost the same for the entire scenario (S2 vs. S3). Finally, when copper was printed on biocomposite instead of etching, the impact was further reduced by 43% (S3 vs. S4). All in all, the lowest impact from the manufacturing can be expected when printing copper on biocomposite. Such design would allow to reduce the impact of the Demonstrator by more than 50%.

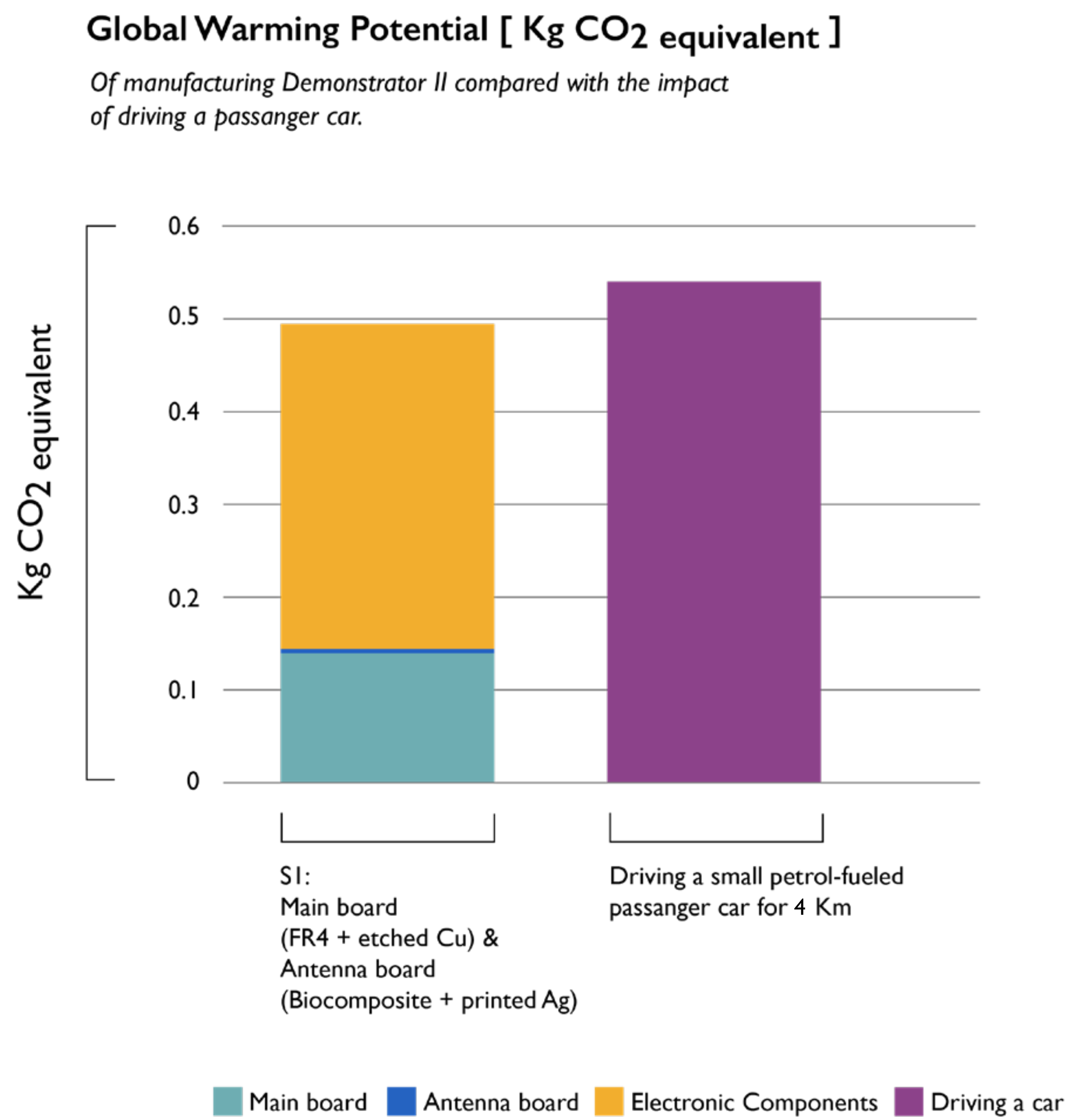


Figure 64. *GWP of manufacturing Demonstrator II compared with the impact of driving a passenger car.*

The LCA study did not include the EoL stage of the demonstrator. However, if considering that the demonstrator would be used for monitoring environmental conditions and be left in nature, no additional impact from was processing would occur, yet waste would accumulate in nature. When considering the use of biodegradable substrates, the amount of waste persistently present and accumulating in nature could be reduced significantly (see Section 4.4 Biodegradability tests). Still, the metals used in the demonstrator would further be present in nature. The deinking tests conducted with printed inks within the project showed low resistance of inks to mechanical iterations which were caused by agitating the solution. Such results can potentially mean that the printed inks would disintegrate or erode into smaller particles. Finally, considering the small mass of the device, low risk from the metals potentially released is expected.

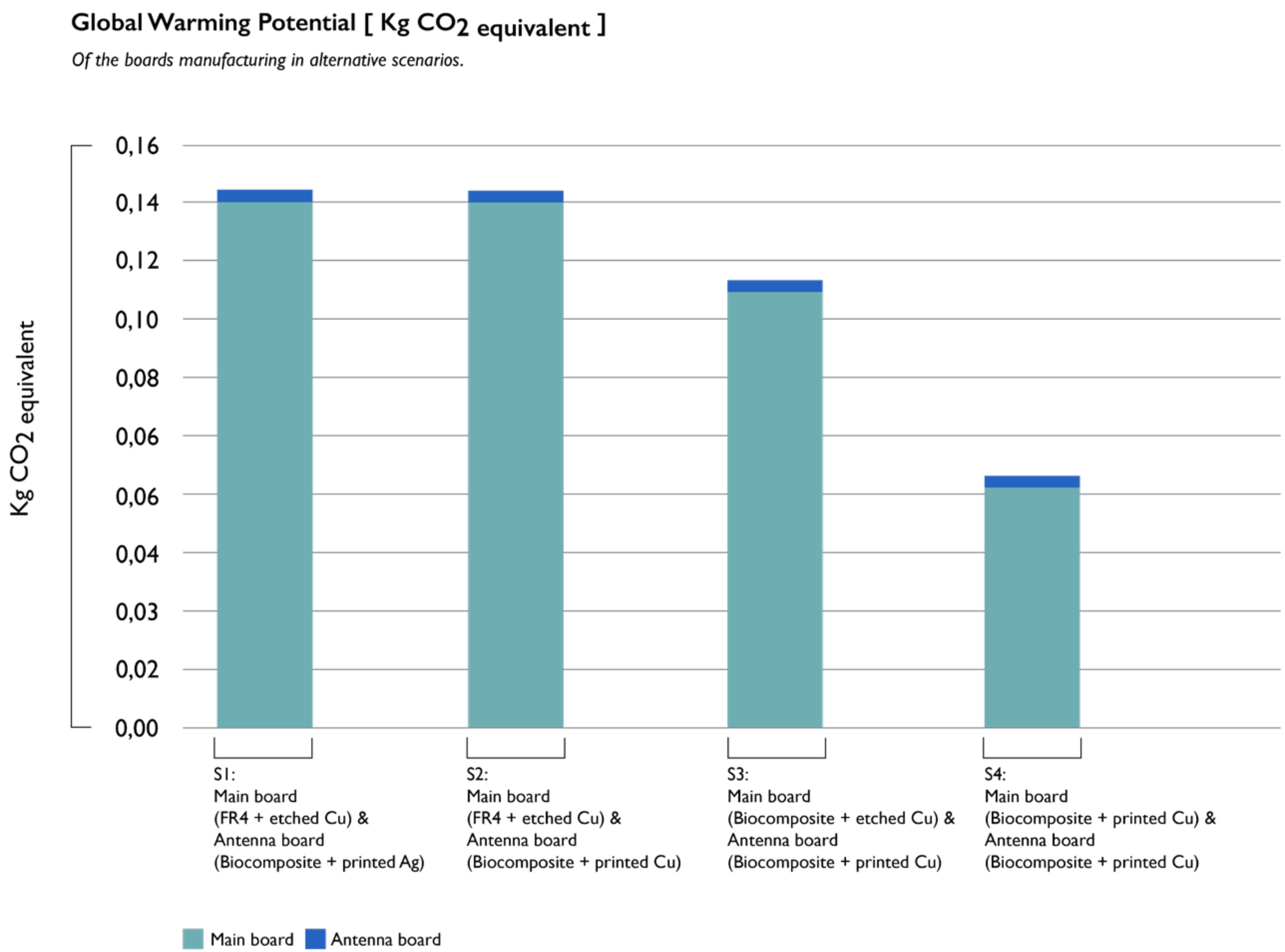


Figure 65. *GWP of the boards manufacturing in alternative scenarios.*

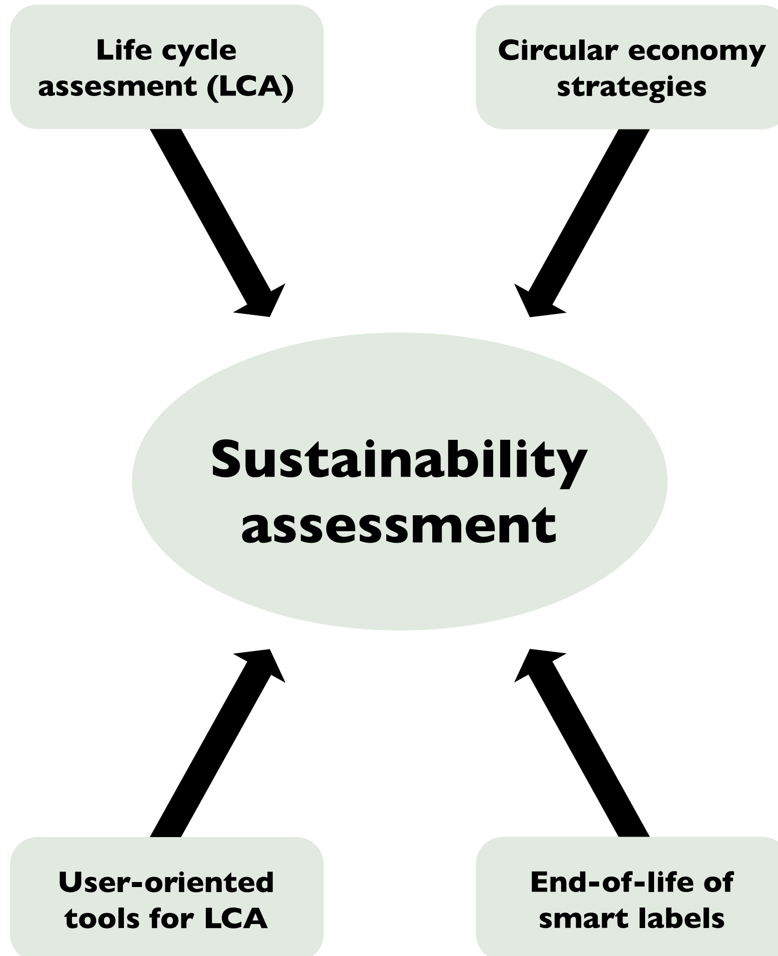
5 Tools for quantification of environmental impact

Figure 66. *Benefits for the Earth*

5.1 Introduction

The impact of electronics and optics on the environment originate at different stages. Most of the impact can already be already be estimated during the design phase when choosing between the raw materials and production methods. In this part of the project, the research focused on:

1. **Analyzing the circular economy strategies**
2. **Assessing environmental impacts**
3. **Developing user-oriented tools for impact assessment, and**
4. **Determining the pathways of smart labels in various waste streams.**



5.2 Circular economy workshops

5.2.1 Introduction

Circular economy has recently been gaining momentum with numerous legislative proposals, forums, and events taking place. The future of the European Union is now driven by the EU Green Deal[1], which is a roadmap to sustainable economies. One policy area of the Green Deal is the EU action plan for the Circular Economy[2], i.e. so-called Circular Economy Package or Action Plan. A recent report[3] by the Platform for Accelerating the Circular Economy, which is hosted by the World Economic Forum, in collaborations with the UN's E-waste coalition states the need for circular economy solutions for electronics due to their increasing amounts. The Ellen MacArthur Foundation has also published a report[4] exploring circular economy possibilities for electronics. The Finnish- Innovation Fund Sitra hosts annual World Circular Economy Forums[5] to boost implementation of circular economy principles.

