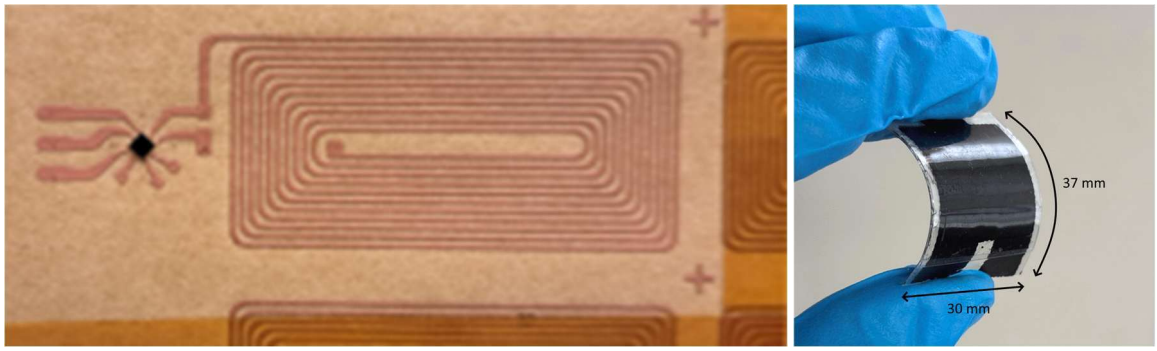
RESEARCH REPORT

VTT-R-00261-26



Report on implementation of Sustronics project at Finnish national level

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Preface

This document is the public research report of work carried out in Finland during Sustronics project 1.6.2023-31.5.2026. The report focuses on outcomes and results of the two Finnish research partners: VTT Technical Research Centre of Finland Ltd. (VTT) and Tampere University (TAU). The six participating Finnish companies have also provided a summary of their participation in this report: Canatu (CAN), Movesense (MOV), Screentec (SCR), Tervakoski (TER), UpCode (UPC) and UPM Raflatac (UPM). The Finnish partners have received funding from the EU under CHIPS JU program and from Business Finland.

During the project implementation seven Steering Group meetings among the Finnish partners and Business Finland have been arranged, once every six months.

Espoo 31.5.2026

Authors

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This work also received funding from the Swiss State Secretariat for Education, Research and Innovation (SERI).

List of acronyms

ACA	Anisotropic Conductive Adhesive
ACF	Anisotropic Conductive Film
CBM	Circular Business Model
CDA	Cellulose DiAcetate
CNF	Nanocellulose film
CNT	Carbon NanoTube
CV	Cyclic Voltammetry
CVH	Constant Voltage Hold
DES	Deep Eutectic Solvent
DPP	Digital Product Passport
DSC	Differential Scanning Calorimetry
ECG	ElectroCardioGraphy
EDLC	Electrochemical Double-Layer Capacitance
EEG	ElectroEncephaloGram
EIS	Electrochemical Impedance Spectroscopy
EoL	End-of-Life
ESR	Equivalent Series Resistance
GCD	Galvanostatic Charge-Discharge
HBA	Hydrogen Bond Acceptor
NBD	Hydrogen Bond Donor
ICA	Isotropic Conductive Adhesive
LCA	Life Cycle Assessment
LDS	Laser Direct Structuring
LED	Light Emitting Diode
MDO	Machine Direction Orientation
NCA	Non-Conductive Adhesive
NFC	Near Field Communication
PC	PolyCarbonate
PCR	Post-Consumer Recycled
PEF	PolyEthylene Furanoate
PET	PolyEthylene Terephtalate
PLA	PolyLactic Acid
PP	PolyPropylene
R2R	Roll-to-Roll
RFID	Radio Frequency IDentification
S2S	Sheet-to-Sheet
SMD	Surface Mounted Device
TGA	Glass transition temperature
TPE	ThermoPlastic Elastomer
TPU	Thermoplastic PolyUrethane
TPZ	Tetrapyrazinoporphyrazine
UV	Ultra Violet
WP	Work Package

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1 Introduction

Sustronics was a European joint research project carried out in 2023-2026 between 46 partners from 11 European countries representing the industry, research and development, and academics – coordinated by Philips. The Finnish consortium consisted of one RTO, one university and six companies, altogether eight partners. The overall objective of Sustronics was to build an ecosystem to demonstrate how the electronics industry can benefit from sustainable materials and manufacturing, eco-design, energy-efficiency and circular business models. The research activities included:

- Materials and process development,
- Component and device development based on the novel materials and processes,
- Development of sustainable electronics functionality relying on hardware and software integration,
- Pilot integration to highlight arising opportunities for sustainability and circularity
- Quantification of sustainability and circularity including development of new methodologies,
- Development of circular business models for new kinds of sustainable electronics,
- Investigation on end-of-life (EoL) management concepts, and
- Activities to ensure community and stakeholder engagement.

The project consisted of six work packages (WPs) with respective schedule:

- WP1 Material and process development (M1-M24)
- WP2 Component and device development (M1-M30)
- WP3 Use case integration (M1-M36)
- WP4 Sustainability assessment and eco-design (M1-M36)
- WP5 Dissemination, exploitation, communication and community building (M1-M36)
- WP6 Project management (M1-M36)

This report summarises the results of VTT and TAU within the WPs as well as a summary of the involvement of the Finnish companies (Section 6). Section 2 focuses on material and process development (WP1 and WP4 with linkage to WP3), Section 3 on component development (WP2 with linkage to WP3) and Section 4 on quantification of sustainability and circularity (WP3-5). Section 5 summarises the various dissemination and communication activities conducted by VTT and TAU during Sustronics.

2 Material and process development

2.1 Film processing

Biopolymer substrates were fabricated at VTT's pilot film processing facility. Granulate form materials were processed to films using laboratory or pilot-scale cast film equipment depending on the availability of materials. Table 1 presents the materials and process parameters for the film processing. All materials were pre-dried before the cast film extrusion at 50-60°C for 18 h in vacuum oven excluding PET (Polyethylene terephthalate) grades that were dried in dry air dryer at 120°C for 6 h.

Four materials were processed with laboratory-scale equipment (19/25 D single screw extruder Brabender Plastograph EC Plus) and plastic film sheets were created. The extruder was equipped with a 120 mm wide sheet die with adjustable die gap. Conical screw geometry with compression ratio of 1:3 was used. Furthermore, temperature-controlled, glossy chill roll unit with adjustable line speed was used after the sheet die.

The rest of the materials were processed with pilot-scale cast film extrusion PLASCO-line and plastic film rolls were manufactured. The film samples were processed with 35 mm single screw extruder with adjustable back pressure. Possible impurities were filtered from the polymer melt before beaker plate. The cast film line was equipped with a 550 mm wide film die with adjustable die gap. Temperature controlled and glossy chill roll was used in the laminator unit. Moreover, Helios edge trimming equipment was used to cut the sample rolls into suitable width for further processing. Machine direction orientation (MDO) of the selected materials was performed with roll-to-roll MDO equipment. The equipment had temperature-controlled preheating, orientation, annealing and cooling rolls. Furthermore, the orientation factor was adjustable between the brake and drawing rolls. The process parameters of the MDO process are presented in Table 2. Figure 1 shows the equipment used for the film processing.

Table 1. Process parameters for the film processing of biopolymer substrates at VTT.

Substrate	Equipment	Melt T, (°C)	Chill roll T (°C)	Film thickness (µm)	Notes
PLA Luminy L175	PLASCO	207	60	125/250	clear and clean film, stable processing
Bio PET Eastlon CB-602AB	PLASCO	287	80	125/250	overloaded torque, throughput fluctuation, poor film quality
Cuma-PET L04-100	PLASCO	282	70	125/250	holes, inadequate melt strength, poor film quality
Cuma PET RE 1704 R	PLASCO	284	85	125/250	clear and clean film, stable processing
Bio TPU Estane Eco 12T80E	PLASCO	209	40	125/250	very elastic, difficult to rewind evenly, wrinkled
Loimu Tough Heat	PLASCO	196	50	125/250	stable processing, slightly striped tone
Ecozen T95	PLASCO	252	85	125/250	clear and clean film, stable processing
Durabio D5380R	PLASCO	233	90	125/250	narrow processing window, inadequate melt strength or insufficient processing temperature
Franplast Bio-TPE	Brabender	190	60	125/250	stable processing, even film quality
Danna PLH	Brabender	160	40	-	powder form, insufficient feeding, uneven thickness
Hexpol Bio-TPZ	Brabender	200	70	200/(150)	poor melt strength, thin films elusive
UPM Formi 3D20 (white)	Brabender	180-190	60	800-1000	easy to process, some unevenness

Table 2. Machine-directional orientation process parameters for different biopolymer films.

Substrate	Equipment	MDO factor	Orientation T, (°C)	Annealing T (°C)	Film thickness (µm)
PLA Luminy L175	PLASCO	3-3.4	78	137	125/250
Bio PET Eastlon CB-602AB	PLASCO	3	83	177	125
Loimu Tough Heat	PLASCO	3	78	128	125



Figure 1. VTT Laboratory scale cast film extrusion line (left) and VTT pilot-scale cast film extrusion process (PLASCO-line) and MDO equipment (right).

Tensile strength properties of biopolymer substrate films are shown in Table 3. Bio-PET (3.0xMDO), PLA (Polylactic acid), and PET (REF1) had high strength and moduli values meaning that these foils were very stiff and strong and suitable to be used in the packaging industry. The orientation process of Bio-PET improved the film properties significantly. Bio-TPE (Thermoplastic elastomer), Bio-TPU (Thermoplastic polyurethane), and Bio-TPZ (Tetrapyrazinoporphyrazine) films were very soft and stretchable. DANNA and Formi 3D20 films were stiff but fragile and were found to be not suitable for replacing common plastic substrates.

Table 3. Tensile strength results for polymer substrates in MD (machine direction) and TD (transverse direction).

Substrate	Thickness	Tensile strength (at yield), MPa		Tensile modulus (Auto Young's), MPa		Strain (at yield), %	
		MD	TD	MD	TD	MD	TD
PET (REF1)	125	70		5560		1.5	
PLA, 3.5xMDO	70	85	27	6700	3070	1.6	1.1
Cuma-PET	133	44	43	2660	2940	1.9	1.8
Bio PET	130	33	29	2080	2040	1.8	1.7
Bio-PET	250	45	38	2430	2180	2.5	2.1
Bio-PET, 3.0xMDO	110	191	60	6820	2990	30	3.4
Loimu, 3.0xMDO	117	54	31	4190	3090	1.6	1.2
Durabio	100	47	49	2160	2350	4.6	3.4
Ecozen	110	32	32	1630	1580	2.8	2.7
Ecozen	190	36	35	1660	1650	3.1	2.9
Bio-TPE	270	5		12		420	
Bio-TPU	165	6 (break)		15		123	
Bio-TPZ	200	3 (at max)		43		127 (break)	
DANNA	527	5		267		7	
Formi 3D20	1150	17		3220		0.7	

Table 4 shows the DSC (Differential Scanning Calorimetry) and TGA (Glass transition temperature) results for the biopolymer films. PET-foils (PET, Bio-PET, Cuma-PET) had high thermal and dimensional stability, wide thermal window, and they crystallized controllably during cooling. PLA film had poorer thermal stability than the PET-based films. Stretchable Bio-TPE, Bio-TPU, and Bio-TPZ films were soft and flexible and had low melting enthalpy, thus showing rubbery behaviour. Ecozen and Durabio films were nearly amorphous, soft, and clear, and showed low crystallization degree (good formability). The thermal stability of Ecozen film was close to the values achieved with PET foils. Poorest thermal stability was achieved with Loimu, DANNA, Formi 3D20 and Bio-TPE films.

Table 4. DSC- and TGA-results for biopolymer films. DSC-results show thermal properties of the polymer films (glass transition temperature T_g, melting temperature T_m, enthalpy ΔH, crystallization temperature T_c) during heating and cooling.

Substrate	Heating			Cooling		T for corresponding degradation-%, °C			Residual mass, %
	T_g, °C	T_m, °C	ΔH, J/g	T_c, °C	ΔH, J/g	1%	5%	10%	at 800-900°C
PET (REF1)	125	254	-51	186	44	376	392	402	0.9
PLA, 3.5xMDO	69	175	-55	100	3	316	332	339	0.9
Cuma-PET	74	249	-42	191	42	376	393	403	1.3
Bio PET	80	251	-43	191	39	364	391	402	0.8
Loimu	60	150/175	-40	-	-	280	291	298	1.1
Durabio	102	236	-5	-	-	323	342	352	0.8
Ecozen	92	216	-3	-	-	379	392	398	0.8
Bio-TPE	<0	181	-5	5	-	235	283	311	0.8
Bio-TPU	97	225	-1	-	-	304	329	344	0.7
Bio-TPZ	<0	128	-56	112/80	61	285	325	344	0.7
DANNA	44	162	-21	17	37	266	286	298	0.8
Formi 3D20	62	151/164	-24	123	8	-	-	-	-

Table 5 presents the roughness, transmission, surface energy, and contact angle data of the polymer films. Biopolymer films were rougher than the reference PET substrate. In addition, the outside surface of the biopolymer films was often smoother than the inside surface resulting from the manufacturing process with the PLASCO line. The smoothest biopolymer films were Ecozen and Durabio and the roughest film was Loimu. The reference TPU substrate was rougher than the Bio-TPU substrate film. Loimu substrate had the lowest transmission due to its whiteness and haziness, but other substrates were rather clear and had high transmission. PLA, Ecozen, Durabio, and Bio-TPU substrates had higher transmission than the reference substrates and their transmission was over 90 %. Surface energy and contact angle data showed that Bio-TPU substrate might suffer from poor ink wetting and levelling due to its high contact angle (>90°) and low surface energy values. Other substrates showed rather similar values and good ink wetting and levelling was expected.

The heat stability of the biopolymer films was variable in hot-air oven drying experiments. Some films, such as Cuma-PET and Bio-PET (no MDO), became hazy, curled, bended, and blistered at elevated temperatures of 100-140°C. Furthermore, most films got soft at elevated temperatures (especially Ecozen and Durabio substrates), thus making the warm film handling as sheets difficult. This led easily to plastic deformations as the films cooled down. The dimensional stability and visual appearance of the films was better when the films were oriented, as seen with Bio-PET (3.0xMDO). Bio-TPU withstood the heat treatments but showed increased stickiness. Other thermally stable films were reference PET, reference TPU, PLA (3.3xMDO), and Loimu (3.0xMDO).

*Table 5. Surface roughness, transmission, surface energy, and contact angle with water of the biopolymer film substrates. *=measurement is taken with the new measuring device*

Substrate	Ra roughness (nm)		Transmission 400-800 nm (%)	Thermal stability (°C)	Surface energy (mN/m)		Contact angle with water (°)	
	IN	OUT			IN	OUT	IN	OUT
PET (REF1)	8	10	89.5	140	46.3	48.0	68.1	65.6
TPU (REF2)	721	420	89.0	140	47.5	43.4	66.9	72.1
PLA, 3.3xMDO	100	49	93.4	120-140	42.4	45.0	71.4	71.6
Cuma-PET	53	34	88.3	<100	40.1	46.0	72.1	71.8
Bio-PET	112	130	89.9	<80	43.5	44.4	77.7	74.5
Bio-PET, 3.0xMDO	131	34	87.8	120-140	54.5*	53.0*	59.4*	64.1*
Loimu, 3.0xMDO	916	874	65.1	120	56.2*	49.2*	49.9*	63.9*
Ecozen	16	11	91.0	80	51.7*	48.5*	69.7*	74.9*
Durabio	34	23	92.5	<80	50.3*	51.3*	78.3*	69.1*
Bio-TPU	85	104	91.9	120	30.7	29.0	106.1	106.4

Films processed at VTT were mainly used in Pilots#1.2, #1.3, #2.2, #2.3, #3.1, #3.2, and #3.3.