However, despite all the efforts and knowledge transfer related to the circular economy, its wide implementation has not been adopted yet with the world economy being only 8,6% circular[6]. The wider implementation of the circular economy might be hindered by various factors, where the lack of measurement frameworks, legislatively binding targets, and company-level knowledge might be the most common reasons. A bundle of ISO standards is being prepared by the ISO/TC 323. Those include the standards on framework and principles for implementation of circular economy, guidelines on business models, and finally measuring circularity framework. Once legislation will adopt common principles, companies will be driven to engage in reporting their efforts towards achieving circular economy.

As of the current situation, one of the most powerful mechanisms affecting on adoption of circular economy, might be identification of the circular economy strategies suitable for companies and revealing the economic value hidden therein. According to one study[7], there were more than 100 definitions of circular economy out there. So, harmonized approach to the term of circular economy and its strategies is needed.

Circularity deck (Figure 67) is one possibility to discover and evaluate various circular economy strategies suitable for a specific product, its business model, or even an entire ecosystem. The tool is fully described in their study[8]. The tool consists of 51 circular economy strategy. The strategies are divided into 5 categories: slow, narrow, close, regenerate, and inform. Each strategy belongs to either a product level, a business model level, or an ecosystem level. The strategies are implemented as a playing deck.

Figure 67. *Circularity deck (www.circularitydeck.com)*

1 https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en
2 https://ec.europa.eu/environment/strategy/circular-economy-action-plan_en
3 https://pacecircular.org/sites/default/files/2019-03/New+Vision+for+Electronics-+Final%20(1).pdf
4 https://ellenmacarthurfoundation.org/circular-consumer-electronics-an-initial-exploration
5 https://www.sitra.fi/en/projects/wcef/
6 https://www.circularity-gap.world/2021
7 https://www.sciencedirect.com/science/article/pii/S0921344917302835
8 https://www.mdpi.com/2071-1050/12/1/417

5.2.2 Workshops

During the project, six workshops were arranged with participating companies to ideate on their possibilities to implement circular economy strategies for some of their products using the circularity deck. The workshops were held online for each company individually. The workshops were led by Green Company Effect. At first, the participants were introduced to the concept of circular economy. Then, the circularity deck was introduced along with the rules of the workshops. When discussing each strategy, they were assigned to one of the following categories:

"Implemented": the group of strategies currently implemented by the company for a specific product,

"To be implemented": the group of strategies planed for implementation in the future, or

"Not relevant": the group of strategies which are not seen applicable to a specific product, its business model, or ecosystem.

The results were then analyzed as average values for all companies in the project (Figure 68).

The results indicated that circular economy was implemented by the companies in 25% of the cases. In there, the largest contribution was due to the "Narrow" category meaning more lightweight products, enabling fewer consumption, and localized supply, among other categories.

In 36% of the cases, companies were seeking to implement circular economy strategies. The biggest interest was for closing the loops, i.e. using recycled materials, as well as ensuring recycling of their products at the end-of-life. Finally, a large share of strategies was seen inapplicable to the companies representing electronics sector. Those strategies were from the categories "Inform", and "Regenerate". The "Inform" category represent the use of data, such as the use of artificial intelligence. In this case, the electronics sector might actually be seen as an enabler of such strategies. Finally, the strategies from the "Regenerate" category which were seen irrelevant are the recovery of nutrients and managing the critical ecosystem services. Still, the out of the regenerating category, such strategies as designing with self-charging services and non-toxic materials.

The circular economy workshops were widely seen by participating companies as eye-opening events shedding light on the plethora of existing strategies. Academically, the work done helped to identify the research focus for the future through the strategies which are sought by industrial players.

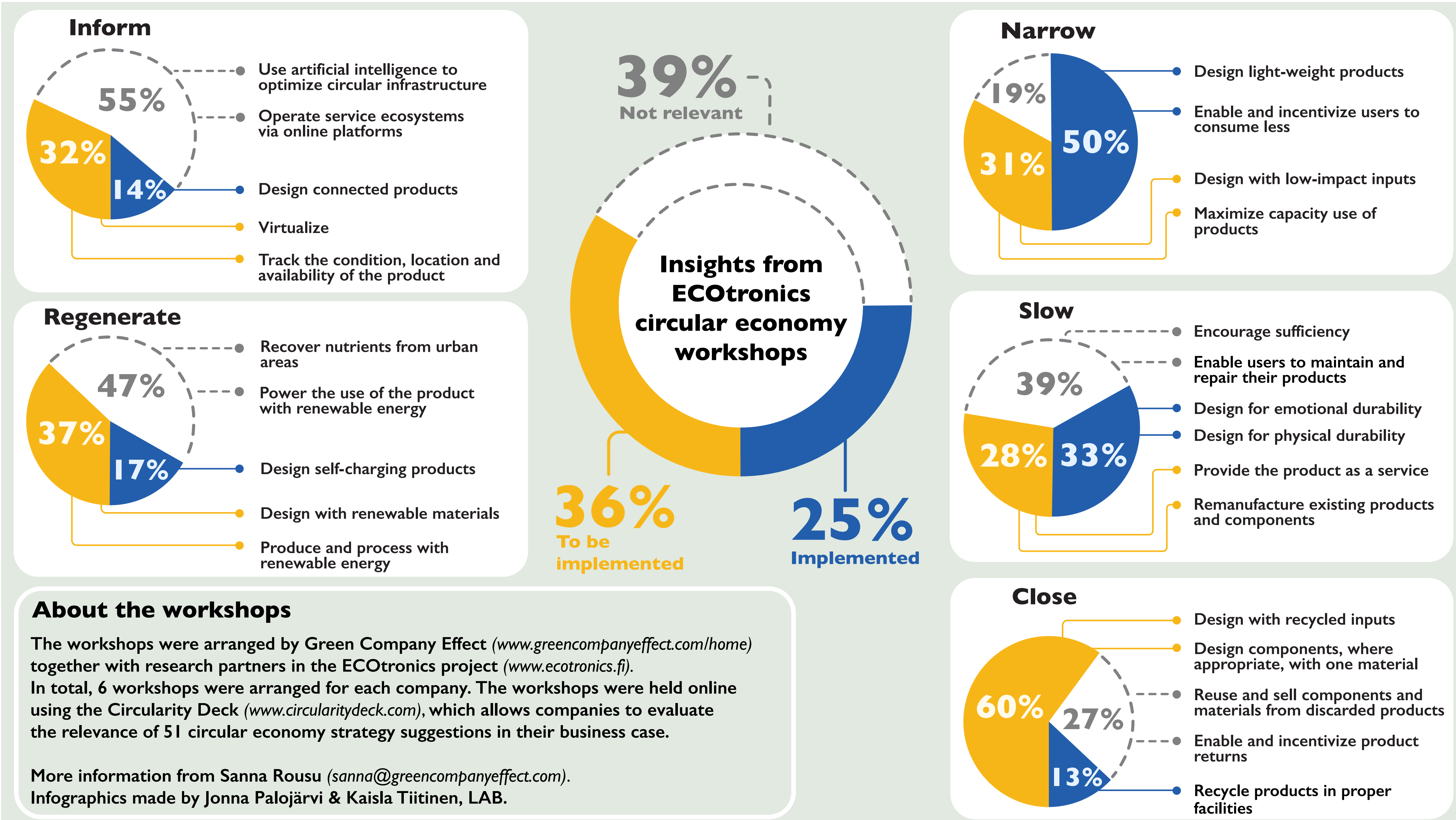


Figure 68. *Results of CE workshops.*

5.3 Life cycle assessment studies

In the project, several life cycle assessment (LCA) studies were conducted to better understand the impacts of the electronic products on the environment which could occur during the changes in the substrate materials or production methods studied in the project. The studies were conducted using SULCA or GaBi software and ecoinvent as a primary source of secondary data. Each case study was developed independently together with collaborating companies. In this chapter, only the cases developed for products are reported while the LCA studies of the demonstrators are presented along their description.

5.3.1 Introduction to LCA

LCA is a standardized methodology of assessing potential environmental impacts of products and services along their entire life cycle from cradle – extraction of raw materials – until cradle – disposal of the products. LCA studies were conducted following ISO 14040 and ISO 14044 standards as a basis, but not entirely complying to it, especially in terms of critical review. The review was, however, conducted for the studies published in academic literature. Further deviations from the standards were due to a research-oriented approach of these studies giving a rather indicative measure of the studies impacts.

LCA studies have four stages which are not strictly consecutive owing to an iterative approach of the methodology expressed in the ISO standards:

- **Goal and scope definition** – a stage when the studied product is decided, as well as the studies system boundaries,
- **Life cycle inventory analysis** – a stage when all the inventory data on the product manufacturing and impact occurring elsewhere in the product life cycle is being compiled,
- **Life cycle impact assessment** – a stage when the data from the LCI stage is being converted into the different impacts on the environment, such as climate change, and
- **Life cycle interpretation** a stage when the results are analyzed again the goal of the study and conclusions are drawn.

SCENARIO	SUBSTRATE	CONDUCTIVE MATERIAL
S1	FR4	Etched copper
S2	FR4	Ag NPs
S3	PET	Ag NPs
S4	PLA60%-GF40%	Ag NPs
S5	Paper	Ag NPs

Table 8. *Scenarios of the PCB case.*

5.3.2 Printed circuit boards (PCB)

In this study, printed circuit boards (PCBs) were analyzed. The goal of the study was to assess and compare the environmental impacts of alternative production methods and materials used for PCB manufacturing. Table 8 shows the alternative scenarios studied. The functional unit was set to $1 m^2$ of 4-layer PCB. Figure 69 illustrates the system boundaries of the PCB case.

The main findings from the study (Figure 71) showed that the conventional PCB manufacturing using FR4 as a substrate material and etched copper as a conductive material (S1) has the highest environmental impact compared to other four alternative scenarios (S2-S5). The global warming potential (GWP) of 1 m^2 of a conventional PCB was 34.8 kg $CO_{2\text{-eq}}$.

Changing from subtractive manufacturing (etching) to additive manufacturing (printing) has the potential to reduce environmental impacts by more than 50% across all impact categories.

When also changing the substrate from FR4 to PET, PLA/GF, or paper, the impact reduction could be further decreased down by 80% compared to the baseline scenario (S1). Therefore, both the production method of the conductive material, as well as the substrates, have a high potential for reducing the environmental impacts of PCBs.

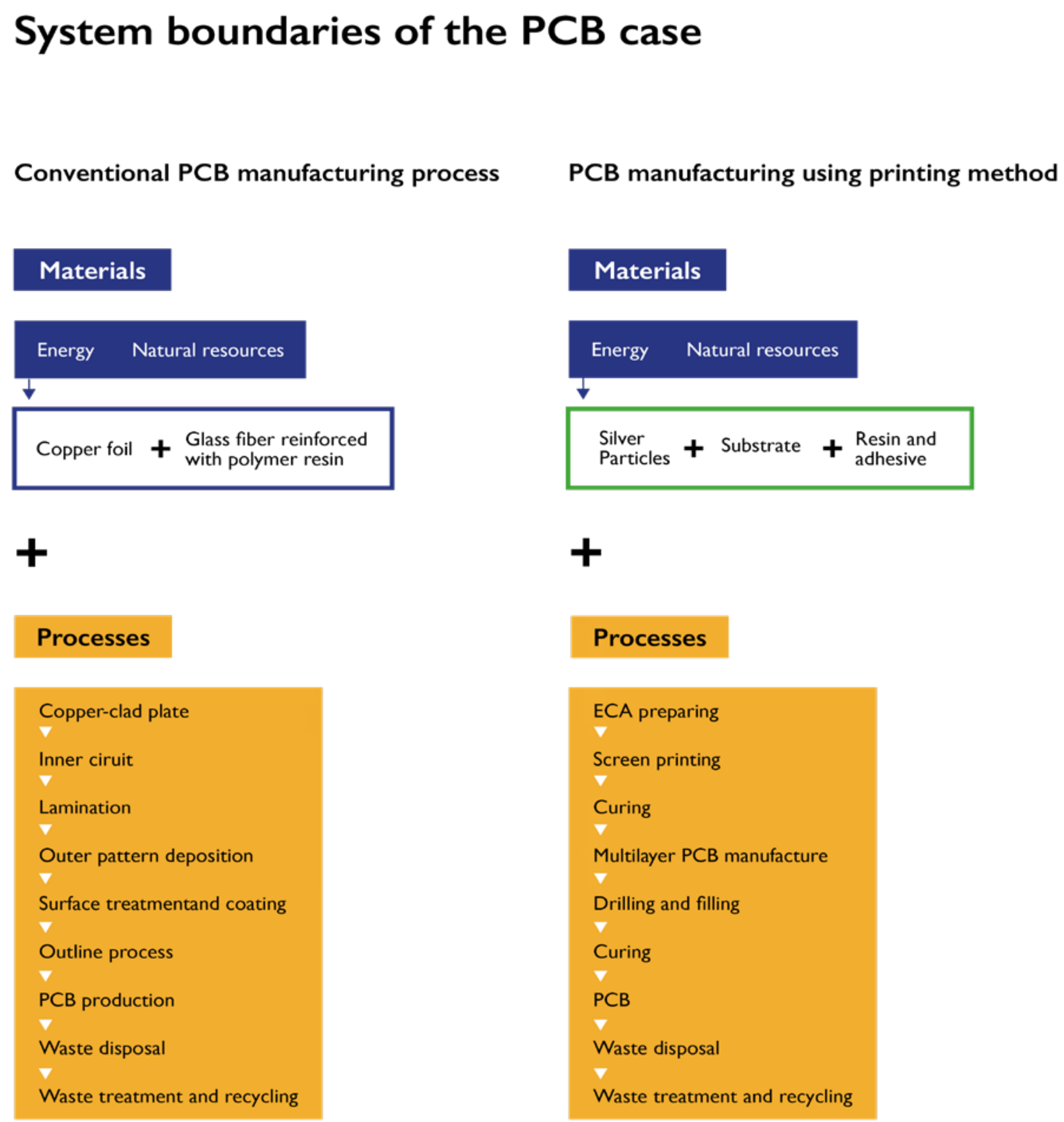
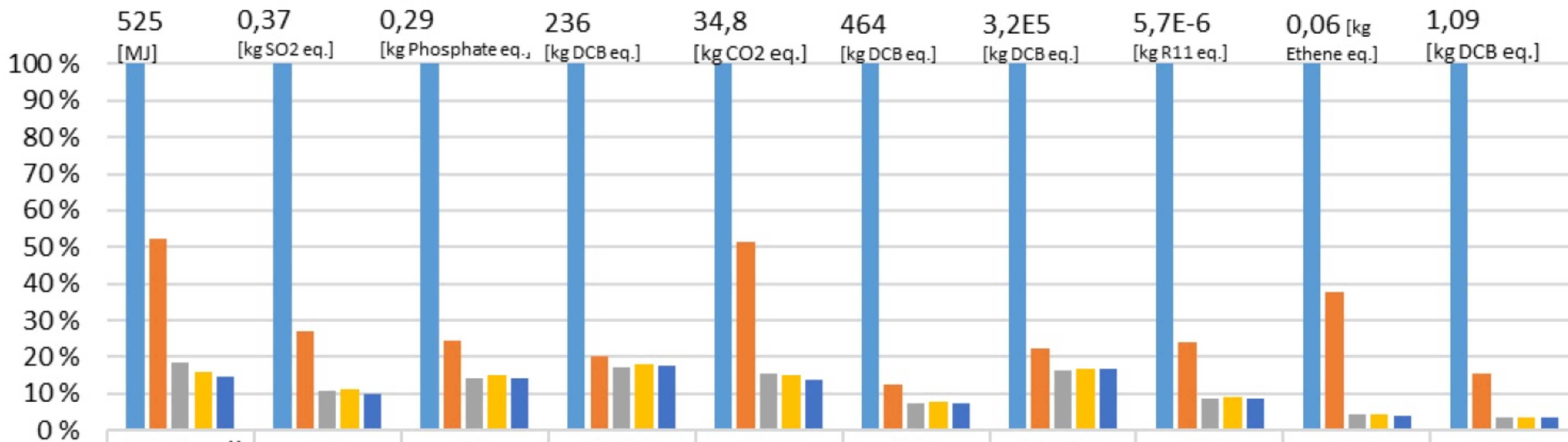


Figure 69. *System boundaries of the PCB case.*



	ADP Fossil	AP	EP	FAETP	GWP	HTP	MAETP	ODP	POCP	TETP
S1	100 %	100 %	100 %	100 %	100 %	100 %	100 %	100 %	100 %	100 %
S2	52 %	27 %	24 %	20 %	51 %	12 %	22 %	24 %	38 %	15 %
S3	18 %	11 %	14 %	17 %	15 %	8 %	16 %	9 %	5 %	4 %
S4	16 %	11 %	15 %	18 %	15 %	8 %	17 %	9 %	5 %	3 %
S5	14 %	10 %	14 %	18 %	14 %	7 %	17 %	9 %	4 %	3 %

Figure 70. *Results of the PCB case.*

5.3.3 Shielded flat flexible cables (SFFC)

Another study focused on shielded flat flexible cables (SFFCs) which are shown in Figure 71. The goal of the LCA study was to assess its environmental performance and to compare it with a comparator cable. In addition, the impact of varying the metals used in the SFFCs was analysed. The functional unit was set to 1 m of cables. The study set its scope to cradle-to-gate excluding the impacts from the end-of-life of the cables. Table 9 lists the studies scenarios.

The results comparing the studied cable and its comparator case are shown in Figure 72. As can be seen, the standard sable – SFFC with silver – has the highest impact compared to all other alternatives. The largest contribution was from the silver paste production used as a conductive material. When silver was replaced with copper, the impacts were reduced dramatically to below those of a reference cable.

SFFCs have a much lower mass, i.e. 8,75 g per one meter, compared to a conventional copper cable weighting 90 g per meter. The mass reduction potentially enables reduction of environmental impacts elsewhere in the value chain. In order to assess the potential impact of this, the climate impacts of a case where cables were used in a passenger vehicle throughout its lifetime of 250 000 km were analysed.

It was identified that the length of cables in a single car is 780 m. The results (Figure 73) indicated that impacts are considerably reduced even for a basic case of SFFC using silver. Yet, the results should be read with caution since the assessed mass reduction in the car weight is marginal, and the anticipated emission reductions are therefore uncertain.

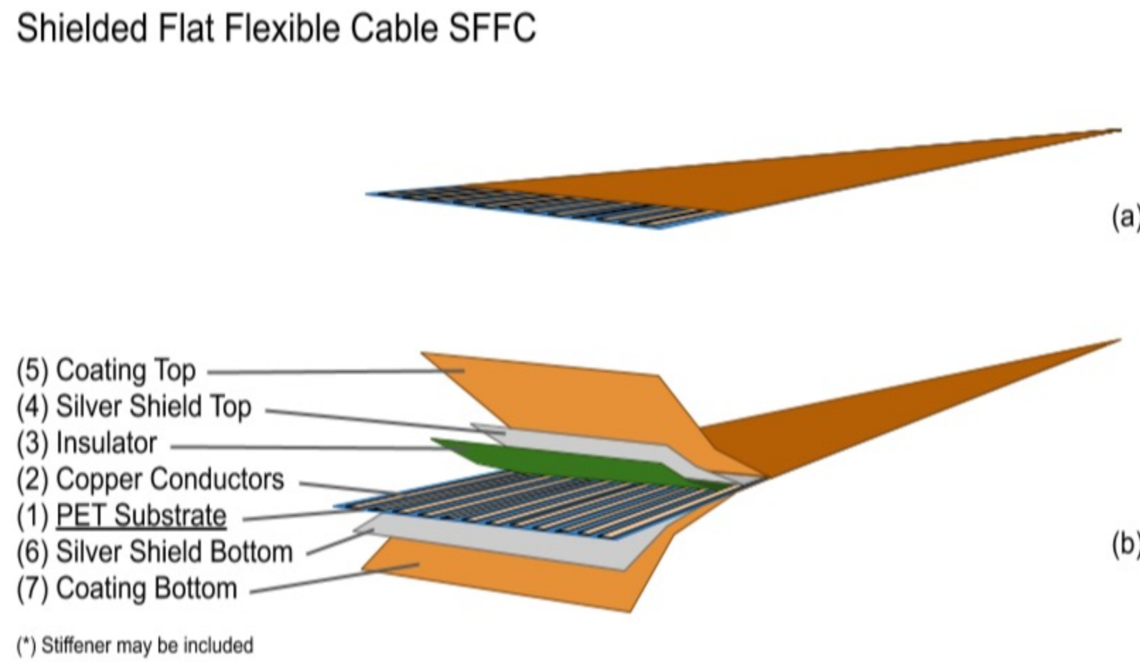


Figure 71. *Illustration of a studies shielded flat flexible calbe.*

SCENARIO	STUDIED PRODUCT
Standard cable	SFFC
Copper+	SFFC where silver is replaced with copper
Comparator cable	LAPP 16 core cable

Table 9. *Scenarios of the SFFC case.*

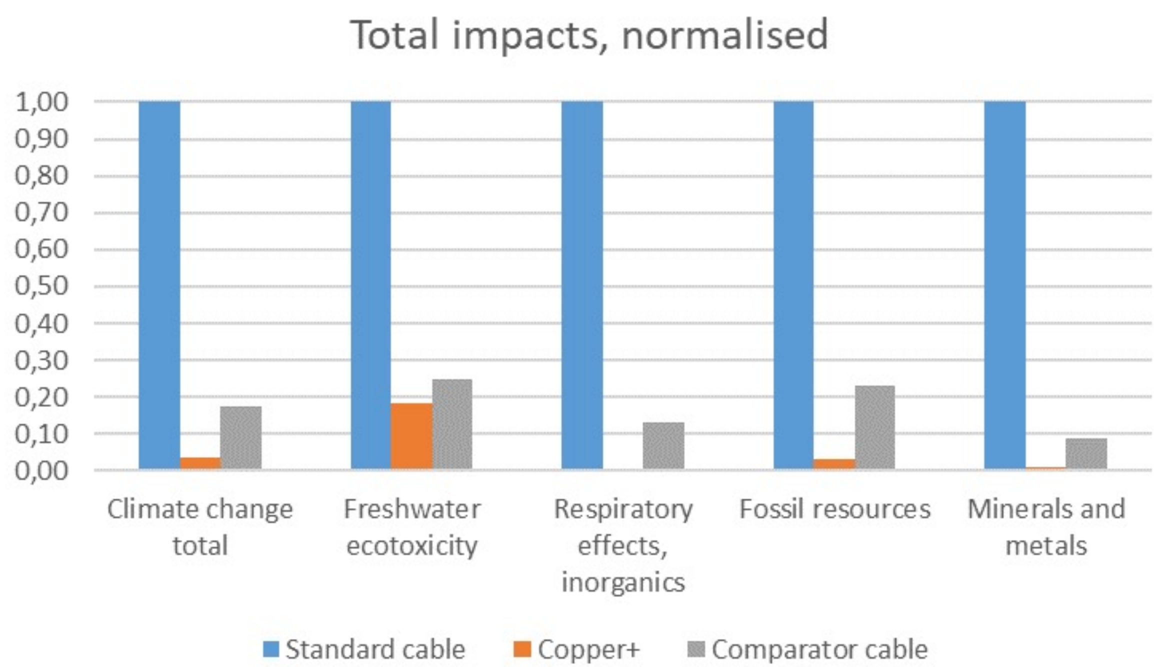


Figure 72. Results of the SFFC case.