2.2 Printability development and testing

Printing experiments onto bioplastic and paper substrates were performed using EKRA XH S2S (sheet-to-sheet) screen printer or VTT's ROKO R2R (roll-to-roll) rotary screen printing line, shown in Figure 2. Both silver (Ag) Asahi LS-411AW and carbon (C) Loctite EDAG PF-407A inks were used. Used substrate materials and test points are listed in Table 6.

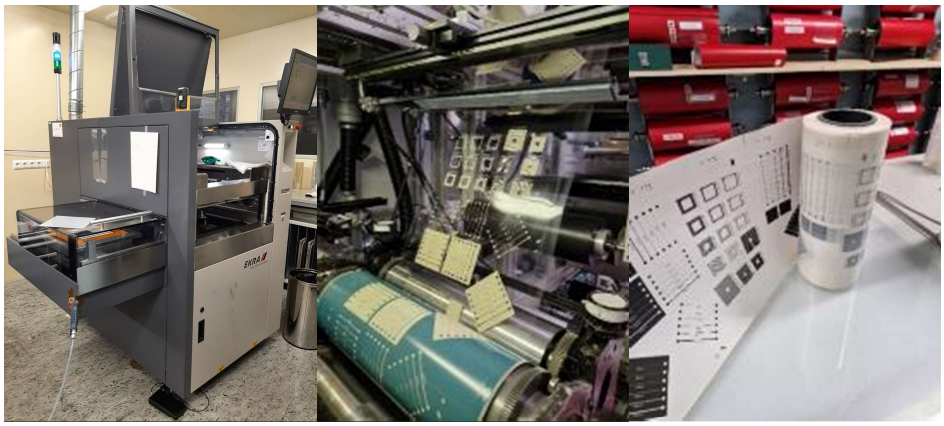


Figure 2. EKRA XH S2S screen printer (left), rotary screen printing with ROKO line (middle), and R2R printed bioplastic Loimu Tough Heat substrate roll.

Table 6. Substrate materials and test points

Substrate type	Substrate	S2S printing	R2R printing
Reference substrates	PET Melinex ST506 (125 µm)	Ag, C	Ag, C
	TPU Platilon U073 (100 µm)	Ag, C	Ag, C
Paper substrates from TER	White coated paper (60 gsm)	Ag	-
	Electrical insulation paper low (18.6 gsm)	Ag	-
	Electrical insulation paper high (105 gsm)	Ag	-
	Analytical paper (250 gsm)	Ag	-
	Analytical paper (165 gsm)	Ag	-
	Analytical paper (90 gsm)	Ag	-
	Filter paper (92 gsm)	Ag	-

Substrate type	Substrate	S2S printing	R2R printing
	Coated paper (50 µm)	-	Ag, C
Bioplastic substrates from VTT Tampere	PLA Luminy L175 (125 µm, 3.0xMDO)	Ag, C	Ag, C
	Cuma PET RE 1704 R Natural (125 µm, no MDO)	Ag, C	-
	Cuma PET RE 1704 R Natural (100 µm, 3.2xMDO)	-	Ag
	Bio PET Eastlon CB-602AB (125 µm. no MDO)	Ag, C	Ag
	Bio PET Eastlon CB-602AB (125 µm, 3.0xMDO)	Ag, C	-
	Bio PET Eastlon CB-602AB (50 µm, 3.0xMDO)	-	Ag
	Loimu Tough Heat (125 µm, no MDO)	Ag, C	-
	Loimu Tough Heat (125 µm, 3.0xMDO)	-	Ag, C
	Bio TPU Estane Eco 12T80E (125 µm, no MDO)	Ag, C	-
	Ecozen T95 (125 µm, no MDO)	-	Ag
	Durabio D5380R (125 µm, no MDO)	-	Ag
	r-PET (100 µm, 3.2xMDO)	-	Ag
Commercial paper-based substrates	Fastweb Brite (90 gsm)	-	Ag, C
	Sylvicta (145 gsm)	-	Ag, C
Commercial bioplastics	Bio-TPU Platilon LPT4201 AUV CQ EC (50 µm)	-	Ag
	Forest PE Clear FTC85 (85 µm)	-	Ag
	Forest PP Clear FTC50 (50 µm)	-	Ag, C
	Natureflex 45NK (45 µm, regenerated cellulose)	-	Ag

Different paper substrates from TER were S2S screen-printed using Ag ink, as shown in Figure 3. Filter paper substrate was found to be unsuitable for conductor line printing because of its highly irregular and rough surface that prevented the ink transfer. Other paper substrates showed good print quality with good layer coverage, low spreading, and sharp printed edges. In addition, high conductivity was achieved on all suitable substrates without any significant differences in print quality or layer performance. The sheet resistances of the printed layer were 24-32 mΩ/sq. and volume resistivities were 5.8-7.0E-05 Ω·cm. Some visual defects were seen on analytical papers due to their surface softness and porosity.

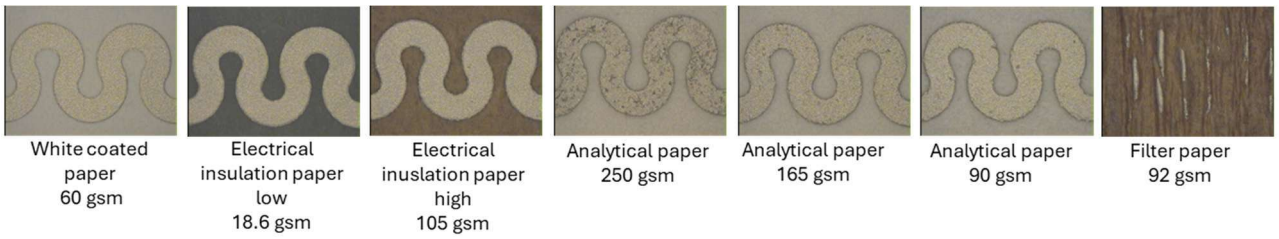


Figure 3. S2S print quality on conductor lines on paper substrates from TER. The width of the conductor line was 1000 µm.

S2S screen printing trials were performed using both Ag and C inks onto different bioplastics. Good print quality with good detail rendering (low ink spreading) and sharp edges was achieved on every bioplastic substrate and no difference in quality was seen with the reference substrates (Figure 4). Carbon ink spread slightly more on Cuma PET substrate, because of which narrow features needed to be scratched open to avoid short circuits. Bio-TPU substrate tended to stick onto the screen due to its very low surface energy, thus creating print defects, missing features, and variable conductivity. Un-oriented Bio-PET and Cuma PET substrates suffered from poor thermal stability (<100°C) so that the substrates became whitish/hazy and more brittle, wrinkled, and blistered during ink layer drying. The MOD process during film manufacturing improved the thermal and colour stability significantly, thus it should be performed to all bioplastic films.

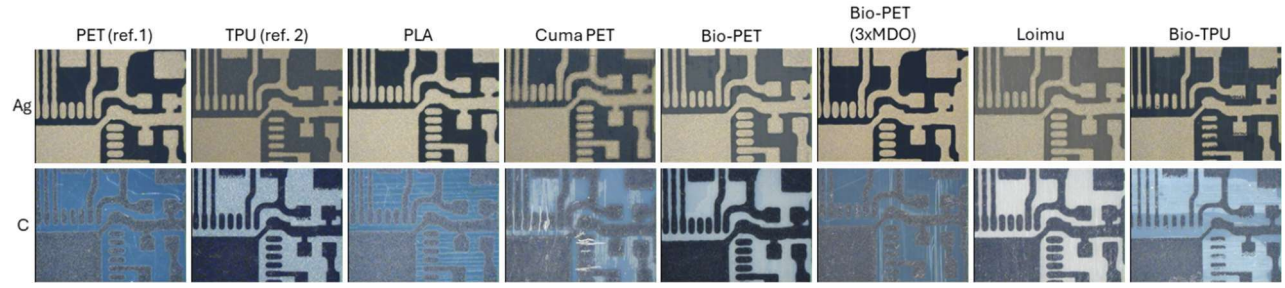


Figure 4. S2S print quality of Ag and C conductor ink patterns on different bioplastics.

Silver ink gave good adhesion to all substrates, and the printed layers had high conductivity. The performance was similar or even better as with the reference PET and TPU substrates. The sheet resistance was 38-72 mΩ/sq. and volume resistivity 6.3-9.7E-05 Ω·cm. The poorer conductivity as compared to the TER paper samples was caused by the lower drying temperature required by the bioplastics. With carbon ink, the adhesion to bioplastics was variable, conductivity was poorer on stretchable TPU substrates, and conductivity was expectedly significantly poorer than with silver ink. Total ink layer delamination was seen with PLA and oriented Bio-PET substrates, and poor or mediocre adhesion (conductivity of printed lines lost) was achieved with un-oriented Bio-PET and Loimu substrates. Sheet resistance values of carbon ink layers were 67-92 Ω/sq. and volume resistivities 3.7-6.0E-02 Ω·cm on non-stretchable substrates. These values were rather similar as with the reference PET substrate.

In R2R printing trials, the printability of bioplastic, paper, and TPU substrates was good and high print quality with good detail rendering was achieved with both silver and carbon inks (Figure 5). Slightly more ink spreading was seen on PLA and Loimu substrates. In addition, slightly poorer detail rendering was seen with carbon ink than with silver ink due to the coarser screen used. Bioplastic substrates from VTT had process-related longitudinal stripes that easily caused the ink to flow along them during printing, thus making localized detail rendering poorer. In the case of Bio-TPU substrate, the very low surface energy created ink wetting and levelling issues, thus resulting in ragged and splashed printed lines with decreased line width. Commercial substrates, coated paper (from TER) and translucent paper, suffered from uneven and poor ink transfer. Both silver and carbon inks had mainly good ink layer adhesion to all substrates. Poor adhesion with severe ink layer delamination was only seen with PLA substrate when printing with the carbon ink. For multilayer printing, the repetition lengths on Loimu, Natureflex, and Bio-TPU substrates were over 1 mm shorter or longer than the original repetition length, thus indicating difficulties in registration.

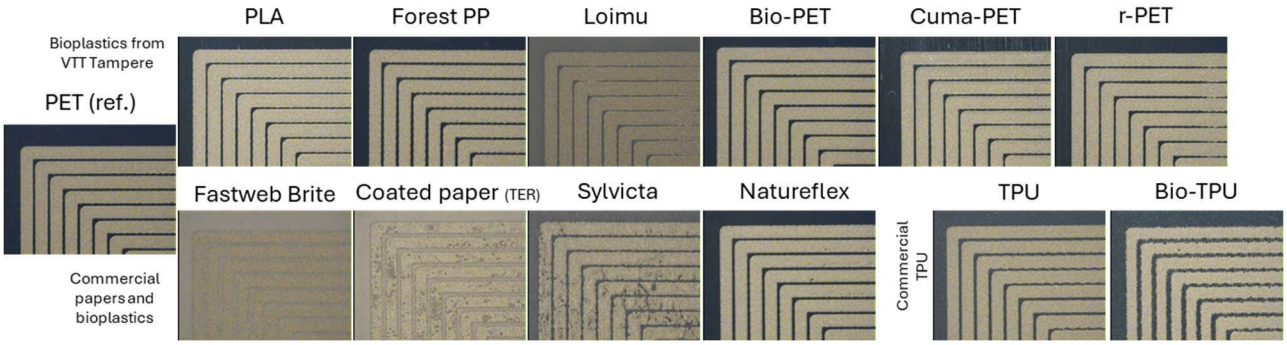


Figure 5. R2R print quality of Ag conductor ink antenna patterns on different bioplastic, TPU, and paper-based substrates. The line width was 500 µm and gap width was 100 µm.

With the silver ink, the layer conductivity was better on bioplastics, paper-based, and TPU substrates than on reference PET. This resulted most likely from the better solvent removal during drying with the thinner and more absorbent substrates, and better particle alignment on rougher surfaces, thus

increasing the particle-to-particle contact points. Highest conductivities were achieved on TPU, Bio-TPU, Loimu, PLA, and Natureflex substrates whereas PET-based and paper-based substrates had lowest conductivities. The achieved sheet resistance values were 36-62 mΩ/sq. and volume resistivities 4.3-6.8E-05 Ω·cm. As expected, carbon ink layers had significantly lower conductivity than silver ink layers. In the case of the carbon ink, the sheet resistance was the lowest on Sylvicta and Fastweb Brite substrates but higher volume resistivity values than with PET were obtained on all tested bioplastics and coated paper from TER meaning that carbon flakes required smoother surfaces for the flakes to come into better contact with each other. The achieved sheet resistance values were 52-77 Ω/sq. and volume resistivities 3.0-4.3E-02 Ω·cm.

Bioplastics and paper-based substrates could be used to replace fossil-based PET and TPU substrates in R2R printing, thus increasing sustainability. The printability, print quality, and detail rendering on bioplastics were similar to that achieved on PET. With silver ink, the conductivity was even higher on bioplastics, Bio-TPU, and paper-based substrates than on PET because of their higher substrate roughness that increases the number of particle-to-particle contacts. However, bioplastics had some limitations: their thermal stability was not as good as with PET and process-related surface grooves caused print defects. In addition, Bio-TPU suffered from poor ink wetting and levelling as well as ink splashing and some absorbent papers from poorer ink transfer evenness.

2.3 Biodegradability

Biodegradability can be an important feature in certain printed electronics applications. For instance, sensors used for environmental monitoring in remote or natural settings are often difficult or impossible to retrieve after deployment. In such situations, biodegradable materials offer a way to limit long-term environmental impact. Similarly, in agricultural applications, sensors designed to monitor soil moisture, temperature, or nutrient content may be left in place after use, where their ability to safely biodegrade over time is beneficial. Sensors integrated into packaging, such as freshness indicators or temperature monitors, are frequently disposed of together with organic waste management. Here, the use of biodegradable electronic components helps to minimize contamination and aligns with circular waste management principles.

VTT implemented the biodegradability experiments to simulate industrial composition conditions with focus on substrates and inks for printed electronics. The substrates used in the study were commercial film NatureFlex™ NP (Futamura Group), commercial PLA film prepared from Luminy® L175 (TotalEnergies Corbionin), and white coated paper (TER). Microcrystalline cellulose was used as a biodegradable reference sample. All substrates were evaluated for biodegradability without any printing and with silver-based conductive ink. Fiber-based material was also tested with copper and carbon-based inks. A flatbed screen printing machine was used to prepare printed substrates by SCR. The filing factor of ink in the substrates were 6% of the surface area. The inks used were: (i) conductive carbon ink; (ii) conductive silver ink and (iii) copper (Cu) particle paste (contains also 10% silver).