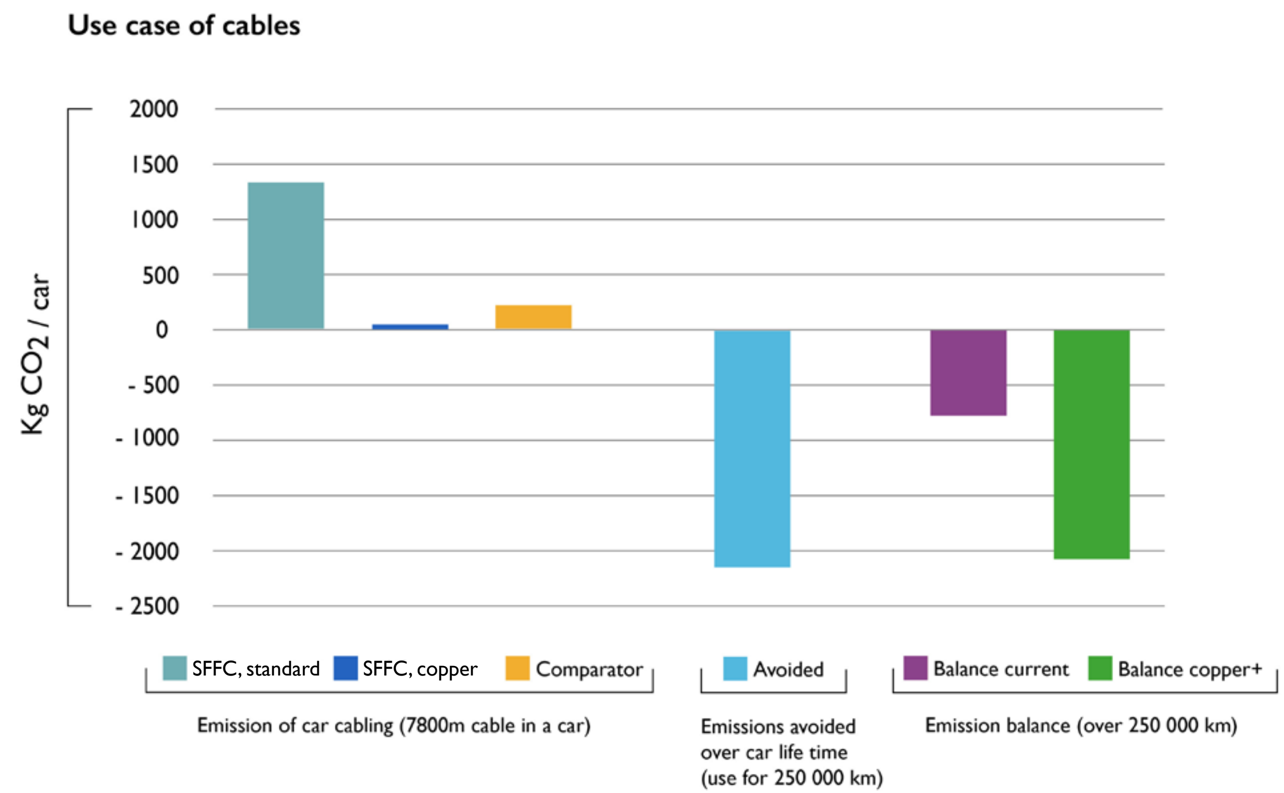


Figure 73. Use case of cables.

5.3.4 Radio-frequency identification (RIFD) tag

In this study, radio-frequency identification (RFID) tags were studied. The goal of the study was the assess the environmental impacts of RFID tags production and to compare the impacts with those originating from the use phase of the tags. In the assessment, 1000 RFID tags were used as a functional unit. The study was scoped as cradle-to-gate for the production, as well as the use phase. The tags were made of paper substrate placed on silicone liner, etched antenna, adhesive, and naked IC chip. The study is missing data on electricity consumption from the tags manufacturing due to its unavailability.

The study indicated that the carbon footprint of a single RFID tag is around 30 g CO2-eq. (Figure 74), yet caution should be given to this number accounting for the lack of information on the electricity consumption and its impacts. 60% of the impact originated from the antenna manicuring. When switching from the etching method of antenna manufacturing to its printing a smaller impact on climate change of 17 kg CO2-eq. could be achieved. The impacts on other categories are reduced alike when switching form one production method to another (data not shown).

Since RFID tags are used to achieve a valuable function elsewhere, the impact from the use phase are important for the product. In this study, the use of RFID tags in a hypothetical case of logistics was analyzed.

Two scenarios were compared:

Scenario 1. Delivery of 1000 parcels, 20 kg each, to customers over 500 km distance without RFID tags with 5% of the parcels sent to a wrong recipient which were then delivered back and again to the right customers, and

Scenario 2. Delivery of 1000 parcels, 20 kg each, to customers over 500 km having RFID tags on each parcel, thus avoiding any mis-shipment.

The results (Figure 75) showed that the impact of tags production compared to the impact of logistical operations is relatively small. Furthermore, it is lower than the impact of additional logistics due to the mis-shipped parcels. Sensitivity analysis of three parameters showed the breakeven points at which the use of RFID tags is justified:

- at mis-shipping rates above 2%,
- for parcels weighting more than 8 kg,
- when delivering for over 200 km.

The results of the study clearly indicated that the extra impact from producing the RFID tags can be compensated by the avoided impacts during its intended use, thus giving this product a clear handprint.

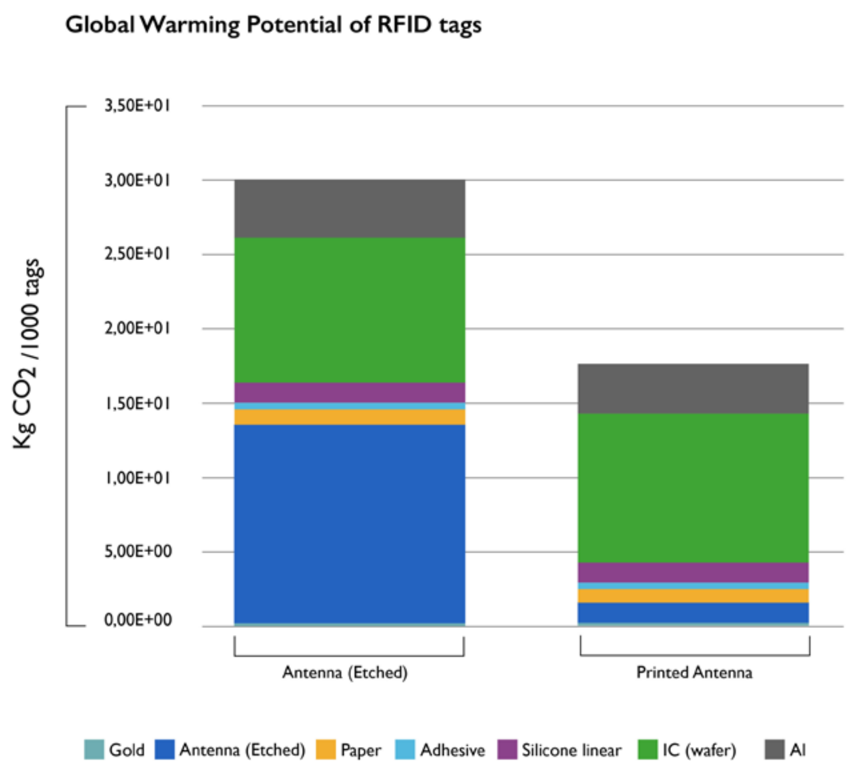


Figure 74. *Global warming potential of RFID tags.*

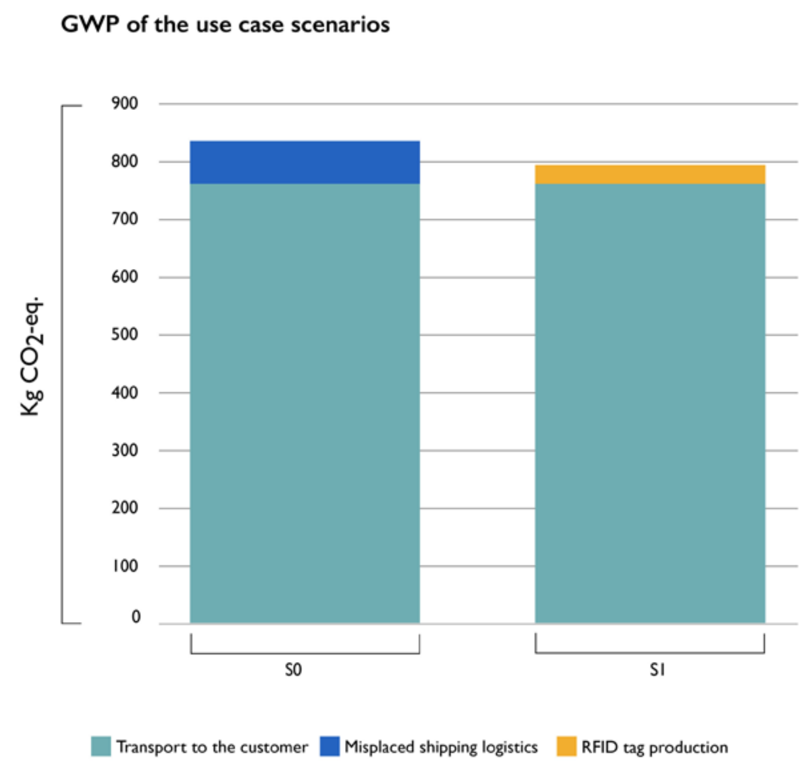


Figure 75. *Impact from the use phase of RFID tags.*

5.3.5 Mobile devices

In this study, GE Healthcare's product under development (hereafter called Product 1) was compared to an alternative product from a competitor (hereafter called Product 2). In addition, an estimation of the carbon footprint and cumulative energy demand of GE Healthcare's disposable sensor, presently on the market, with a 6 m copper cable was made (hereafter called Product 3). Functional unit of the analysis were 100 products. It was assumed that the cable in Product 3 can be used for one year, thereby covering the use of 100 disposable products.

Since no information was available on the energy and other inputs needed in the manufacturing phase, the study focused on analyzing impacts resulting from raw material production and waste management (recycling, incineration/energy recovery, disposal). Four environmental impact classes were considered: Climate change, respiratory effects, eutrophication (both freshwater and marine water) and abiotic resource depletion (materials and fossil fuels separately). Impact assessment methods were based on EU and IPCC (CO2 equivalents) recommendations.

The results showed that Product 1 had about 30% lower carbon footprint than Product 2 (Figure 76). This difference mainly stems from differences in the PCBs, batteries and the cable in Product 2. However, comparison to Product 3 showed that its carbon footprint is only about 20% of that of Product 1.

For products 1 and 2, other environmental impacts were also calculated. For both products, batteries have fairly high contribution to the total environmental impacts (Figure 77). The role of pouch is quite large for Product 1 as well, due to the aluminium used as a raw material. Also PCB production has a large share of the total environmental impacts in the case of Product 1. On the other hand, for Product 2, the contribution of cable is important, particularly for respiratory inorganics and marine eutrophication due to NO_x emissions.

The results indicate that product under development with a smaller weight, incl. smaller batteries and no cable can achieve lower carbon footprint in comparison to mobile devices presently on the market. However, its carbon footprint and cumulative energy demand were considerably higher than those of the Product 3. This primarily resulted from the batteries needed in Product 1 and its larger PCB.

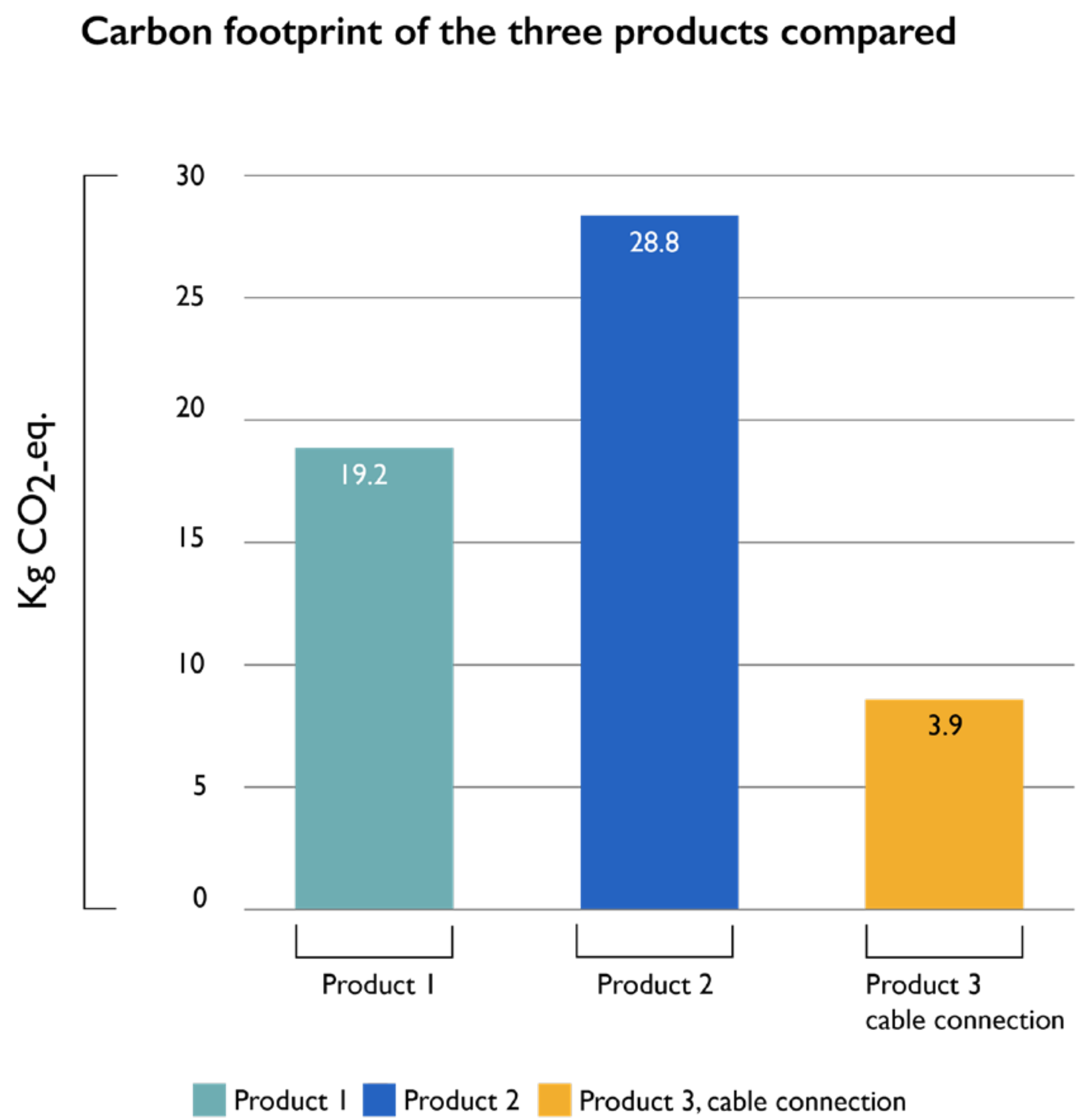


__Figure 76.__ Carbon footprint of the three products compared

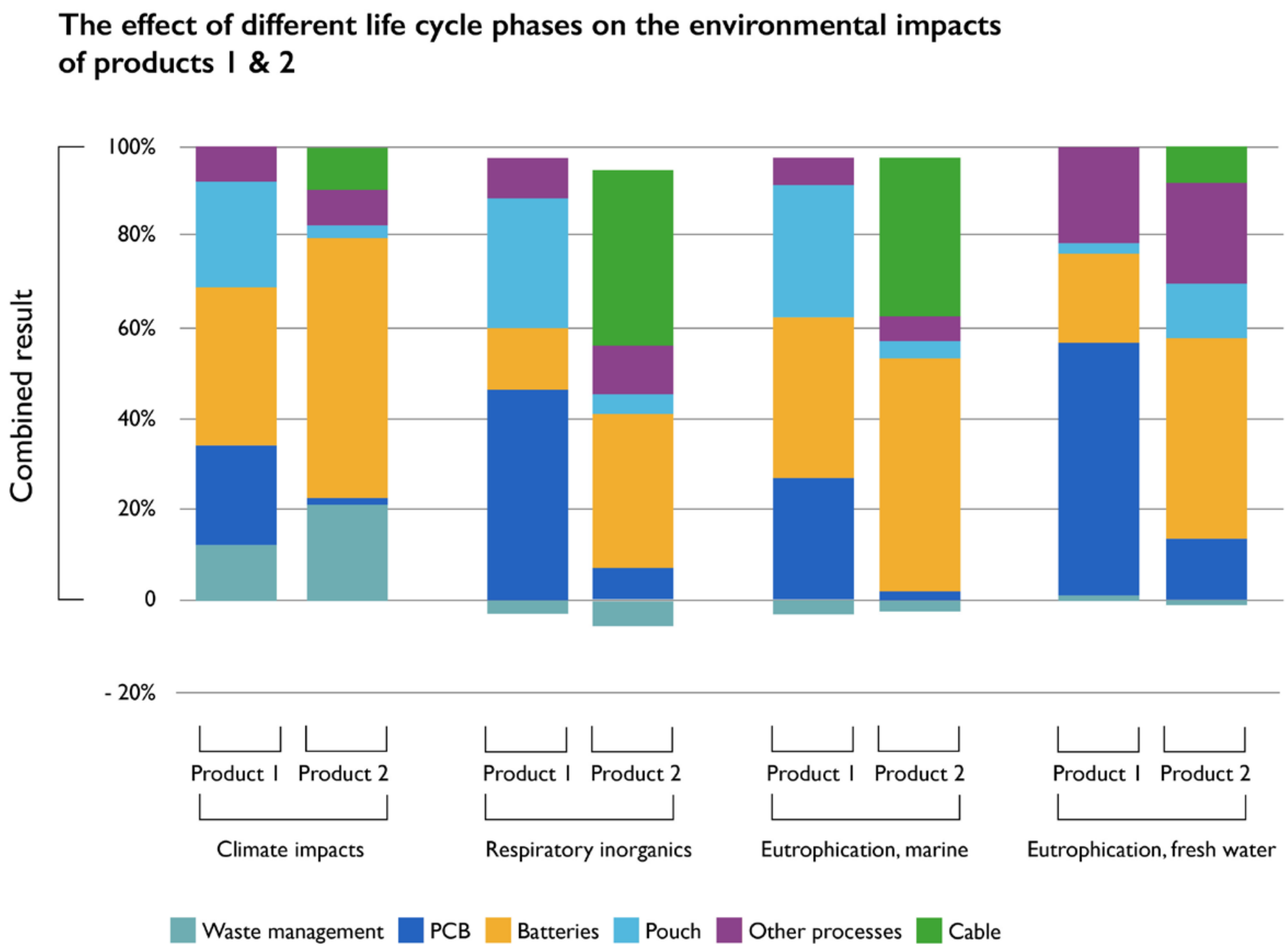


Figure 77. *The impact of different life cycle phasesto the environmental impacts of products 1 and 2.*

5.3.6 Conclusions from LCA

The findings of the LCA studies helped to better understand the environmental impacts of various types of electronics within their core processes, as well as along the upstream and downstream values chains. In all cases, the production of electronics with alternative bio-based substrates or using advanced production methods showed smaller impacts than the currently available products if looking at the overall life cycle. In the case of PCB, the substrates themselves had lower impacts, whereas in the case of SFFCs and RFID tags, the avoided impact was associated with the avoided burden in the use phase.

5.4 Excel-based tools for streamlined LCA

Considering the research-based nature of this project, high uncertainty and variability is expected in the developed materials and products. Therefore, a single-value LCA result might not always represent the changes done to the product structure. For this reason, two Excel-based tools for streamlined LCA analysis were developed in the study: one for the PCB case and one for the SFFC case. Both tools include aggregated data from the ecoinvent database for the materials, energy, and processes included. The tools allow the users to modify the values and estimate the environmental impacts.

5.4.1 Tool for PCB

The PCB tool (Figure 76) allows the user to specify the type of the PCB studied using the following parameters: substrate material (paper, PLA+GF, FR4, PET) and its mass, conductive ink (copper etched, silver and aluminum printed) and their mass, mass of adhesive and resin, number of layers of PCB, surface area of ink and its thickness, present of IC on PCB, electricity consumption in production and recycling rate at the end-of-life. The tool also has default values which were used in the scientific article by Nassajfar *et al.* (2021). The results are then calculated for several impact categories and are visualized as comparative values for several scenarios and then as contribution values from specific components of life cycles of the PCB.

5.4.2 Tool on SFFC

Similarly to the PCB tool, the SFFC tool (Figure 77) allows the user to modify several parameters, such as width and length of the studied cables, select the substrate material (fossil PET, bio-based PET or Durabio), as well as the metal used (silver or copper), and thickness of all materials used. The results are then calculated for five impact categories including climate change and compared with the baseline traditionally used cable.

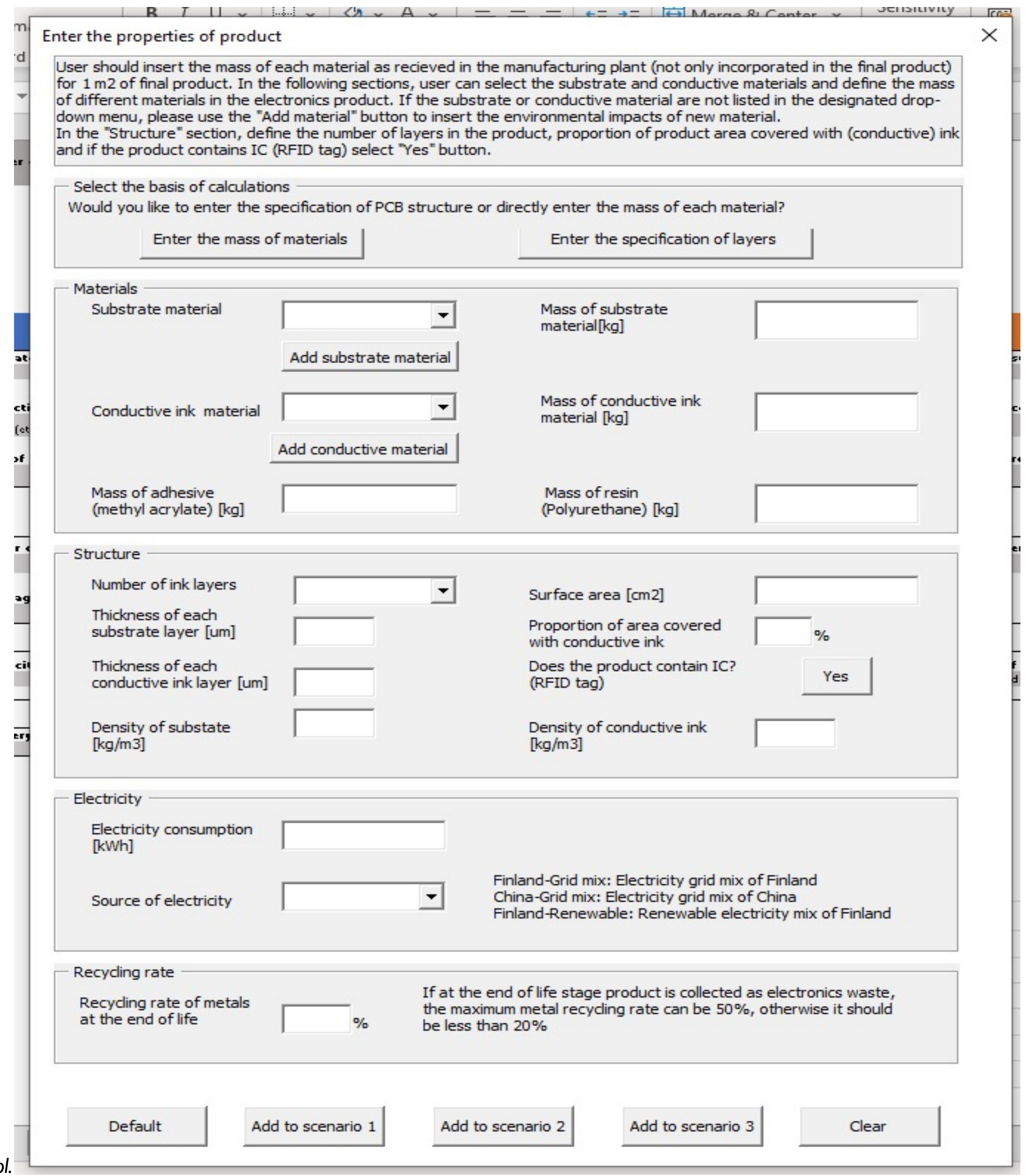


Figure 78. *Screenshot of the input window of the PCB tool.*

Tool to assess the environmental impacts of SFFCs

User guide:
Value can be modified
Select material from a list
Do not modify value