Biodegradability was evaluated using the standardized method EN14046, which is part of the testing requirement for industrial compostability of packaging materials. The milled samples were mixed with a compost matrix and incubated at a constant temperature of +58 °C in an incubator. The compost inoculum was obtained from industrial composting facility (Espoo, Finland) treating kitchen and green garden biowaste The CO_2 concentration in the exhaust gas was measured automatically using an infrared analyser to evaluate biodegradability of the samples. The percentage of biodegradation (mineralization to CO_2) and the weight loss of the samples during experiment (volatile solids of the test material and the compost matrix) were calculated. In order to further evaluate the impact of ink type on degradation, VTT's in-house disintegration method was applied. In this test, the paper-based substrate with three different inks (C, Cu, Ag) were attached to photographic slide frames using three replicate samples. Samples were buried in mature compost inside the test vessels, which were incubated at +58 °C. Disintegration was evaluated visually at regular intervals.

Both biodegradability and disintegration tests indicated that silver- and copper-based inks reduced the biodegradability of the substrates, and the effect was more pronounced with the copper ink (Figure 6). The weight loss data from the composting experiment also showed reduced values for both inks across all tested substrates. The disintegration test in the compost environment confirmed that the degradation of the paper substrate was reduced when Ag and Cu inks were applied (Figure 7). Similarly to the biodegradability test, a greater effect was observed with the copper ink. Paper with carbon-based ink disintegrated as rapidly as paper without any inks.

Both copper and silver have been shown to possess antimicrobial properties, primarily due to their ability to release ions that can disrupt microbial cells. The reason why copper exhibits significantly greater inhibition than silver is likely due to the experimental conditions (e.g. high temperature, pH, compost), which could promote more efficient oxidation of copper and release of copper ions compared to silver. These outcomes suggest that further studies are required to clarify the environmental implications of printed electronic inks in industrial composting and in broader environmental settings.

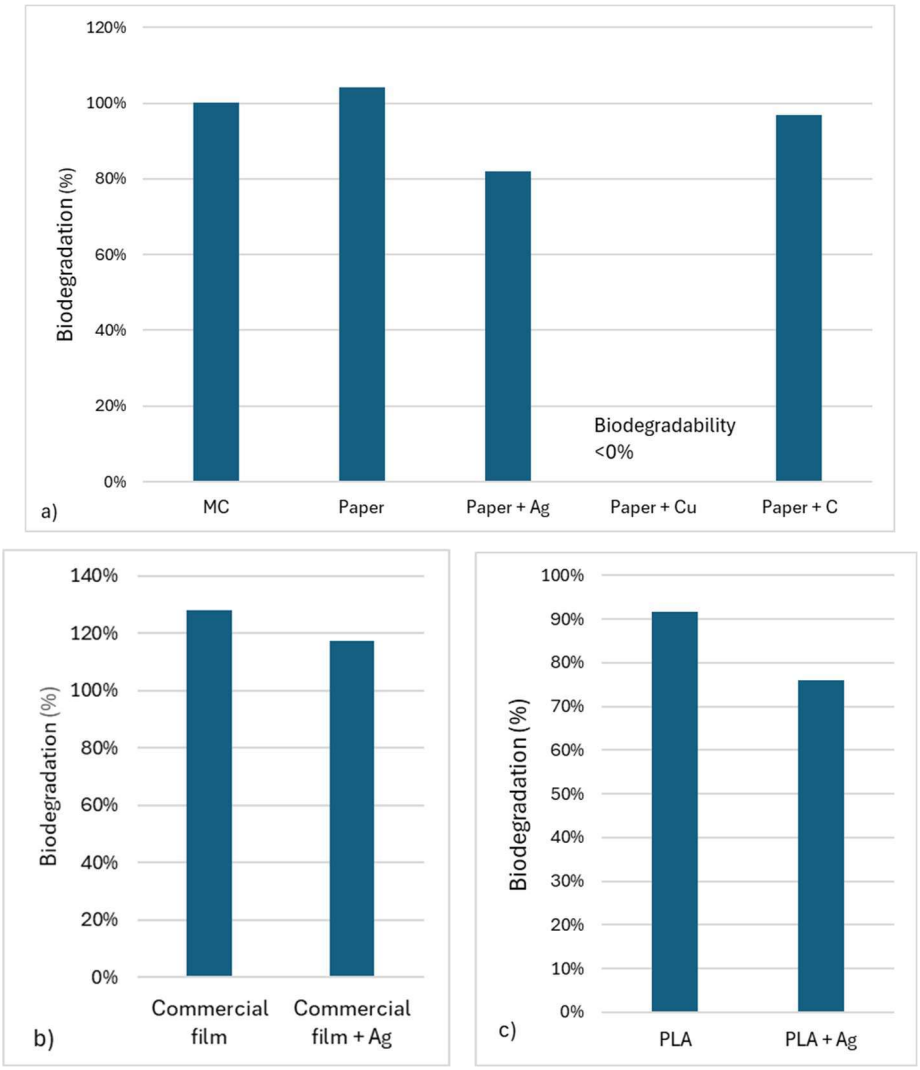


Figure 6. Biodegradability of a) paper-based substrates with C-, Ag- and Cu-based inks (45 days), b) Commercial film with Ag ink (45 days) and c) PLA with and without Ag-based ink (140 days).

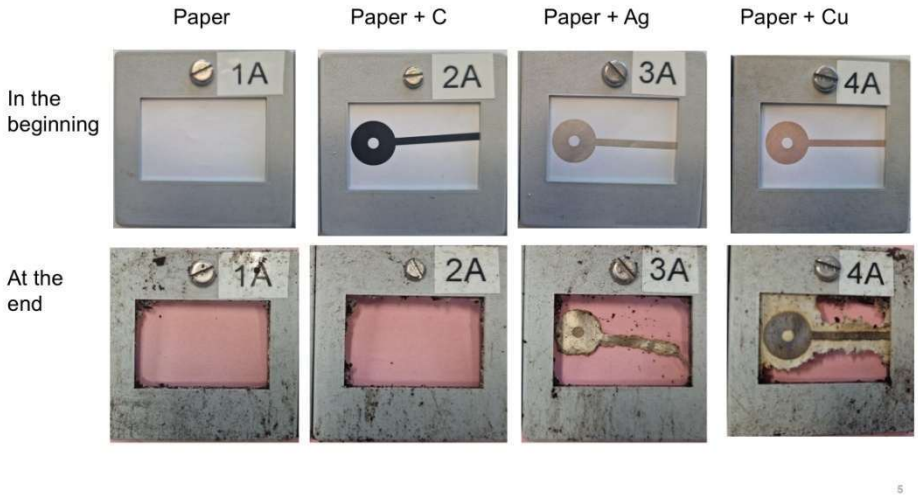


Figure 7 Disintegration of paper-based substrates in compost at +58 °C.

2.4 Component assembly development and testing

The manufacturing process of flexible electronics typically consists of substrate processing using either printing or etching process, component assembly and bonding processes and testing of final assembled system. This chapter concentrates on sustainable bonding materials and processes investigated at VTT. The commonly applied method for SMD component bonding on flexible substrates has been contacting component electrically to substrate using isotropic conductive adhesive (ICA) and supporting component mechanically by non-conductive adhesive (NCA). Typically, ICA curing is performed by heat and NCA curing by UV (Ultra Violet) light. Heat curing typically utilizes more energy than UV curing. Example of the traditional SMD (Surface Mounted Device) component bonding on printed flexible substrates using ICA is shown in Figure 8.

Utilization of bare device/chip bonding affects positively on LCA (Life Cycle Assessment) by lacking packaging materials and applied energy in the packaging process, and by decreasing energy consumption by means of lighter total system weight and decreased amount of process steps. Typically applied bonding process for device/chip bonding is performed either using Anisotropic Conductive Adhesive (ACA) or Anisotropic Conductive Film (ACF) material. In these processes, contact pads are first covered with dispensed ACA/ACF after which chips are placed onto the dispensed material, and heat and pressure are applied on chips using thermode. Heat softens the bonding material, and the device is electrically contacted to substrate using pressure to contact pads. When substrate cools down the bonding material contracts resulting in a decrease in distance between component contacts and bonding pads, which effects positively to achieved bonding quality and reliability. An example of ACA component bonding is shown in Figure 8.



Figure 8. Example of traditional SMD capacitor component bonding on printed flexible substrates using ICA (left) and example of ACA component bonding (right).

2.4.1 Bonding experiments

Bonding experiments were performed with screen-printed silver layers on white PET, white smooth inkjet printing paper, and brown electrical insulation paper. Assembly tests were initially performed using Epo-TEK H20E ICA adhesive and contacts were mechanically supported by using Dymax 9008 UV curable adhesive to improve bonding reliability. ICA adhesive curing was performed in an oven at 120°C for 1 h. One resistor, three capacitors, and one QFN56 SMD component were assembled onto the printed substrates, as shown in Figure 9. The contacting and functionality of QFN56 component was successful on every substrate.

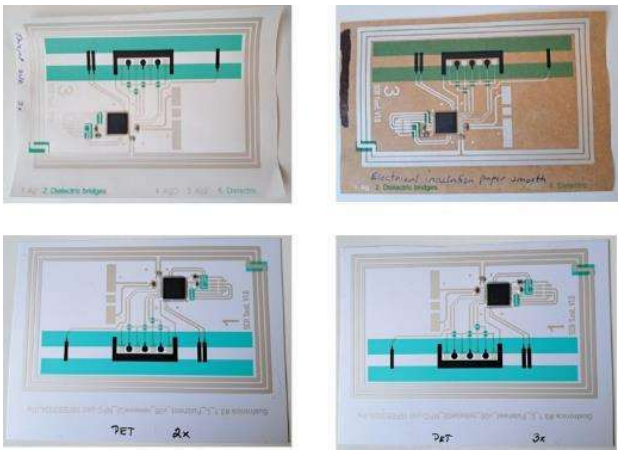


Figure 9. System assembly with ICA and NCA bonding on smooth inkjet printing paper (top, left), insulation paper (top, right) having two silver ink printed layers and on PET (bottom) having two (left) or three (right) silver printed layers.

More sustainable ICA (DELO Dualbond IC343) and NCA (DELO Dualbond AD345) materials were also evaluated in the assembly process. Short UV light illumination was performed to lock components in correct position on contact pads after SMD pick-and-place assembly. The final curing of both materials was done with heat in the oven. These materials also showed successful component functionality and contacting. These materials improved also the results in LCA calculations (see Section 4.1.1) significantly, thus making the assembly process more sustainable.

More sustainable ACF material (25 µm thick) from CondAlign, which was applied in bonding process using only pressure at RT, was also tested with printed PET substrate (Figure 10). This decreased the energy consumption as compared to the traditional bonding process with ACF materials. QFN56 component bonding and contacting was not achieved with this novel ACF material. This resulted from the too high material thickness and the lack of heating during bonding.

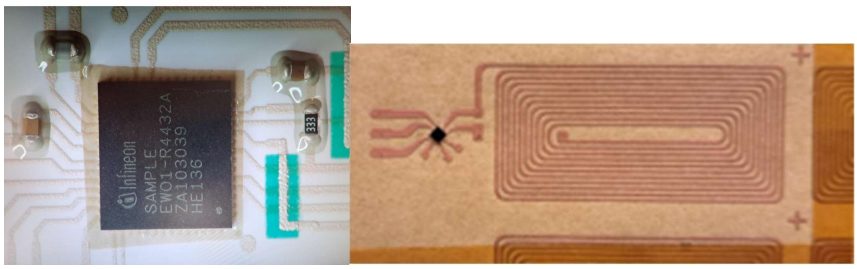


Figure 10. QFN56 component assembled on printed PET substrate using CondAlign 25µm thick ACF (left) and SIC4341 chip bonding performed on paper substrates (right).

RFID (Radio Frequency IDentification) Tag (SIC4341) was bonded onto printed copper ink on plastic and paper substrates using two methods. First, NFC (Near Field Communication) chip contacts were

equipped with 17.5 µm gold (Au) studs (electrical contacting) before performing bonding tests. Bonding of chips on substrates performed with Finetech flip-chip bonder using temperature of 80°C and dispensed DELO NCA (Dualbond AD345). Secondly, ACA (DELO Monopox AC2264) bonding was applied. The adhesive was cured with thermode at 150°C for 9 s. Functionality and contacting of both chip bonding methods gave positive results. Example of this chip bonding is shown in Figure 10.

2.4.2 Bonding for project pilots

Examples of bonding processes were developed primarily for Pilots 1.3 (Sustainable luminaire led by Signify), 3.1a (In vitro diagnostics led by Infineon Austria), and 3.2 (Smart hygiene led by Essity).

LEDs (Light Emitting Diodes) and required other SMD components for lighting elements were assembled using VTT's LAKO R2R assembly line Figure 11. Assemblies were processed on printed recycled PET substrate using ICA for component electrical coupling and NCA for component mechanical support. In Figure 12 dispensed ICA material tiny dots and NCA underfill material large dots and lines for component mechanical bonding are shown.



Figure 11. VTT's LAKO R2R SMD component assembly line.

Dispensing of ICA and NCA material performed on contact areas by Vermes dispenser shown in Figure 12. Component pick-and-place performed using by both S2S and R2R applied in assembly of lighting elements in Pilot 1.3.

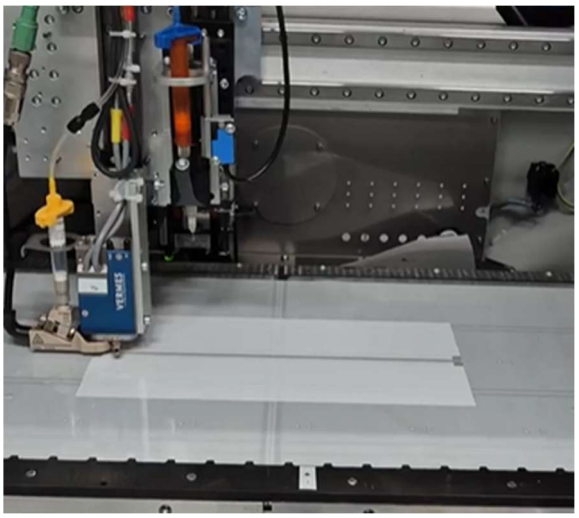


Figure 12. Vermes dispenser applicating ICA dots and NCA lines on LAKO R2R assembly line to downward lighting element.

Example of patterned ICA and NCA adhesives for electrical and mechanical bonding of SMD components in Pilot 1.3 are shown in Figure 13.

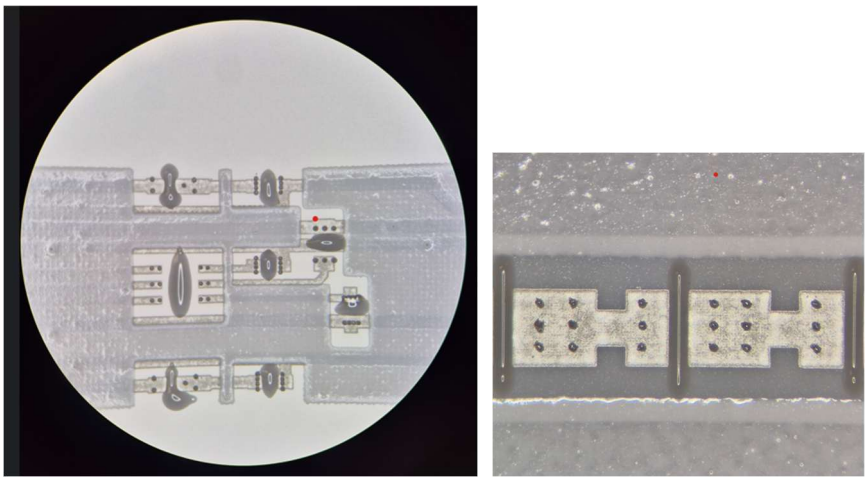


Figure 13. Example of dispensed ICA small dots (on left) and larger NCA underfill material lines (on right) for electrical and mechanical bonding of SMD components for LED lighting element S2S (left) and R2R (right) assemblies.