Cable specifications		
Width of the cable	16,8	mm
Lenght of the cable	1000	mm

Selection of materials		Parameters				Relative impacts				
		Thickness	Density	Volume	Mass	Climate change total	Freshwater ecotoxicity	Respiratory effects, inorganics	Fossil resources	Minerals and metals
Layer	Material	µm	g/cm3	cm3	g	kgCO2-eq/kg	CTU/kg	kgNMVOC-eq/kg	MJ/kg	kgSb-eq/kg
1	Fossil PET substrate	50	1,38	0,84	1,16	3,30	5,00	0,01	69,00	0,00
2	Copper Conductors	35	8,96	0,588	5,27	4,81	104,91	0,00	60,54	0,00
3	Insulator: DuPont 5018	22,5	1,28	0,378	0,48	2,60	1,00	0,00	60,55	0,00
4 & 6	Copper+	35	8,96	0,588	5,27	5,73	75,30	0,07	74,16	0,00
5 & 7	Coating Top & Bottom: Peters 2490/201	35	1,1	0,588	0,65	5,57	3,90	0,02	98,98	0,00
					12,83					

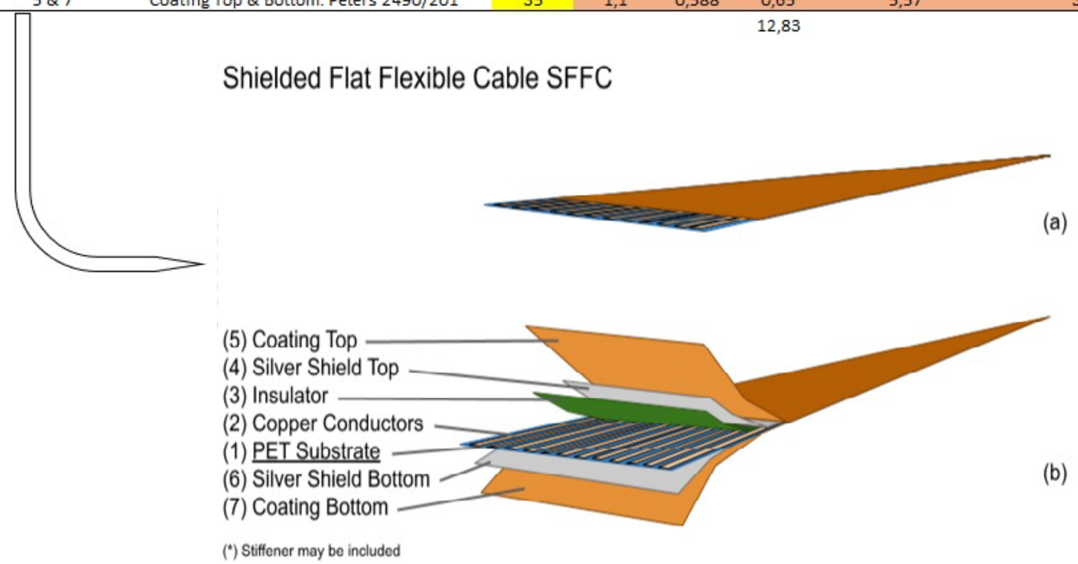


Figure 79. *Screenshot of the SFFC tool.*

5.5 End-of-life of smart electronics

In Finland, there is a system for waste electric and electronic equipment (WEEE) collection and recycling. However, smart and printed electronics differ from the electronics in their general perception by the way they are utilized. Smart electronics, unlike electronic devices, are meant to be used as a part of other products, e.g. packaging.

In such a way, smart electronics are likely to follow the waste management routes of the products they are attached to, which makes their recycling more challenging.

In this part of the project, the work focused on analyzing the pathways of smart electronics through the recycling chains of packaging waste. The results are, however, reported in Demo 1 where an example of such electronics was developed.

6 Dissemination activities

Figure 80. *ECOtronics exhibition at LAB university of Applied Sciences*

ECOtronics project carried out different types of dissemination activities including press releases, website and visual identity, social media appearance, conference presentations and papers, scientific papers, participation to exhibitions and fairs, and implementation of questionnaire and webinar targeted for external stakeholders.

The ECOtronics website at www.ecotronics.fi contained basic project information, but also dynamic information in the form of regular updates to research blog section.

Selected highlights of dissemination efforts include:

- **Press release** 28.11.2019 about project initiation: Electronics developers start extensive co-operation to advance circular economy, https://www.vttresearch.com/en/news-and-ideas/electronics-developers-start-extensive-co-operation-advance-circular-economy and 26.1.2022 about project completion: Sustainable electronics reduce environmental load and enable new applications, https://www.vttresearch.com/en/news-and-ideas/sustainable-electronics-reduce-environmental-load-and-enable-new-applications
- **Conference paper:** Laura Sokka, Jari Keskinen, Marja Välimäki. Life Cycle Impact Assessment (LCIA) of Resource Consumption: Comparing Impacts of Supercapacitors and Li-Ion Batteries, 4th South East European Conference on Sustainable Development of Energy, Water and Environment Systems, SDEWES 2020 - Online, Sarajevo, Bosnia and Herzegovina, 28.6.-2.7.2020.
- **Conference paper:** Hakola, L., Immonen, K., Sokka, L., Välimäki, M., Smolander, M., Mäntysalo, M., Tanninen, P., Lyytikäinen, J., Leminen, V., Naji Nassajfar, M., Horttanainen, M. & Venetjoki, P. Sustainable materials and processes for electronics, photonics and diagnostics, Proceedings of the Electronics Goes Green 2020+. Stuttgart: Fraunhofer Verlag, p. 45-52, 1.9.2020.
- **Conference presentation:** Liisa Hakola. Sustainable solutions for electronics, photonics and diagnostics, E-Waste World Virtual Summit, 18.-19.11.2020, Frankfurt, Germany, Online.
- **Conference paper:** Antti Vasara, Liisa Hakola, Marja Välimäki, Marja Vilkman, Hannes Orelma, Kirsi Immonen, Katariina Torvinen, Jukka Hast, Maria Smolander. Beyond Flexible Towards Sustainable Electronics. Proceedings of SID Display Week 2021, 16.-21.5.2021, USA/online. 4 p.
- **Conference paper:** Panu Tanninen, Sami Matthews, Ville Leminen, Juha Varis. Analysis of paperboard creasing properties with a novel device, Proceedings of the 30th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2021) & Procedia Manufacturing journal, 2021.
- **Scientific paper:** Mohammad Naji Nassajfar, Ivan Deviatkin, Ville Leminen, Mika Horttanainen. Alternative Materials for Printed Circuit Board Production: An Environmental Perspective. Sustainability 2021, 13(21), 12126; https://doi.org/10.3390/su132112126
- **Master's thesis:** Tommi Kohtaniemi, MECHANICAL MODIFICATION OF PACKAGING MATERIAL STRUCTURES, Lappeenrannan–Lahden teknillinen yliopisto LUT, Mechanical Engineering, 2021, 69 pages.
- **LOPEC trade fair,** 23.-25.3.2021, Messe München, online: VTT boot with sustainability as one of the 3 highlighted topics, www.lopec.com
- **Article:** Kirsi Immonen, Johanna Lyytikäinen, Janne Keränen, Kim Eiroma, Mika Suhonen, Minna Vikman, Ville Leminen, Marja Välimäki, and Liisa Hakola. 2022. Potential of Commercial Wood-Based Materials as PCB Substrate Materials, 2022, 15, no. 7: 2679. https://doi.org/10.3390/ma15072679
- **Article:** Elina Jansson, Johanna Lyytikäinen, Panu Tanninen, Kim Eiroma, Ville Leminen, Kirsi Immonen, Liisa Hakola. Suitability of Paper-Based Substrates for Printed Electronics. Materials 2022, 15, 957. https://doi.org/10.3390/ma15030957
- **Award:** Smart Label as 'Best Publicly Funded Project Demonstrator' in OE-A Competition 2022

To gather up opinions of external industrial stakeholders ECOtronics organized an online questionnaire that was open during 15.4.-31.5.2020. A total of 21 responses from 17 individual companies were received from Finnish and international companies. The summary of participants and their plans towards sustainable solutions are presented in Figures 81 and 82.

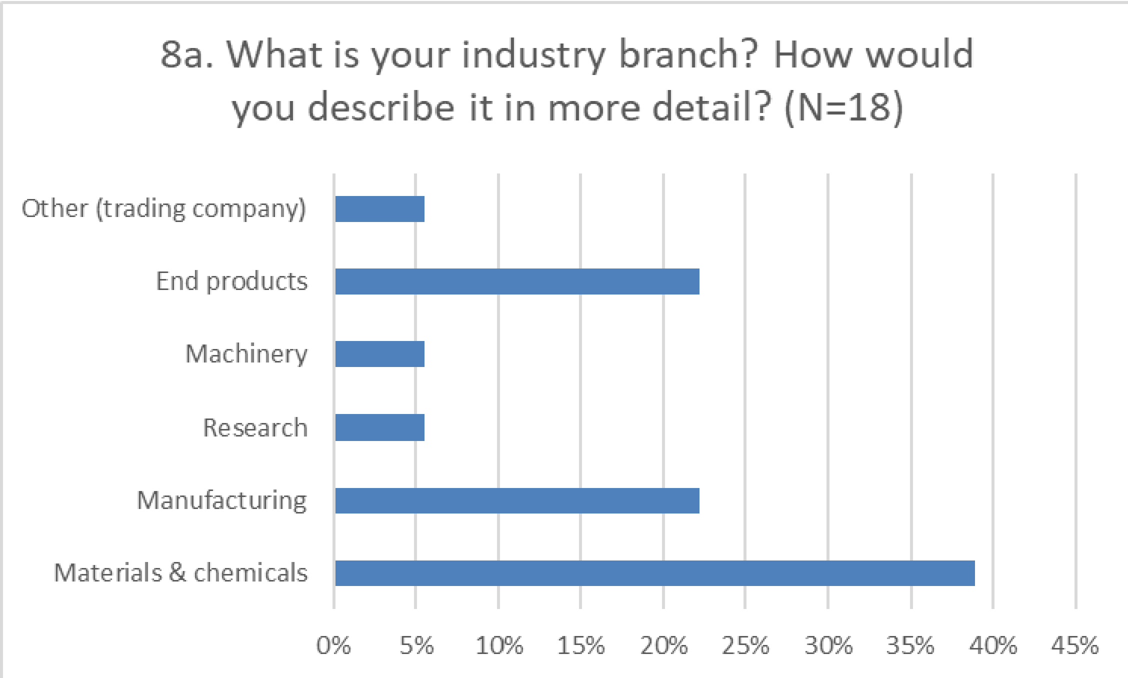


Figure 81. *Participants for ECOtronics questionnaire, and the industrial branch their represent.*