Component pick-and-place on substrates performed using Fuji NXT III equipped with DynaHead for multiple nozzles providing component size down to 0402 (imperial) corresponding 1,0 mm x 0,5 mm and maximum throughput of 27000 CPH. In Figure 14 assembled downward lighting element LEDs and element functionality testing are shown.

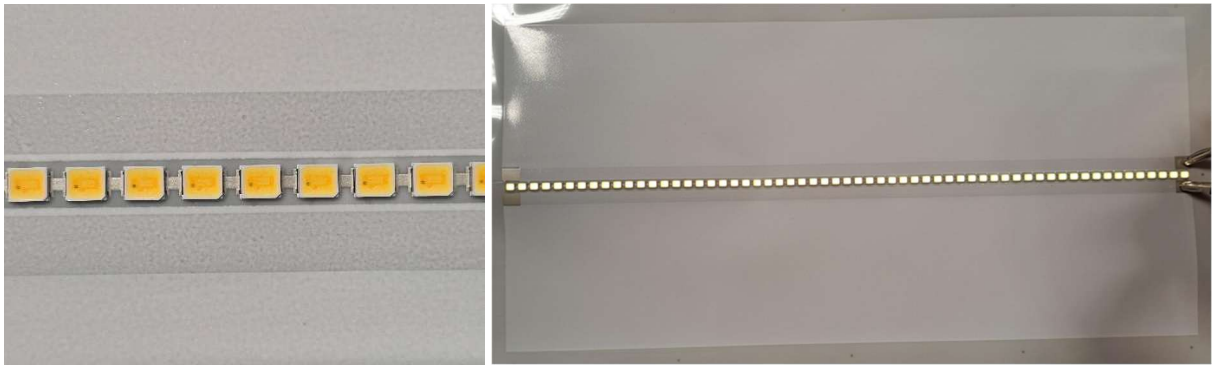


Figure 14. Example of assembled LEDs (left) and functionality testing of assembled (right) in downward lighting element.

In Figure 15 detail of assembled LED and Zener diode component in upward lighting element is shown.

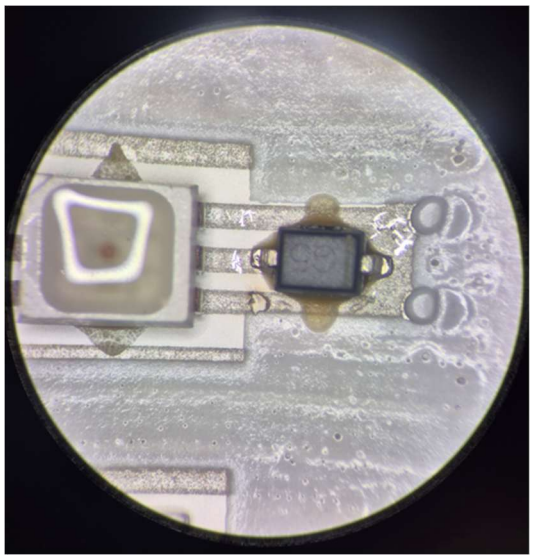


Figure 15. Detail of the upward lighting assembly containing LED and Zener diode component bonded with ICA and NCA underfill adhesives.

Bare silicon chip and super capacitor assembly and bonding processes on copper paste printed paper substrate. Processes were developed and demonstrated for Pilot 3.1a. Silicon chips were first equipped with gold bumps using wire bonder. In assembly process NCA material was dispensed on the bonding area to provide mechanical bonding of chip on substrate. Next the chip contacts assembled on substrate contact pads by flip-chip bonder using heat and pressure. During the bonding process chip bumps were pressed through the contact pads surface layer forming hermetic metal-metal contacting between chip and substrate contact pads.

SMD capacitors were assembled electrically on substrate contact pads using ICA. ICA was cured using heat. Capacitors were supported mechanically using NCA that was cured using UV illumination. Super capacitor was assembled on contacts using ICA and supported mechanically using NCA. Lower curing temperature was applied in assembly compared to lighting elements assembly due to lower temperature requirement with supercapacitor components, which caused increased curing time for ICA leading increased assembly time compared to assembly of lighting elements. In Figure 16 assembly of silicon chip and SMD capacitors is shown.

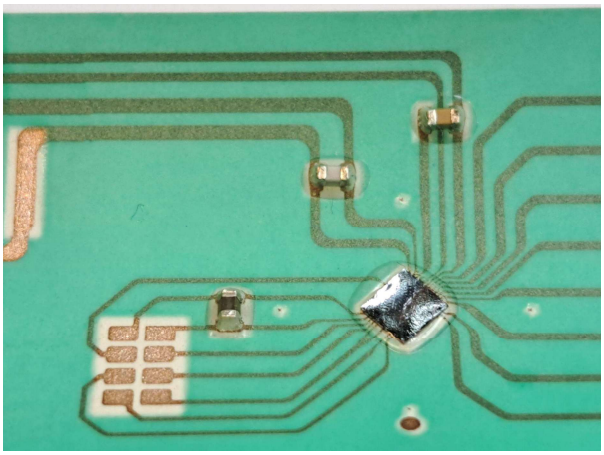


Figure 16. Assembled silicon chip and SMD capacitors on copper ink printed Gen3 substrate.

In Figure 17 assembly of super capacitor is shown.

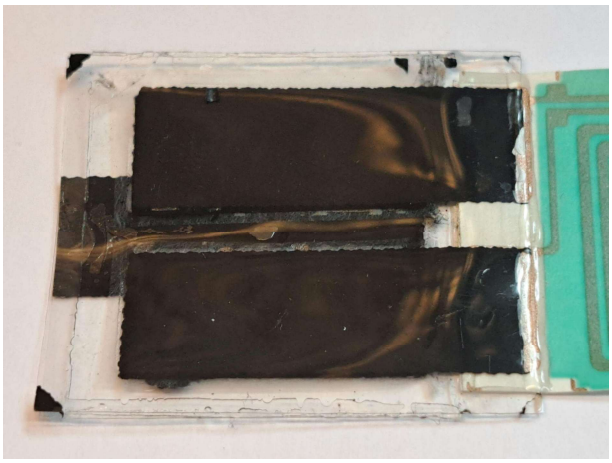


Figure 17. Assembled super capacitor on Gen 3 substrate.

In Figure 18 final assembly is shown.

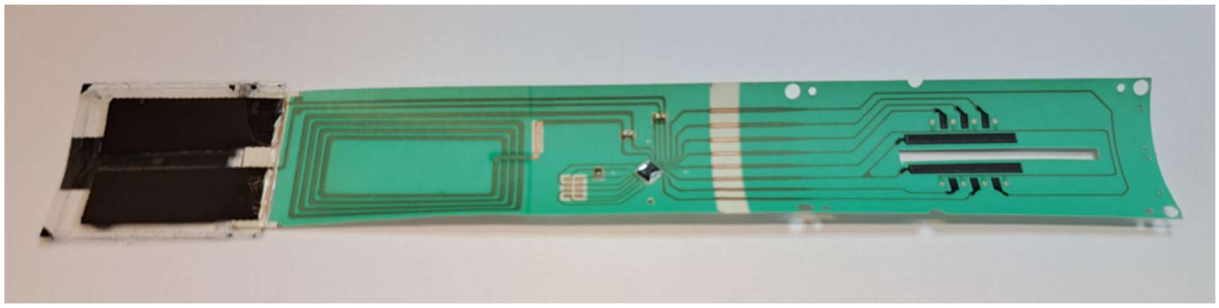


Figure 18. Assembled Pilot 3.1 Gen3 system.

Printed sensors R2R assembly process was demonstrated using R2R converting line at VTT premises in Oulu for Pilot 3.2. The R2R assembly line is based on the Delta R2R converting line equipped with two robotic arms manufactured by Yaskawa. The applied sensor substrate originally printed on R2R line by Beneli was placed on the Delta converting line. Enzyme, pH sensor, and pH reference sensor placed on tray located on the robotic arms table in Figure 19. The white arrow indicates the tray equipped with sensors. The monitor in the upper left corner of Figure 20 displays the machine vision perspective of the assembly area on the printed web.



Figure 19. Sensor components placed with specific PET carriers on a tray pointed with a white arrow.

The R2R assembly process started with robotic arm1, which picked the pH sensor from the component tray as shown in Figure 20.

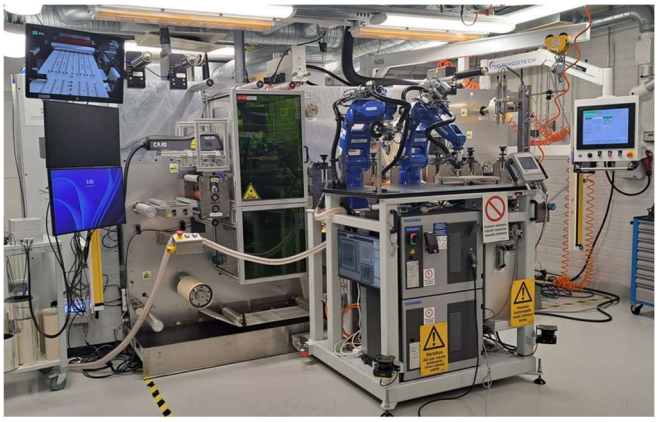


Figure 20. Robotic arm1 picked pH sensor component from the component tray.

Arm1 picked up pH sensor and placed it to PET carrier film removal by arm2 that hen removed carrier film and dumped film into the waste container. Arm1 placed and bonded pH sensor with conductive adhesive on the specific bonding area on printed paper web using machine vision.

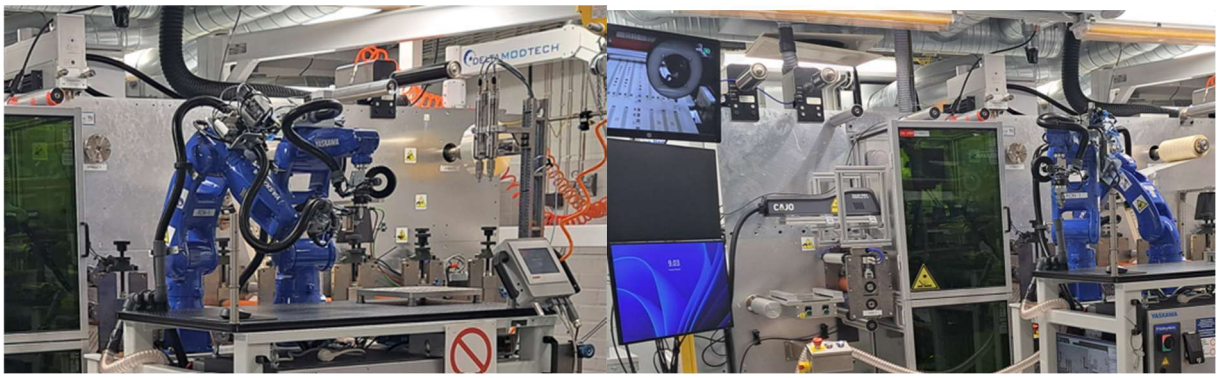


Figure 20. R2R assembly of pH sensor.

Arm1 picked a pH reference sensor from tray and placed it to robotic arm2 for PET carrier film removal. Next arm1 placed pH sensor with conductive adhesive on printed paper web using machine vision, see Figure 21.

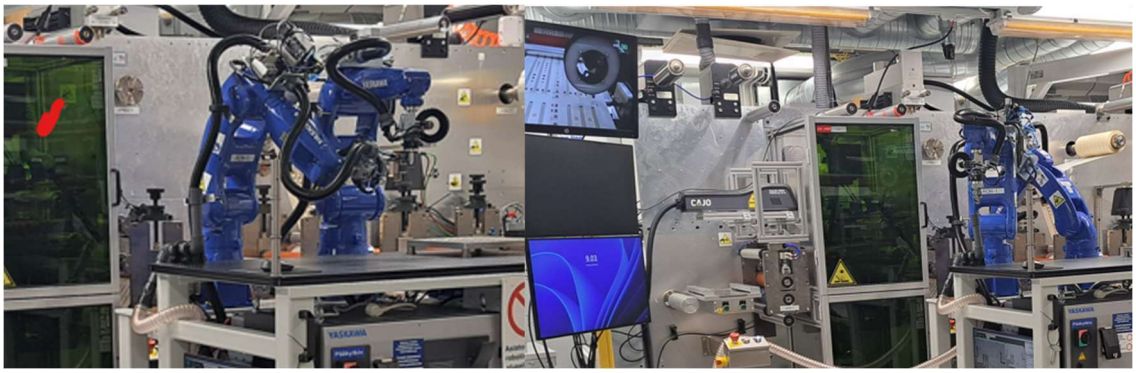


Figure 21. R2R assembly of pH reference sensor.

Arm1 picked an enzyme sensor from tray and placed it to arm2 for PET carrier removal. Then arm1 placed and bonded enzyme sensor with conductive adhesive on the targeted location on the printed web using machine vision, see Figure 22.



Figure 22. R2R assembly of enzyme sensor.

The sensors assembled onto the printed paper web repeatedly until the entire work area was completed. Once the area was completely assembled, the web was moved to the next assembly set position determined by reference points on the web. Process repeated until assembly is finished, held, or aborted. As a conclusion, R2R assembly process applying robotic arms for component picking and removal of PET carrier followed by sensor components placing by robotic arm on contact pads using machine vision guidance was designed, implemented, and demonstrated.

2.5 Mechanical and electrical testing

For the development of sustainable and flexible devices, it is necessary to select a new set of materials. Biodegradability, low carbon footprint, and functionality of the product under mechanical strain were the main emphases in the material selection. Carbon and copper conductors were studied as an alternative to silver conductors, and various paper-based substrates were studied as an alternative to plastic-based substrates such as PET.