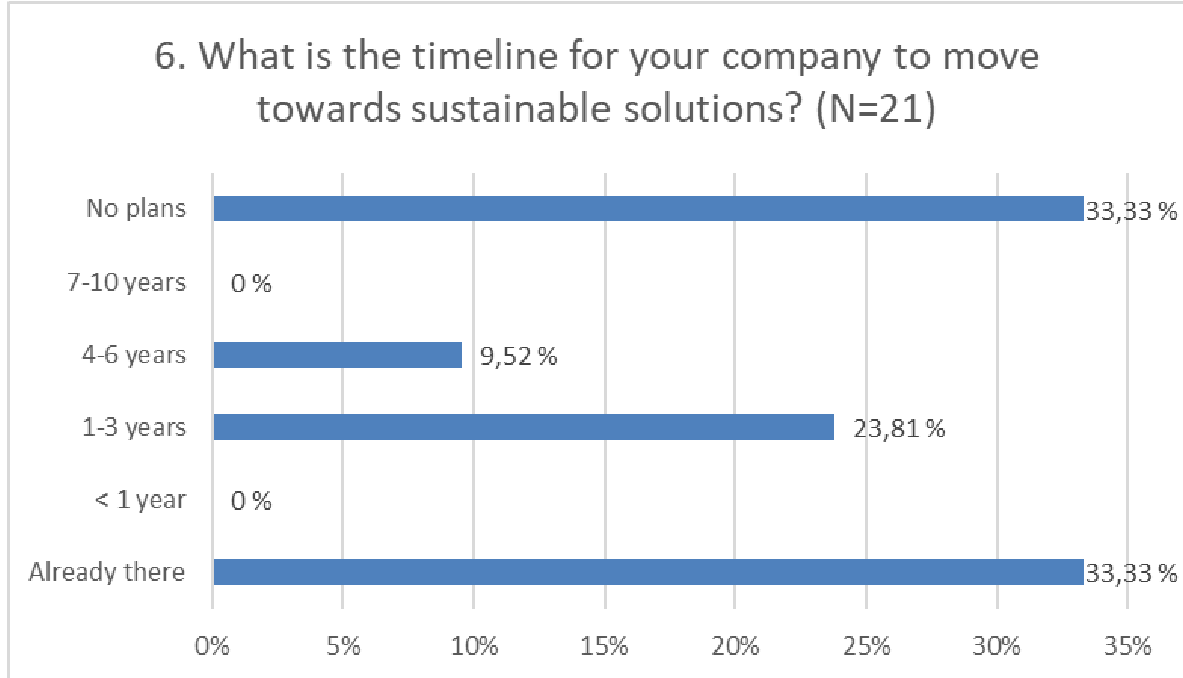


Figure 82. *Participants for ECOtronics questionnaire, and their plans towards sustainability.*

The other questions were focused on drivers, challenges and means to tackle sustainability, and end-of-life and circular business models. Due to small quantity of answers, care must be taken when making conclusions, but some observations can be listed:

- All of the listed drivers towards sustainable electronic and optics were considered important: customer demand, new business opportunities, public opinion, regulatory requirements, material availability
- Main issues come from lack of suitable materials and need to change existing production processes
- Recyclability and new end-of-life management models required

ECOtronics project organized a free webinar on 'Sustainable electronics and optics' on 14.10.2021 (Figure 83). The event included technical presentations from research organizations, industrial presentations from participating companies, and a keynote talk from Sami Nykter from Haaga-Helia University of Applied Sciences on 'Digital marketplaces for pre-owned electronics'. There were 150 registered participants from both industry and academy from Finland and abroad. All registered participants received selected presentations afterwards and the event was recorded for ECOtronics internal use.

At the end of each technical presentation poll questions were presented to the audience. Some key observations are presented in the following pages.

Figure 83. *ECOtronics webinar on 14.10.2021.*

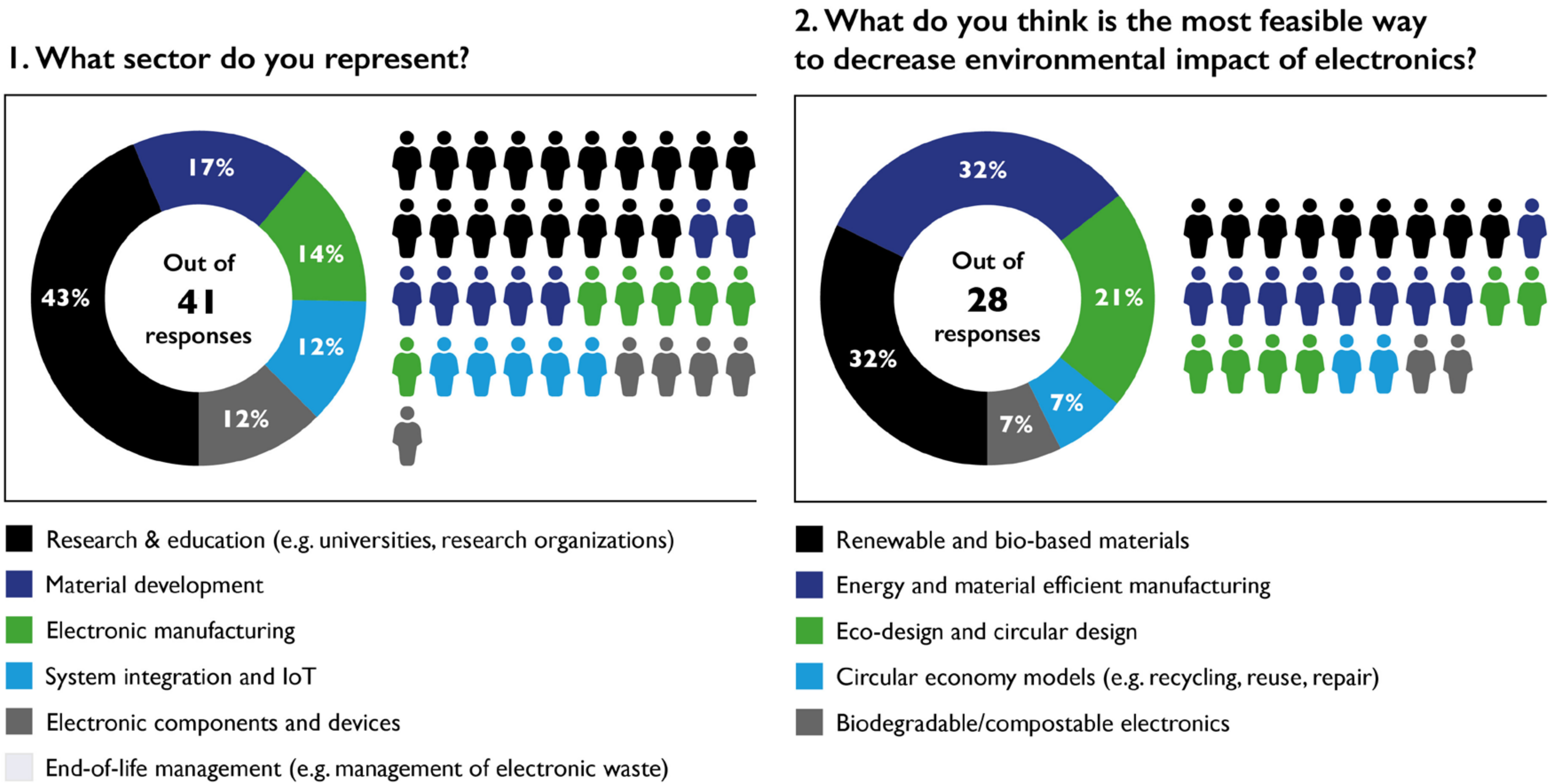
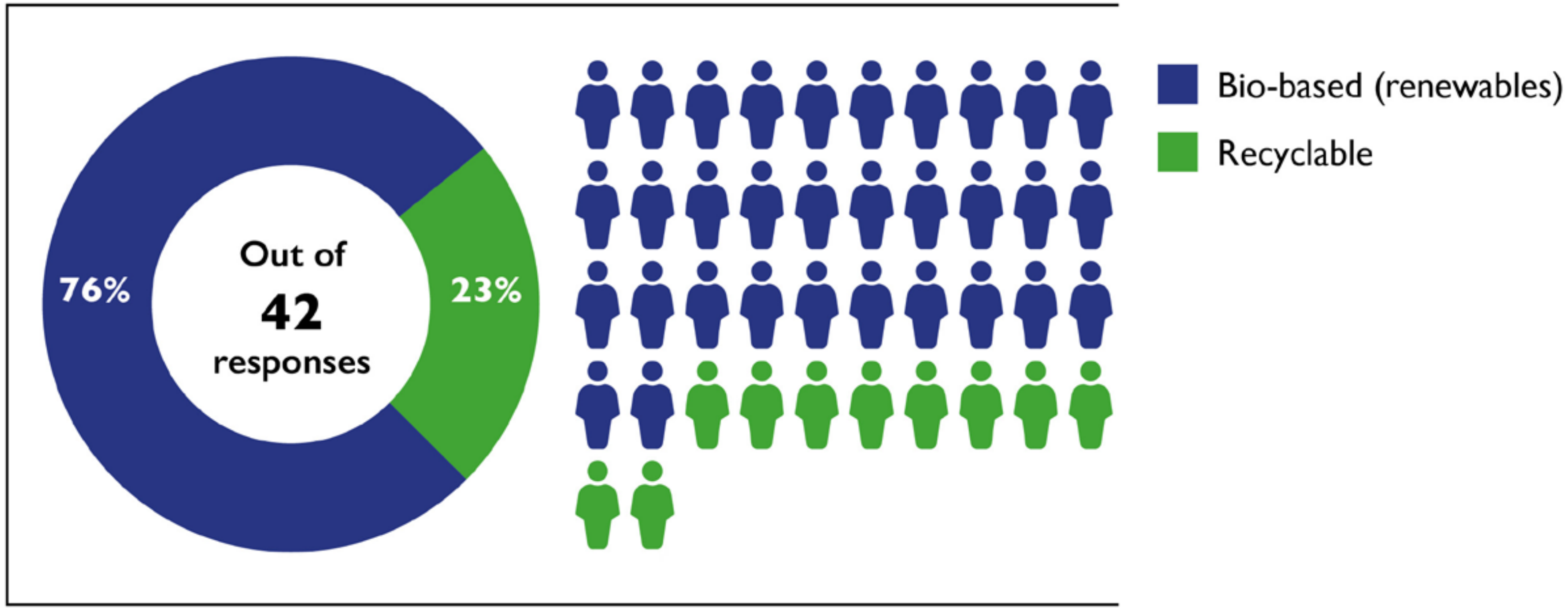
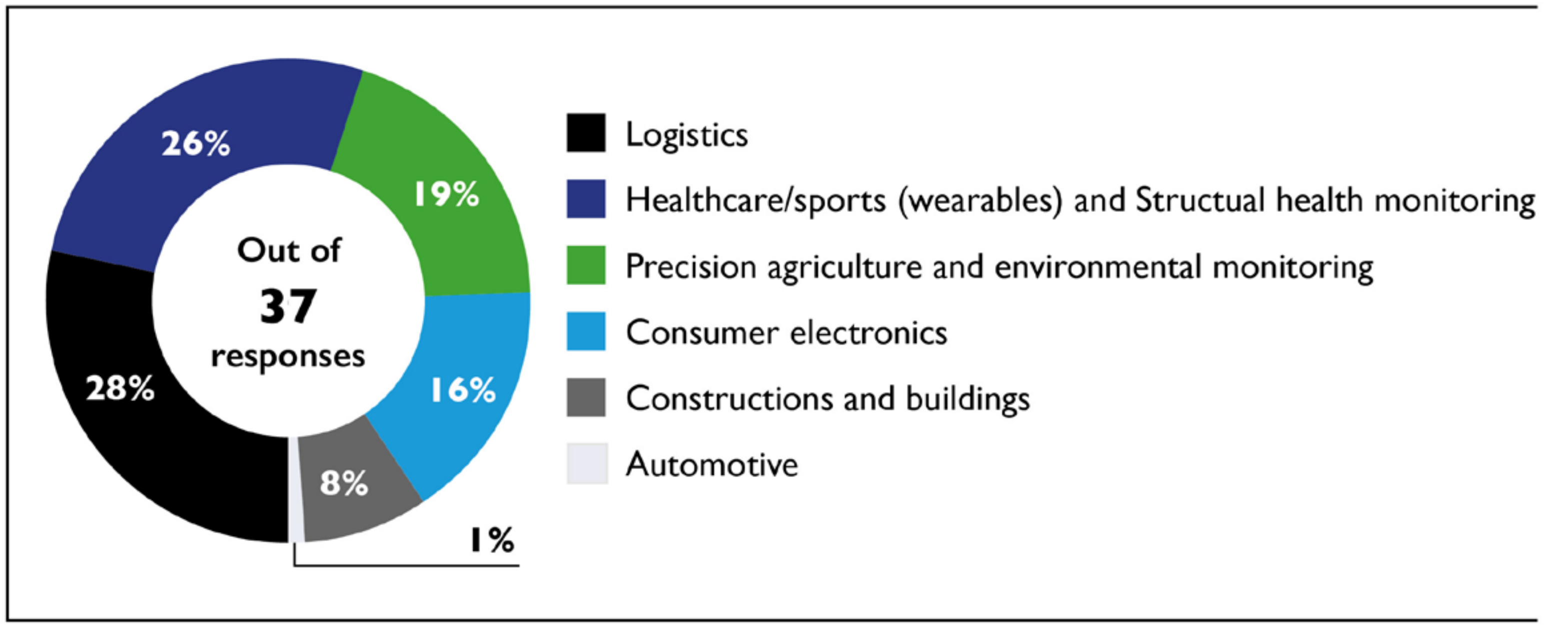