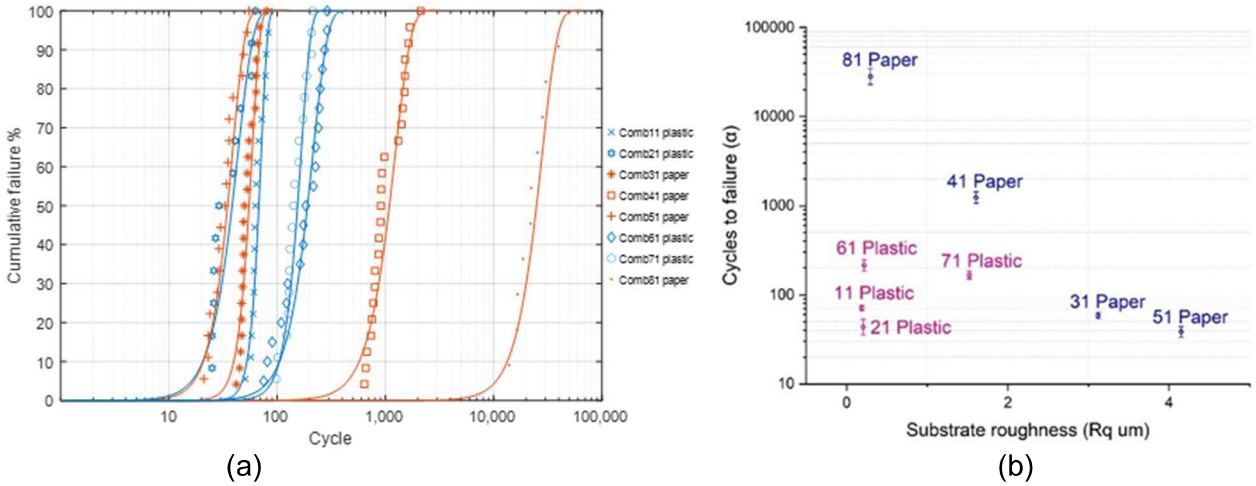
To ensure that the new set of materials operate correctly and consistently, and that the electrical functions of the materials remain stable when exposed to bending the electromechanical reliability of the materials was studied with cyclic bending tests. The test method was parallel plate cyclic

bending with one plate moving and the other stationary. The distance between the plates was adjusted to subject the samples to various bending radii. In the first phases of the project a self-made horizontal bending device was used and in the last phase a Mark-10 measurement equipment was utilized. Mark-10 equipment enabled more precise adjustment of the bending radius. National instruments' (NI) USB-6003 was used for the data acquisition along a program written in LabVIEW. The program logged the resistance of the conductive tracks and a 70% increase in resistance from the initial value was set as a failure criterion. The tracks' resistances were determined based on voltage division and fixed known resistances. In the first generation the material combinations presented in Table 7 were tested.

Table 7. Material combinations used on the first generation.

Combination XY	Substrate	Ink
11	PET-75 µm	Silver
12	PET-75 µm	Carbon A
13	PET-75 µm	Carbon B
14	PET-75 µm	Carbon C
21	PET-120 µm	Silver
31	Brown insulation paper	Silver
41	White coated paper	Silver
51	Sustainable Packing Material (SPM)	Silver
61	Polypropylene white 60 (PP)	Silver
71	Polylactide (PLA)	Silver
81	Regenerated cellulose film	Silver

The samples were subjected to compressive bending with a bending radius of 9 mm. Carbon-based inks on PET showed excellent results as their resistance did not reach the failure criteria even after 30 000 bent cycles. Silver-based inks on plastic substrates reached the failure criteria by around 200 cycles, but silver on regenerated cellulose film survived almost 30 000 cycles as the following Weibull's cumulative distribution in Figure 23 shows.



(a) (b)

Figure 23. (a) Weibull distribution of silver tracks and (b) substrate roughness vs. cycles to failure (on right).

Further material characterization revealed a strong correlation between substrate surface roughness and electromechanical reliability for paper-based substrates as Figure 23b shows. The most reliable substrates with silver ink were also the thinnest. The results are available in more detail in [Puutio et al, 2026].

In the second generation copper ink replaced silver as a conductive material and it was tested with PET, wood-based PP (polypropylene) white, regenerated cellulose film and PLA. The compressive and tensile bending reliability of three different carbon inks were also tested now with 5 mm bending radius. Similarly to generation 1 results the bending tests did not cause carbon inks to degrade even with this smaller bending radius. Their normalized resistance value remained relatively stable between 0.8 – 1.05 times the initial resistance and the 1.7 limit was not thus reached. Compressive and tensile bending showed similar results. Figure 24 shows carbon ink on a thinprint paper substrate with both compressive (C) and tensile (T) bending. Saturation of normalized resistance is evident.

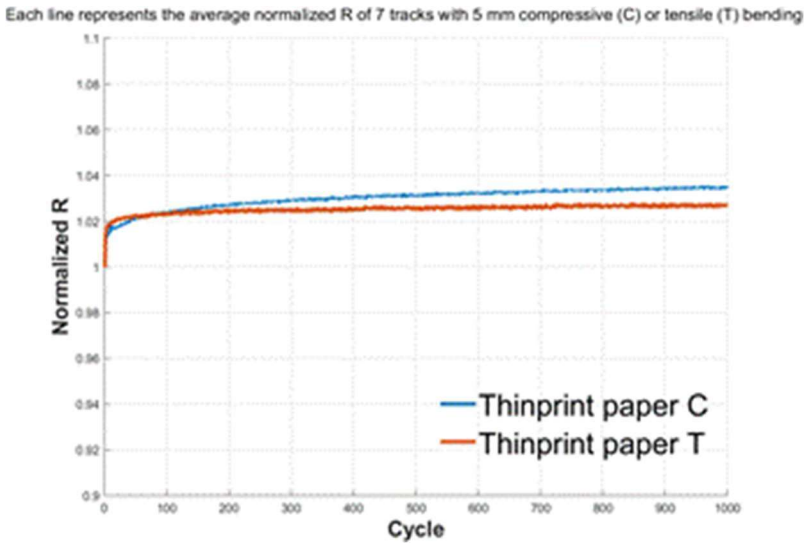


Figure 24. Carbon ink on thinprint paper

Copper tracks were more electromechanically reliable than generation 1 silver tracks across all substrates tested except PLA. On PLA, the copper tracks failed at ~129 cycles, whereas on the other substrates their normalized resistance saturated at ~1.4× the initial value. This is shown in Figure 25a. The normalized resistance of copper ink on a regenerated cellulose film substrate saturates under 9 mm compressive bending. Silver ink on the same substrate failed at ~30 000 bending cycles.

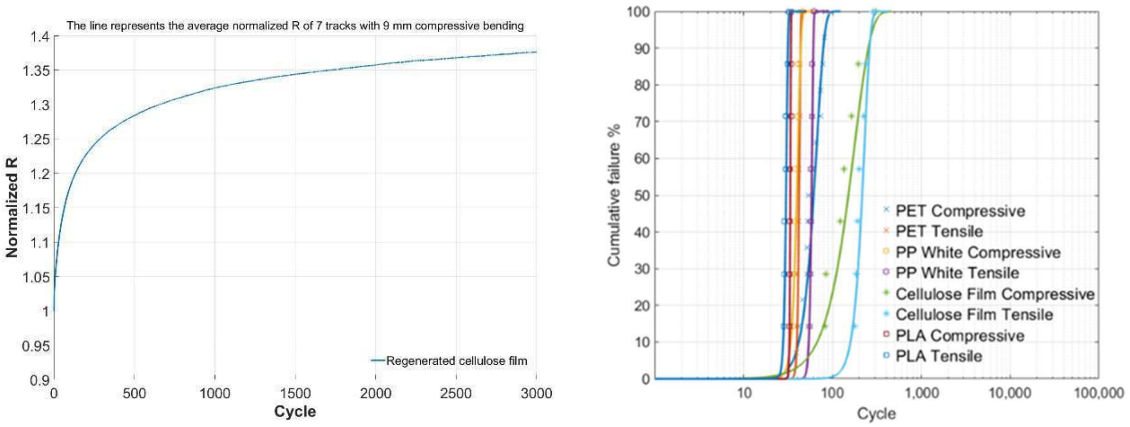


Figure 25. (a) Copper on regenerated cellulose film and (b) Weibull distribution of copper tracks (5 mm)

When the strain on copper conductors was increased by decreasing the bending radius to 5 mm, all samples with compressive or tensile bending failed at the latest after ~200 cycles as Figure 25b indicates. The best reliability was received with regenerated cellulose film.

In the third generation carbon and copper inks were further tested on brown insulation paper, white coated paper, PET and 40% post-consumer recycled (PCR) PET. In addition, a recyclable silver ink on PET was tested; however, it proved unstable, reaching the failure threshold after an average of ~60 cycles under 9 mm compressive bending. Across all substrates tested at a bending radius of 5 mm, carbon□ink tracks showed no valid evidence of degradation, nor were there significant differences between compressive and tensile bending.

For copper ink, the cyclic bending reliability depends on the design parameters. With tensile bending the failure happened earlier than with compressive bending. Figure 26a shows that, at a 5□mm bending radius, copper ink on PCR PET fails earlier in tension than in compression. Cyclic bending reliability increased as the bending radius was increased as shown in Figure 26b. On white coated paper, copper failed after ~120 cycles at a 5 mm tensile bending radius; at 7 mm the average cycles to failure increased to ~4000; at 9 mm, no failure was observed within the test limit. The best results with copper ink were received with white coated paper and PET PCR, which were also the two thinnest substrates. Thus, thinner substrates endured more bending cycles than thicker ones.

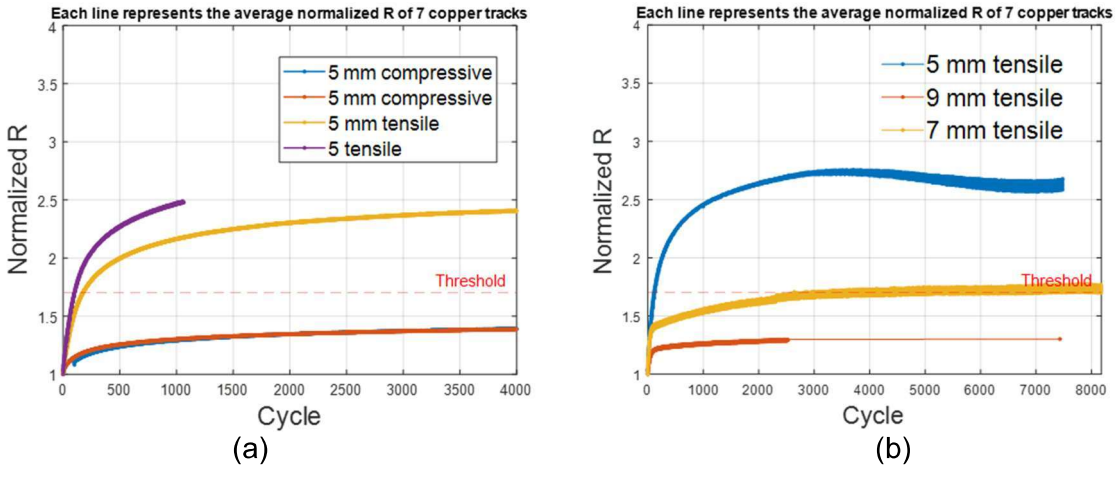


Figure 26. (a) Copper on PET PCR with 5 mm bending radius and (b) Copper on white coated paper

3 Component development

3.1 Supercapacitors

Development of sustainable energy storage components for use case 3 (environmentally compatible single-use electronics) was carried out by TAU. Specifically, the goal was to develop supercapacitor modules capable of substituting batteries in low-power disposable electronics, which was demonstrated using the C-peptide sensor of Pilot 3.1a. The key benefit of supercapacitors as compared to batteries is their more sustainable electrode composition; supercapacitors based on electrochemical double-layer capacitance (EDLCs) employ inert and non-toxic carbon electrodes that can be easily derived from various abundant biomaterials. In addition, EDLCs are capable of rapidly charging and discharging within minutes and have a long lifetime of up to 10,000–1,000,000 charge-discharge cycles. Their main challenges include relatively low energy density, high electrolyte toxicity, and tendency to self-discharge over time. Commercial supercapacitors typically employ tetraethylammonium tetrafluoroborate salt in acetonitrile solvent as their electrolyte, which enables high cell voltages (~2.7 V) and energy densities, but is relatively costly and environmentally harmful. The supercapacitor development carried out under Sustronics thus focused on finding more sustainable alternatives to conventional supercapacitor electrolytes, balancing cost, performance, and environmental impact. Fully disposable supercapacitor devices were fabricated using screen-printing technique and non-critical raw materials to demonstrate suitability for the pilot application.

Over the course of the project, three generations (Gen 1–3) of functioning supercapacitor devices capable of meeting Pilot 3.1a requirements were developed. All devices were designed to have a capacitance of approximately 100 mF and a voltage window of 3.6 V as required by the C-peptide sensor. The initial Gen 1 prototype (Figure 27a) was constructed using a saltwater based electrolyte (3.4 M NaCl), which offered low self-discharge but was limited in terms of cell voltage and energy density. To allow operation at 3.6 V with sufficient margin for cell imbalance, a layout consisting of four series-connected cells was used. In contrast, Gen 2 and Gen 3 prototypes utilised sustainable deep eutectic solvent (DES) electrolytes that allowed higher cell voltages and the use of a more compact 2-cell configuration (Figure 27c), resulting in ~50% reduced size and material consumption. Additionally, Gen 2 and Gen 3 devices could be fabricated using more sustainable substrate materials, as no metallic barriers were required to prevent the electrolytes from evaporating through the substrate films; Gen 1 was printed on aluminium-laminated PET film with Al and PET thicknesses of 9 µm and 40 µm respectively, Gen 2 on plain 125 µm thick PET film, and Gen 3 on 115 µm thick biodegradable cellulose diacetate film. All prototypes were fabricated with a similar layer structure (Figure 27d) consisting of two layers of graphite acting as the positive and negative current collectors, two layers of activated carbon acting as the positive and negative electrodes, and a cellulose-based separator layer sandwiched in between the electrodes. Each layer was fabricated by flatbed screen-printing technique, where the functional material was deposited through a patterned mesh in the form of a high-viscosity functional ink. After printing and curing the layers on two separated pieces of substrate, the printed electrodes and separators were saturated with liquid electrolyte, and the two substrates were laminated together using 3M 468MP adhesive. After fabrication, the supercapacitors were electrochemically characterised using galvanostatic charge-discharge (GCD), cyclic voltammetry (CV), electrochemical impedance spectroscopy (EIS) and constant voltage hold (CVH) techniques. Development of Gen 1, Gen 2, and Gen 3 prototypes is discussed in sections 3.1.1, 3.1.2, and 3.1.3 respectively.