Figure 84. *Interesting polls from ECOtronics webinar.*

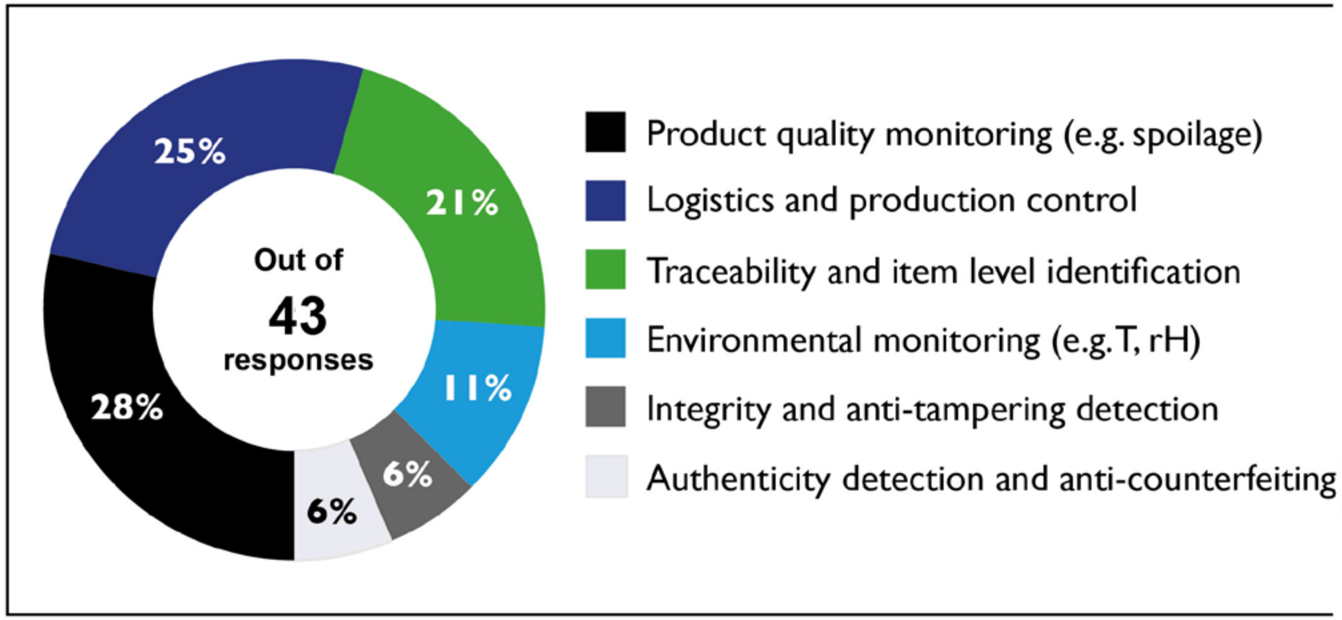
3. Which one is more important: bio-based (renewable) vs. recyclable?



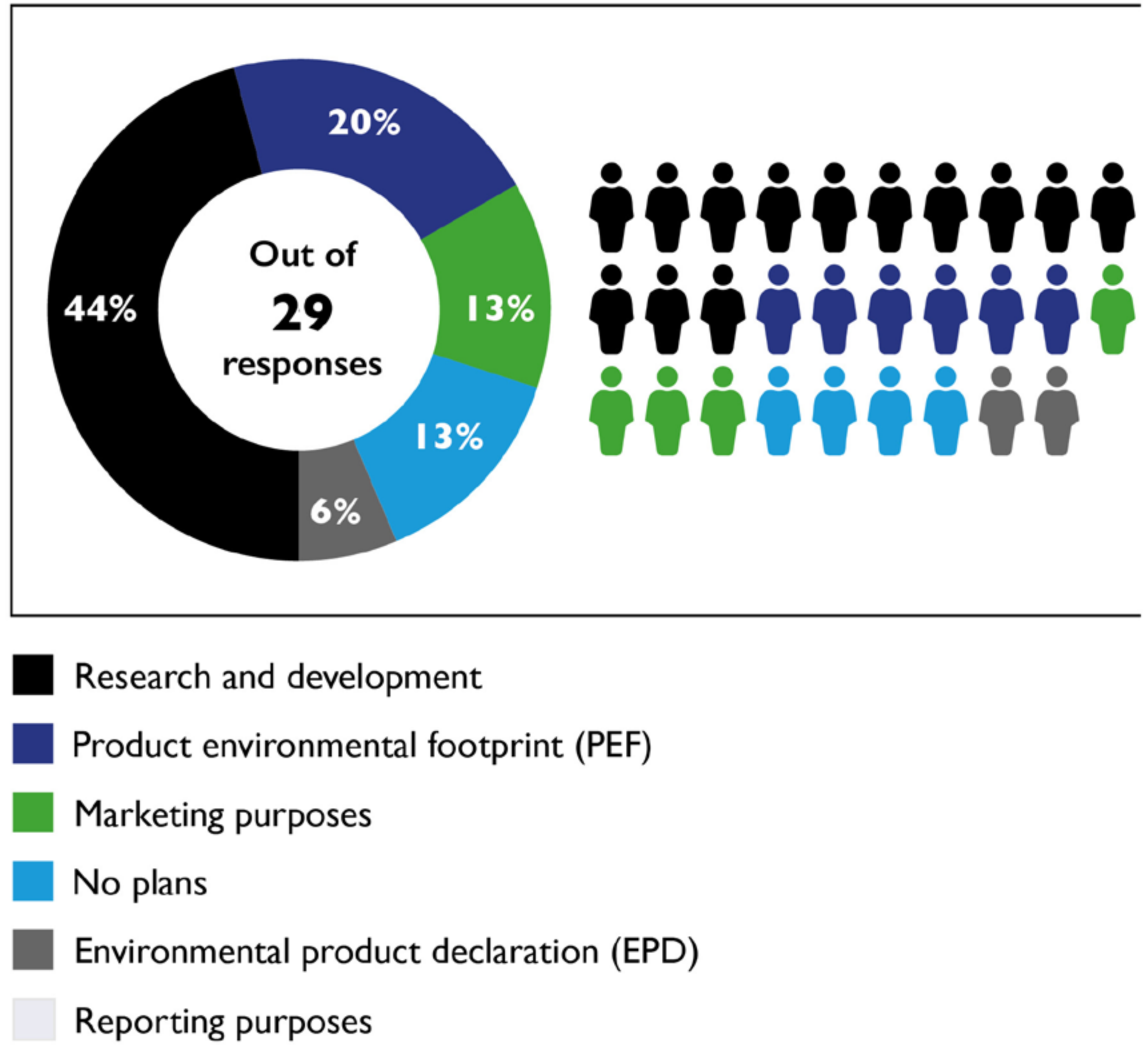
5. In which sectors/applications you see the relevance of the energy autonomous sensors? Choose up to 2 most important.



9. What fields are the most promising for intelligent packaging? Choose up to 2 most important.



13. How do you intend to use LCA results primarily?



A final event to announce the projects's main outcomes was arranged on 25.1.2022. This gathered up over 60 participants on Vimeo and Howspace platforms: https://vimeo.com/668204439

Several infographics used also in this report were implemented. These included infographics for

1. **sustainable substrate evaluation,**
2. **demonstrators,**
3. **circular economy workshops,**
4. **overall project implementation including benefits from sustainability, and**
5. **tables and graphs of the research results.**

The objective for infographics was to visualize the work and results that have been done and received during the project. The design team had to understand what the main things are that need to be shown, this was enabled by meetings with researchers. After discussions, the team was able to ideate how the information could be visualized understandably.

Each infographic had to be approached individually, for example the objective for the overall project implementation was to find a way how to make it interesting and approachable. The result was a path and characters that visualizes all the work packages. With a quick glimpse, the visualization reveals the size of the project, but the viewer needs to take a closer look to see all the details. This represents nicely real life in projects. On the other hand, Circular Economy workshops, and tables and graphs for the final report needed to present more specific results. The design team had to ideate more options of how the results are most understandable and easy to read. The tables and graphs were modified to continue the visual appearance of the project.

7 Summary & Discussion

Figure 85. *Sustainable electronics and optics, visualized possible use cases.*

ECOtronics project has defined what are the main factors affecting sustainability and environmental impact of electronics and optics products throughout their lifecycle. Technical feasibility of these factors has been evaluated focusing on bio-based materials, eco-design, sustainable manufacturing, and circular economy opportunities.

The main results are:

1. Selection, characterization and optimization of sustainable substrates and their coatings to meet requirements of different electronic and optic products

2. Evaluation of sustainable inks and adhesives

3. Analysis of sustainable material compatibility with different sustainable manufacturing methods, including printing, hybrid assembly, converting, hot embossing and overmoulding

4. Development of components based on sustainable materials and processes, including printed OPV, supercapacitor, transistor, and antenna

5. Design and integration of two technology demonstrators:

   (i) intelligent packaging for monitoring food quality, and

   (ii) sensor for monitoring environmental conditions

6. Quantification of environmental impact of demonstrators and other cases supported by the participating companies in order to gain detailed information on real-life products

7. Development of LCA tool tailored for evaluation of environmental footprint of electronic and optic products

8. Definition of end-of-life management models for the demonstrators focusing on recycling and bio-degradability opportunities

ECOtronics project concludes that electronics industry can specifically increase its sustainability by shifting from fossil-based materials to bio-based materials, decreasing use of metals, utilizing printing-based additive manufacturing processes, and benefiting from circular economy models and eco-design targets. Although printed electronics is a sustainability opportunity, there are remaining environmental challenges among the fossil-based substrate materials and metals used. Thereby, new materials originating from renewable and bio-based resources should be considered also for printed electronics.

Sustainable electronics has potential to create new business for electronics and optics industry. The business context of environmental sustainability is getting more aggressive, while investments are growing, future carbon taxation is underway, and customers are driving transformation[1]. Companies face increased pressure from stakeholders to account for ESG (environmental, social and governance) issues[2]. During ECOtronics specifically opportunities from use of new bio-based and renewable materials were found to be important from business perspective. Since the major opportunity for most types of printed electronics is in applications printed on flexible substrates, bio-based flexible materials have a clear opportunity here. However, further development for recycling and circular economy concepts, as well as improvement of compatibility of bio-based materials with traditional electronics manufacturing is required.

Along the tightening regulations and legislation also consumers' concern about carbon footprint and ecological sustainability is increasing, which companies need to take into account, since the requirements of the end users will affect the whole supply chain. The supply chains are also becoming more transparent due to new tools and sourcing awareness. The companies must communicate their commitment to sustainability clearly and truthfully. ECS-SRIA agenda[3] considers LCA as a prerequisite for holistic environmental evaluation. On the other hand, lack of scientific environmental impact and lifecycle assessment data are a challenge related to transition to more sustainable electronic solutions. Therefore, the role of LCA and other tools for quantifying environmental impact should be emphasized. To be in forefront in this aspect, ECOtronics project has taken significant efforts to provide new data on environmental impact of different types of electronic and optic products throughout their lifecycle combined with technical evaluation.

1 Moyer, K., Mesaglio, M., Watt, S., Smith, S., & Chhabra, A. (2020). Sustainability : What to Do When Stakeholders Want You to Save the World. Gartner G00732809 (Issue September)

2 Cossio, M., McNeill, W., Watt, S., Market Guide for Supplier Sustainability Applications. G007355969, Gartner Inc., 2021.

3 ECS-SRIA: Electronic Components and Systems Strategic Research and Innovation Agenda 2021

__Figure 86.__ Visualized process path from component development to product design and from material studies to manufacturing processes and to future scenarios.

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