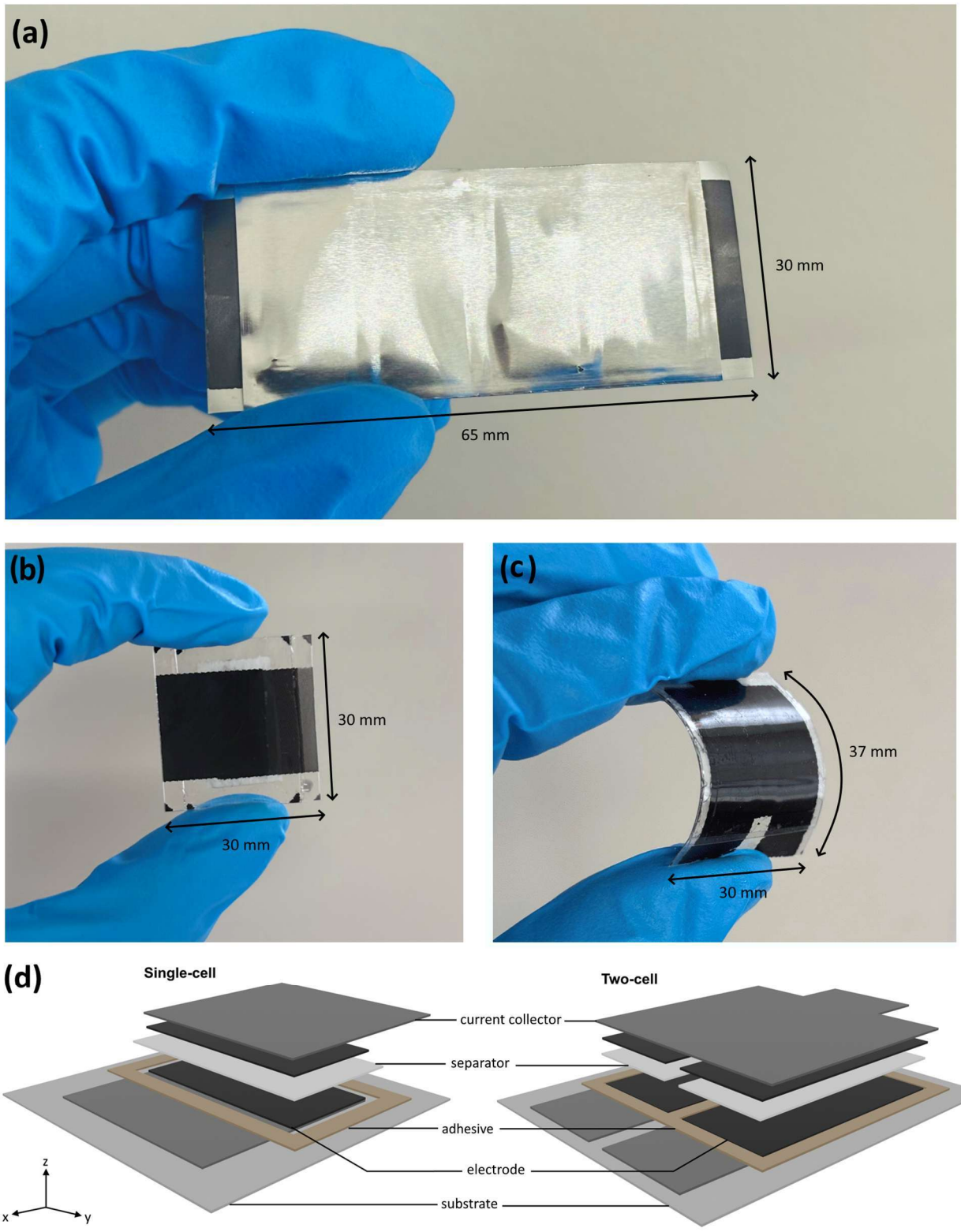


Figure 27. Fabricated supercapacitors. (a) Initial Gen 1 prototype with four series-connected cells and aqueous electrolyte, (b) single-cell supercapacitor used for electrolyte characterisation, (c) 2-cell design used for Gen 2 and Gen 3 supercapacitors, (d) schematic illustration of the layer structure.

3.1.1 Generation 1

Based on an initial assessment, aqueous electrolytes and Reline were considered the most promising sustainable electrolyte alternatives. Aqueous electrolytes consist of salt dissolved in water, and they generally provide high ionic conductivity at a low cost. Reline is a DES composed of choline chloride (ChCl) and urea (UR), where the former acts as a hydrogen bond acceptor (HBA) and the latter as a hydrogen bond donor (HBD). When mixed, the compounds form a viscous liquid that that is less ionically conductive than aqueous electrolytes but is stable at higher cell voltages (>2 V). Initial 3.6 V test supercapacitors with two (1.8 V/cell) and four (0.9 V/cell) series-connected cells were fabricated using Reline and aqueous electrolytes, respectively. The aqueous electrolyte was prepared by dissolving sodium chloride (NaCl) to water in a mass ratio of 1:5 (~3.4 mol/l), while Reline was prepared by mixing ChCl and UR in a molar ratio of 1:2 at 70 °C until a homogeneous mixture was observed. High-performance bioderived activated carbon (Kuraray YP-80F) with a nominal two-electrode specific capacitance of approx. 30 F/g was employed as the active electrode material. To allow screen-printing of the material, a previously developed sustainable ink formulation (~15 F/g with NaCl) was modified to accommodate a higher specific capacitance close to the nominal value of YP-80F. The modified electrode ink (Table 8) achieved a specific capacitance of 29 F/g with NaCl and 38 F/g with Reline at 0.5 mA/cm^2 current density, reducing the amount of active material required in the supercapacitors by approx. 50% compared to the previous formulation. Electrodes and separators were both printed using custom water-based functional inks, in which bioderived chitosan was employed as an environmentally friendly binder material. Commercial conductive graphite paste (LOCTITE EDAG PF 407C E&C) with a sheet resistance of ~10–20 Ω/□ was used as a current collector material to ensure compatibility with the corrosive aqueous electrolyte. Figure 28 shows the printed layers of a 4-cell supercapacitor prior to applying the electrolyte and assembling the device.

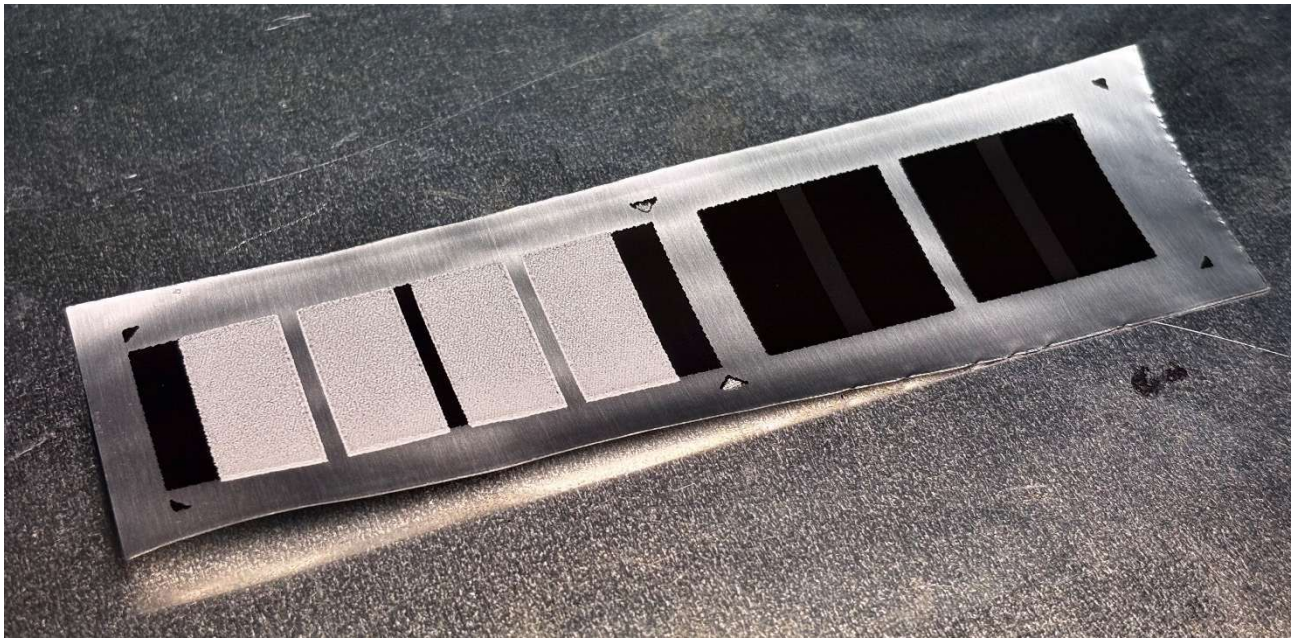


Figure 28. Gen 1 current collector, electrode, and separator layers screen-printed on the PET side of the aluminium-laminated PET substrate.

Table 8. Composition of the sustainable electrode and separator inks.

Material	Electrode ink	Separator ink
Acetic acid	0.6 wt.%	0.6 wt.%
Activated carbon	25.0 wt.%	-
Cellulose	-	8.0 wt.%
Chitosan	1.3 wt.%	1.5 wt.%
Propylene glycol	5.0 wt.%	-
Talc	-	30.0 wt.%
Water	68.1 wt.%	59.9 wt.%

The aqueous 4-cell Gen 1 supercapacitor (Figure 27a) demonstrated an average total capacitance of 79 mF (1 mA discharge), equivalent series resistance (ESR) of 30 Ω (10 mA IR-drop), and leakage current of 22 µA (1 h CVH at 3.6 V), which was found sufficient for powering the sensor. The main drawbacks of the design were its large size (65 mm x 30 mm) due to the 4-cell construction, and the need for metal in the substrate to prevent the aqueous electrolyte from evaporating through PET. In contrast, the self-discharge rate of Reline-based cells was found to be too high to maintain sufficient voltage for the sensor regardless of the cell size. Using the 2-cell layout shown in Figure 27c, an average capacitance of 220 mF, ESR of 58 Ω, and a leakage current of 92 µA was measured. In addition to higher leakage current, a significant increase in ESR was observed, mainly due to the higher viscosity and lower ionic conductivity of the DES.

3.1.2 Generation 2

The goal for Gen 2 was to find an alternative DES with lower self-discharge characteristics to reduce the size and material consumption of the supercapacitor. Three ChCl-based DESs with alcohol-HBDs were investigated for this purpose; single-cell test supercapacitors with an electrode area of 2.0 cm^2 (Figure 27b) were fabricated using the same materials and printing parameters as for Gen 1. DESs with glycerol (GL), propylene glycol (PG), and ethylene glycol (EG) HBDs were synthesised with a similar process as ChCl:UR, using molar ratios of 1:2, 1:3, and 1:2 respectively, and employed as electrolytes in test cells together with ChCl:UR and aqueous NaCl. The main performance parameters, including viscosity (η), ionic conductivity (σ), specific capacitance (C_s), specific leakage current (I_s), ESR, energy density and power density, are summarised in Table 9.

Table 9. Comparison of electrochemical performance in single-cell test supercapacitors (mean ± standard deviation, n=6)

Electrolyte	η (mPa s)	σ (mS cm^{-1})	C_s (F g^{-1})	I_s (µA F^{-1})	ESR_{GCD} (Ω)	ESR_{EIS} (Ω)	ED (Wh kg^{-1})	PD (kW kg^{-1})
ChCl:UR	2905.70	0.65 ± 0.02	38.4 ± 2.3	171.0 ± 14.8	17.5 ± 3.3	15.4 ± 3.6	17.3 ± 1.1	6.9 ± 1.8
ChCl:GL	970.45	1.49 ± 0.02	29.9 ± 1.5	116.2 ± 13.4	17.8 ± 3.6	15.8 ± 3.6	13.5 ± 0.7	7.2 ± 1.3
ChCl:PG	176.35	3.40 ± 0.12	27.4 ± 1.1	103.0 ± 15.9	18.8 ± 3.6	16.7 ± 3.0	12.3 ± 0.5	6.4 ± 1.2
ChCl:EG	157.26	10.44 ± 0.04	30.0 ± 2.1	122.9 ± 16.4	16.0 ± 2.2	17.1 ± 2.6	13.5 ± 0.9	7.5 ± 2.0
NaCl	6.00	187.26 ± 1.29	28.8 ± 2.2	58.1 ± 7.8	13.7 ± 3.1	13.1 ± 2.1	5.8 ± 0.4	4.3 ± 1.4

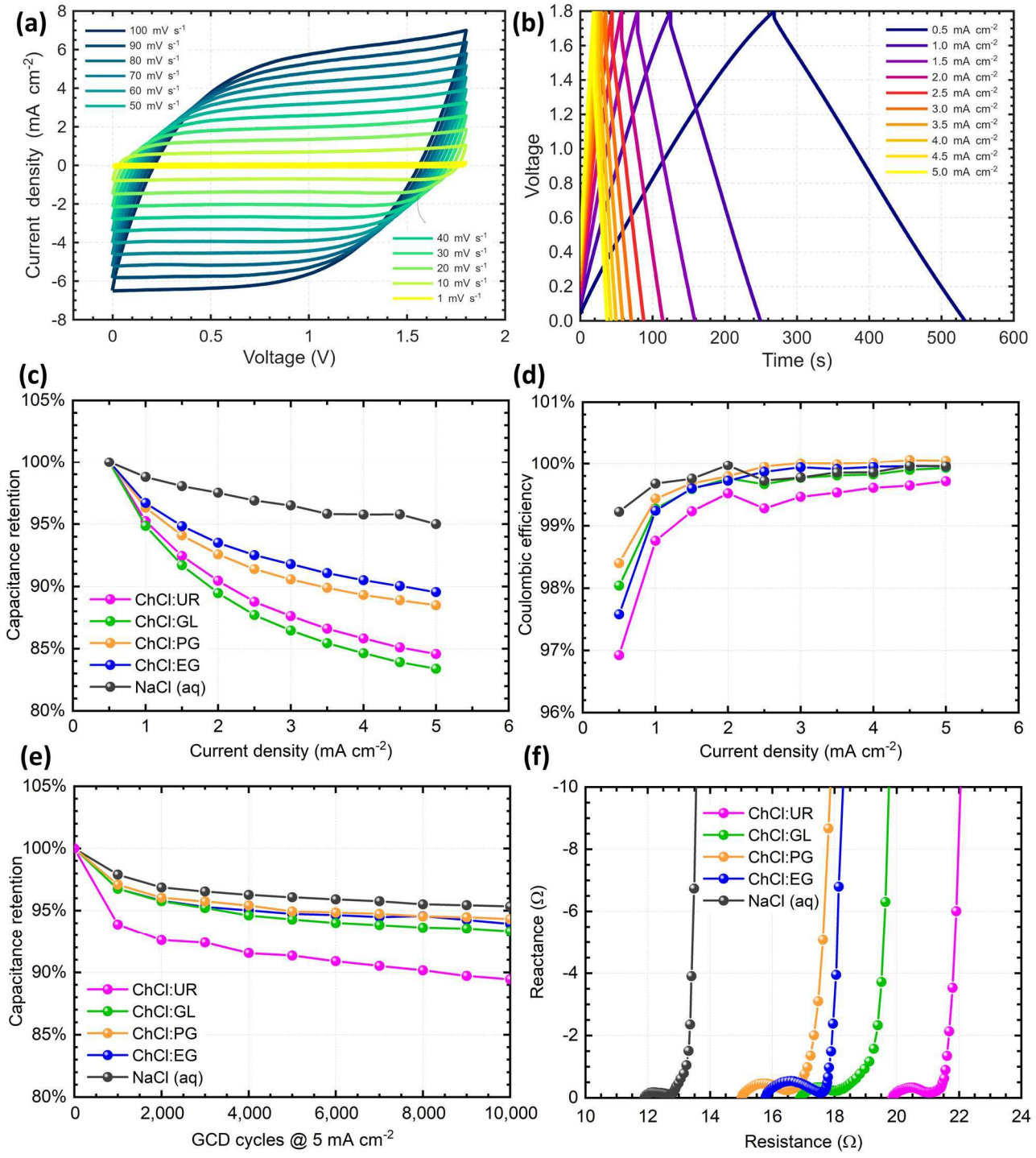


Figure 29.Electrochemical characterisation of single-cell devices. (a) CV of ChCl:PG at 1–100 mV/s, (b) GCD of ChCl:PG at 0.5–5 mA/cm^2, (c) GCD rate capability, (d) GCD coulombic efficiency, (e) cyclic capacitance retention, (f) EIS at 10 mHz to 1 MHz.

ChCl:GL, ChCl:PG, and ChCl:EG supercapacitors all demonstrated similar capacitive performance to the aqueous electrolyte at 0.5 mA/cm^2 current density, while the specific capacitance of ChCl:UR exceeded that by approx. 30%. At higher current densities, the capacitance recorded with all DESs decreased relatively fast (Figure 29c) due to their high viscosity which slows down ionic movement. Typical EDLC-profiles in all recorded CV (Figure 29a), GCD (Figure 29b), and EIS (Figure 29f) plots

were observed; however, significant faradaic activity at the electrode-electrolyte interface was implied by the high specific capacitance and reduced cyclic stability (Figure 29e) of ChCl:UR compared to other electrolytes. Parasitic faradaic reactions were also considered the main reason behind the leakage current and self-discharge of the supercapacitors. With all DESs, the measured leakage current was found to increase exponentially with cell voltage (Figure 30a) and decrease with longer charging time (Figure 30b); however, alcohol-based DESs demonstrated consistently lower leakage currents and better open-circuit voltage retention compared to ChCl:UR. Of the investigated DESs, ChCl:PG was considered the most promising due to its low leakage current and high sustainability. Two-cell supercapacitors fabricated using the layout shown in Figure 27c demonstrated capacitance, ESR, and leakage current values of 118 mF, 71 Ω, and 22 µA respectively, which were found sufficient for the application. The elimination of the metallic barrier film and ~50% reduced size compared to Gen 1 resulted in improved sustainability through reduced material use.

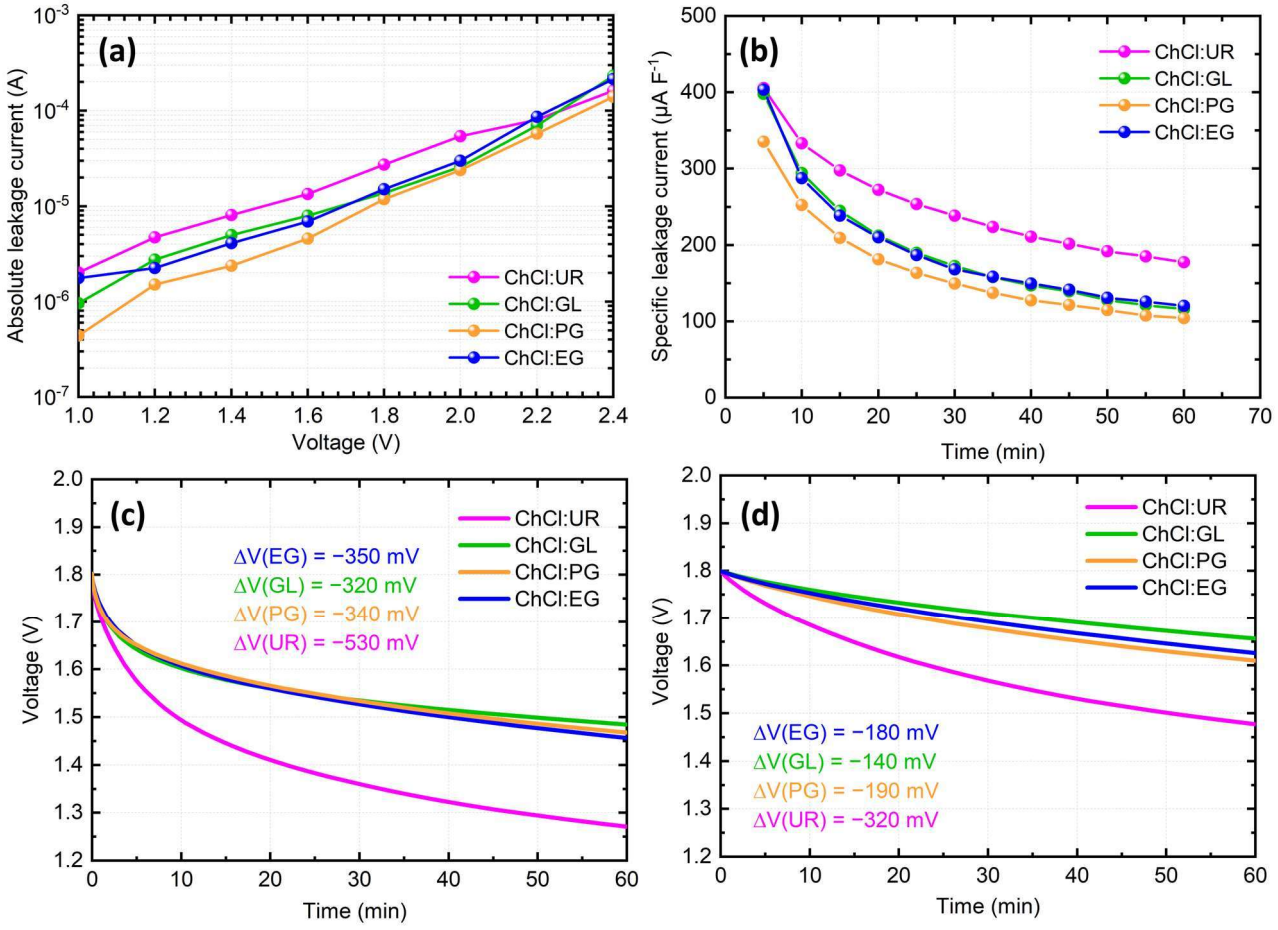


Figure 30. (a) Measured leakage current as a function of voltage, (b) specific leakage current during CVH at 1.8 V, (c) open-circuit voltage retention without prior CVH, (d) open-circuit voltage retention with 1 h CVH at 1.8 V.

3.1.3 Generation 3

To further reduce self-discharge, heat treatment of alcohol-based DESs to remove redox-active impurities from the electrolyte was investigated. The best results were obtained with treatment of ChCl:GL at 90 °C for 24 hours (Figure 31), yielding a capacitance of (140.5 ± 6.8) mF/cm^2 and a specific leakage current of (57.0 ± 6.7) µA/F (mean ± standard deviation, n=8) in single-cell test

supercapacitors. For the final Gen 3 prototype, the PET substrate of the supercapacitor was replaced with a biodegradable cellulose diacetate (CDA) film with a thickness of 115 µm to further improve the sustainability of the design. This required lowering the curing temperature of the graphite ink from 120 °C to 60 °C to preserve the CDA film but did not significantly affect measured resistance. Using the same 2-cell layout as with Gen 2, capacitance, ESR, and leakage current values of 133 mF, 71 Ω, and 17 µA respectively were measured, sufficient for meeting the requirements of the sensor application.

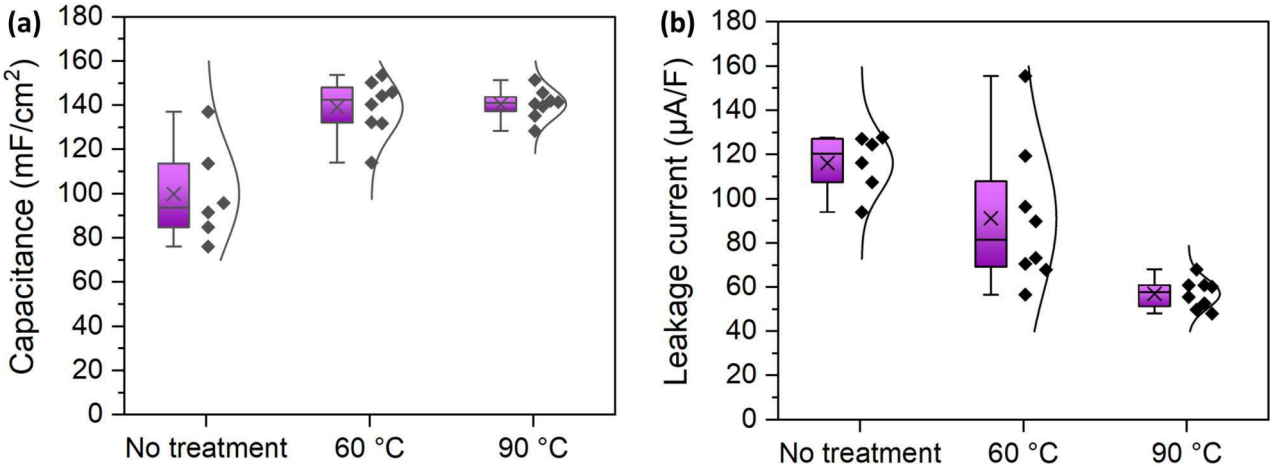


Figure 31. Effect of DES heat treatment temperature on (a) capacitance and (b) specific leakage current of single-cell ChCl:GL supercapacitors.

3.2 Light guides

Connected to Pilot 1.3 VTT developed a highly transparent/translucent biodegradable film for use in an illumination device by light guiding and material modifications. This diffuser film scatter and homogenize light, enhancing visual comfort and performance in various lighting and display applications. The targeted specifications for the illumination device were >60% transparency (at visible wavelengths), a diffusion angle of ca. 80°, no light distortion and no bright spots. Also, films should stand temperatures up to ca. 60 °C and be possible to adapt to a lamp structure (not too fragile).

Diffusion characteristics were varied by using nanocellulose film (CNF) loaded with TiO_2 particles. The amount of TiO_2 was varied from 1% to 7% and the film dry thickness from 20 µm to 100 µm. Test films were prepared using solution casting or bar coating. The film manufacturing is scalable in high volumes quite easily. Transmission was measured using the setup shown in Figure 32a. The system is based on a super continuum light source (450-2400 nm) with an 850 nm low-pass filter, integrating sphere and optical analyser. A pinhole and a silicon photodetector were used for collimated beam alignment. Visible range transmission was measured between 450 nm and 800 nm with 10 nm resolution. The scattering angle was defined with the same supercontinuum light source without any filters. Scattering of 4% CNF-TiO_2 sample in Figure 32b is presented at 75 mm distance in Figure 32c. The angle was calculated with Image J software.

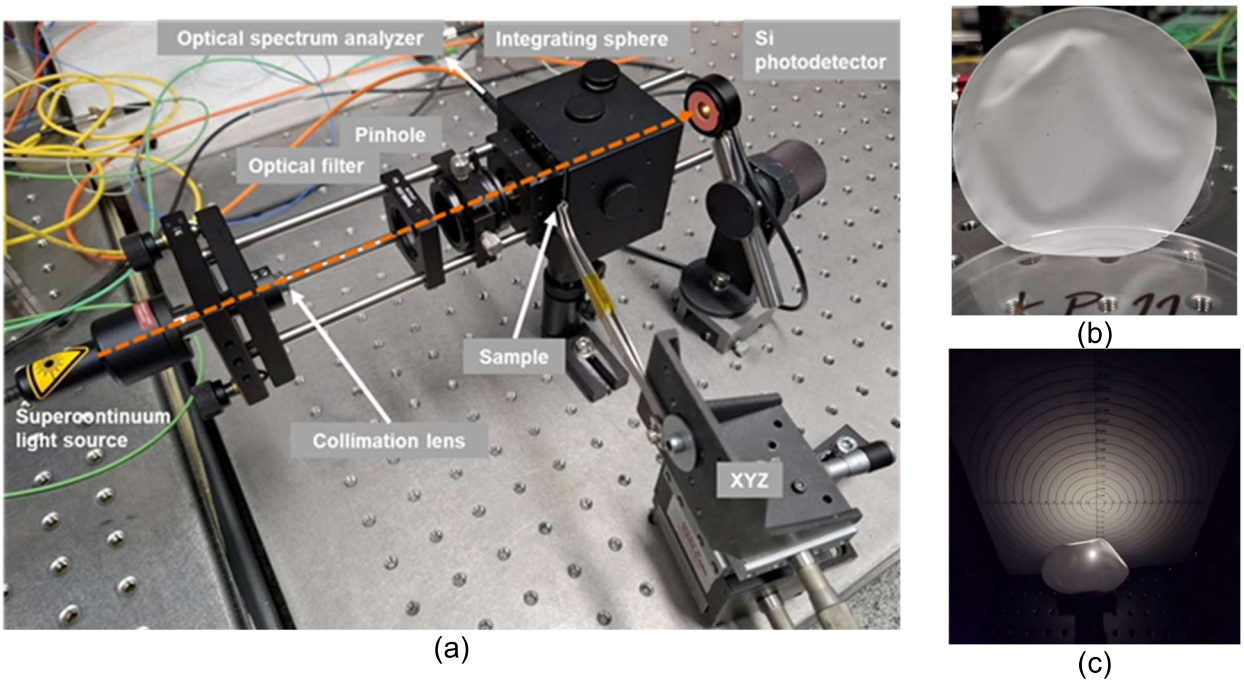
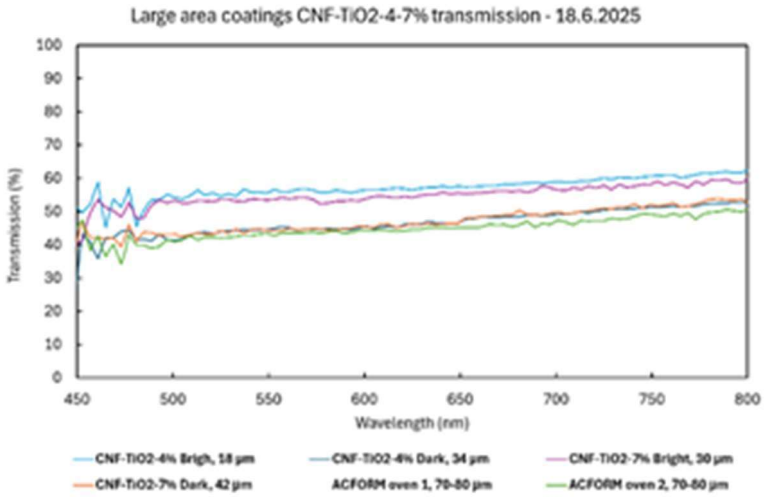


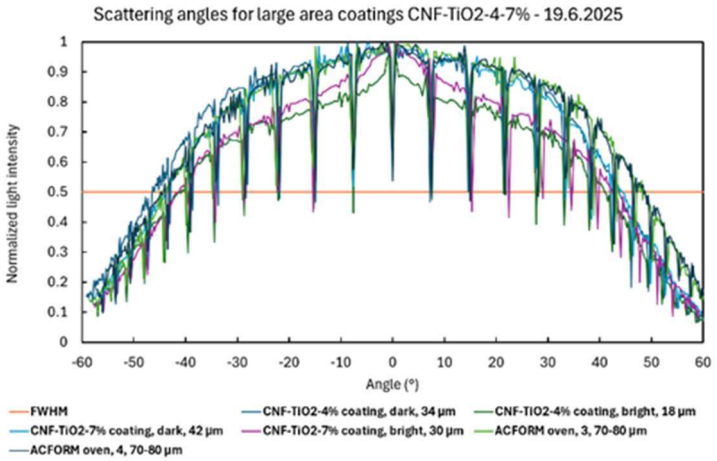
Figure 32. a) Transmission measuring setup based on super continuum light source with 850 nm low-pass filter. b) Scattering angle measurement with c) 4% CNF-TiO_2 sample.

Transmission and scattering angles of the selected diffuser film are shown in Figure 33. It can be seen that the transparency (Figure 33a) and scattering angle (Figure 33b) are very close to the target values. The real illumination device test setup (50 mm x 300mm) in Figure 33c shows that light source gives already very homogenous lightning. Optimising TiO_2 content and film thickness diffuser properties can be customized.

a)



b)



c)



Figure 33. Examples of a) transmission and b) scattering angles of selected films. c) Real test illumination device with CNF/TiO_2 diffuser film (below).

Using a diffuser will allow for utilising the photons in a more efficient way in the use phase of the luminaire as more photons are directed into the desired direction thereby lowering the need for high-power LEDs. The energy consumption in the use phase is therefore reduced. Furthermore, the materials used for the diffuser are chosen because of the reduced sustainability impact of nanocellulose and TiO_2. Nanocellulose material is biodegradable and thereby very good alternative for plastic-based products. TiO_2 is recyclable, and several methods have been developed to recover and reuse it, especially due to its widespread use and environmental impact.

3.3 Paper fluidics

In the development of paper fluidics by VTT for Pilot 3.1a, hydrophobic fluidic channel boundaries were screen-printed onto porous paper substrates using self-formulated coloured beeswax emulsion ink. Channel boundaries ensured that hydrophilic test fluid travelled by capillary force from the sample are to the absorbing area, and no fluid was spreading outside the channel area (Figure 34). The mesh count of the screen was 325 lines/inch and the ink layer was dried in the oven at 65°C for 10 min. To prevent fluid from penetrating through the whole paper matrix, the backside of the paper was initially printed with a fully covering layer of un-coloured beeswax ink using flexography. Flexography was selected for the better control of the ink transfer amount. The ink transfer volume was 39.1 ml/m^2, the printing speed was 10 m/min, and the layer drying was performed at 65°C for 10 min. Figure 34 shows also the screen mesh with paper fluidic patterns and flexographic printing press.

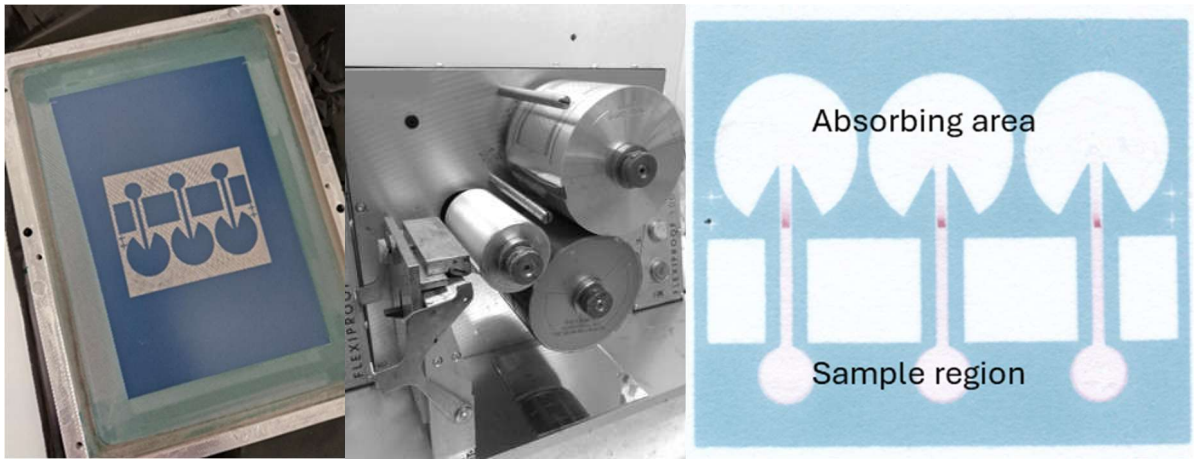


Figure 34. Screen mesh for printing channel boundaries using screen printing (left), flexographic printer RK Flexiproof 100 (middle), and paper fluidics printed onto porous paper.

The developed ink contained beeswax emulsified with 2-butoxy ethyl acetate, ethyl cellulose, and colorant. Slightly different ink formulations were developed for screen printing and flexography because of their different ink requirements, such as solids content, viscosity range etc. The ink solvent was removed from the printed layer during oven drying, thus leaving the sustainable wax layer onto the paper and making the paper fluidic device biodegradable or fully recyclable with existing recycling processes. The low drying temperature removed the solvent but did not melt the beeswax so that wax could spread into the channel area. Filter papers, thin analytical paper (90 gsm) and thick analytical paper (165 gsm) from TER, were used as substrates. These papers were made from 100 % cotton linters, and the papers had high and consistent absorbency and porosity. In addition, the papers were biodegradable and recyclable, thus improving the sustainability of the paper fluidic device.

Good and repeatable print quality of the channel patterns with sharp edges are good coverage was achieved on both papers, but the fluid flow behaviour was different between the papers, as seen in Figure 35. With thin analytical paper paper, coloured water flowed quickly along the channels without staining the background areas. Similar behaviour was seen when using Pilot 3.1a layout (Figure 35). However, on thick analytical paper, severe background staining was seen. This indicated that the paper was too thick and hydrophobic channel boundaries could not be formed through the whole paper thickness. The ink transfer volume of the background printing needed to be less than 45 ml/m^2 to prevent the channel area to turn hydrophobic (prevented fluid flow along the channel).



Figure 35. Printed liquid channels and fluid flow in the channels on thin analytical (left, right) and thick analytical (middle) papers. Use of Pilot 3.1a layout is also demonstrated (right).

The printed paper fluidic samples (Beeswax channel patterns on thin analytical paper) were assessed using mouse/anti-mouse immunoassay. Sample liquid/buffer solution with mouse antibody conjugated to gold was transported by capillary force along the hydrophilic paper channel into the liquid absorbing region where it was captured by inkjet-printed anti-mouse antibody. As an indication of a positive test result, binding on a test line took place between anti-mouse antibody and mouse antibody resulting in red colour on the test line, as shown in Figure 36. As a result of the formation of immunocomplex, red signal appeared in 1 min after sample liquid application and all liquid was migrated into the absorbing area in 15 min (Figure 36). The developed paper fluidics could be used in Pilot 3.1a in later generations.

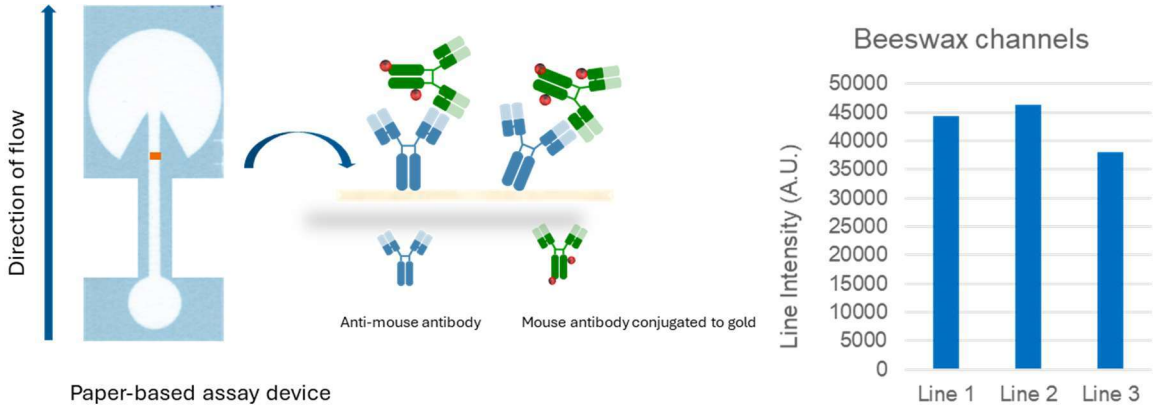


Figure 36. Principle of the mouse/anti-mouse immunoassay for the assessment of the performance of the paper fluidics (left). Performance of the printed beeswax paper fluidics on thin analytical paper in the mouse/anti-mouse immunoassay test (right).

4 Sustainability and circularity

4.1 Quantification of environmental impact with LCA

VTT implemented two types of LCA calculations: material focused calculations and pilot-specific calculations for three pilots: Pilot 2.1 (Embedded electronics for EEG monitoring led by PLUX), Pilot 2.2 (Wearable health monitoring led by SCR) and Pilot 2.3 (Sustainable dashboard for automotive led by Forvia).

4.1.1 Environmental impact of materials

Environmental impacts of sustainable electronic materials (substrates, inks, adhesives) were studied using Pilot 2.2 and the materials studied there complemented with PEF (polyethylene furaonate) from partner Avantium. A life cycle assessment focusing on carbon footprint was conducted to assess the materials sustainability. The results were based partly on calculations done by material suppliers (including Avantium) and partly by VTT using SULCA life cycle assessment tool and ecoinvent 3.10 database with cut-off allocation. Impact assessment by VTT was done using EF3.1.

The chosen **substrate** materials were two types of paper substrates, one PLA substrate, one bio-PP, one PEF and a reference fossil PET, all supplied by project partners. Figure 37 and Figure 38 show the carbon footprint results for all six alternative substrate materials per kg and m^2, respectively. All substrates show possibility of lower carbon footprints. Carbon footprints of bio-PP substrate, PEF substrate and paper substrates 1 and 2 were based on the suppliers' own calculations. PLA substrates carbon footprint was taken from literature, and the reference PET was from ecoinvent v.3.10., *market for polyethylene terephthalate, granulate, amorphous* together with extrusion data also from ecoinvent, a process called *extrusion, plastic film*. However, uncertainties remain due to the differences in availability of data.

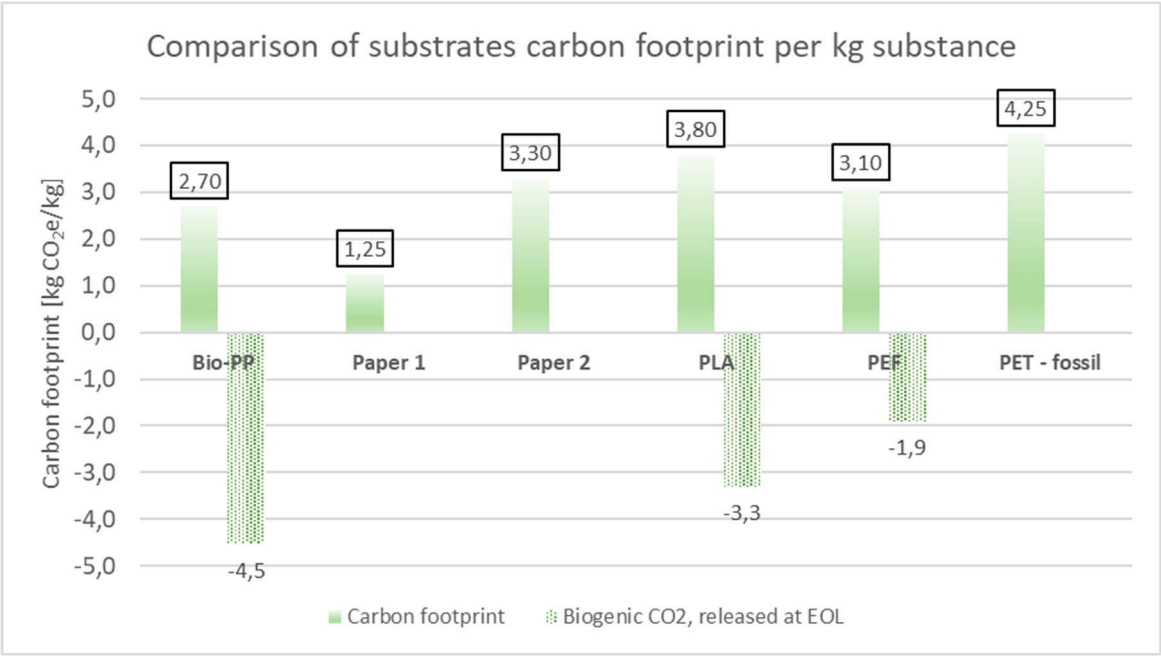


Figure 37. Carbon footprint comparison of different substrate materials per kg. The results are not fully comparable due to differences in how biogenic carbon is included.

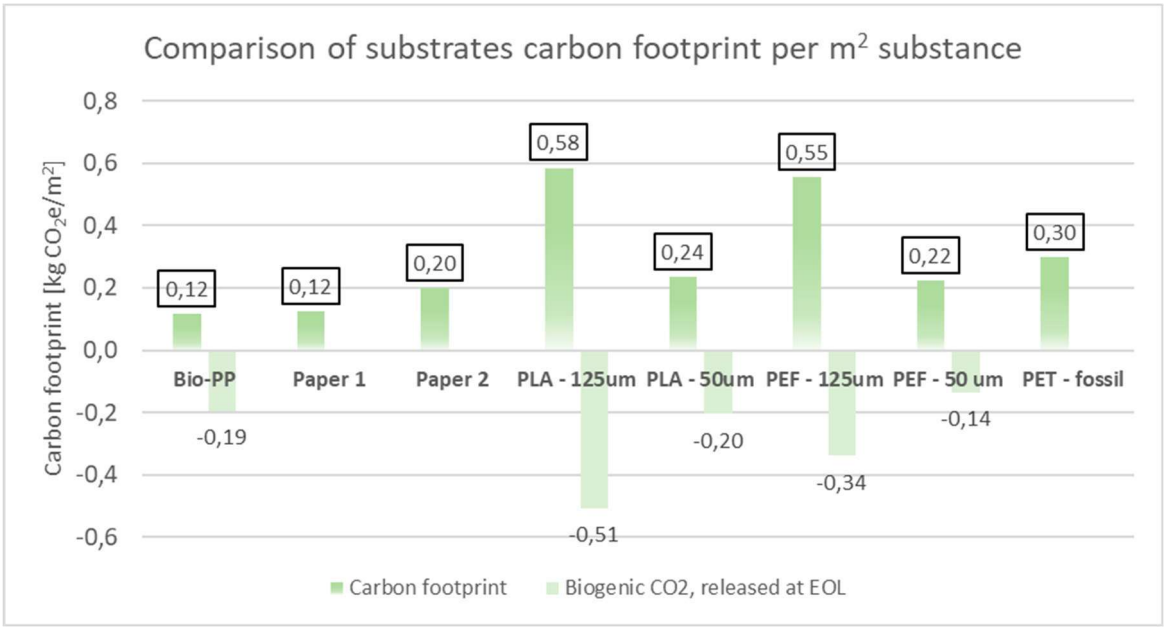


Figure 38. Carbon footprint comparison of different substrate materials per m^2. The results are not fully comparable due to differences in how biogenic carbon is included.

For **ink** comparison, four carbon inks, or pastes, were chosen: Loctite – EDAG PF407C, EMS – CI2051, Saralon – Carbon 700A and Bectron – GP9552. A previous carbon footprint calculation was available for Loctite ink. The supplier of Bectron ink was able to share its full chemical composition and that was used as basis for modelling. The other two were modelled based on chemicals that were stated in the MSDSs. Carbon footprint of the studied inks is shown in Figure 39. Saralon and EMS inks seem to have slightly lower carbon footprints than the other two. However, these results don't take into consideration the different handling techniques or temperatures required by the inks.

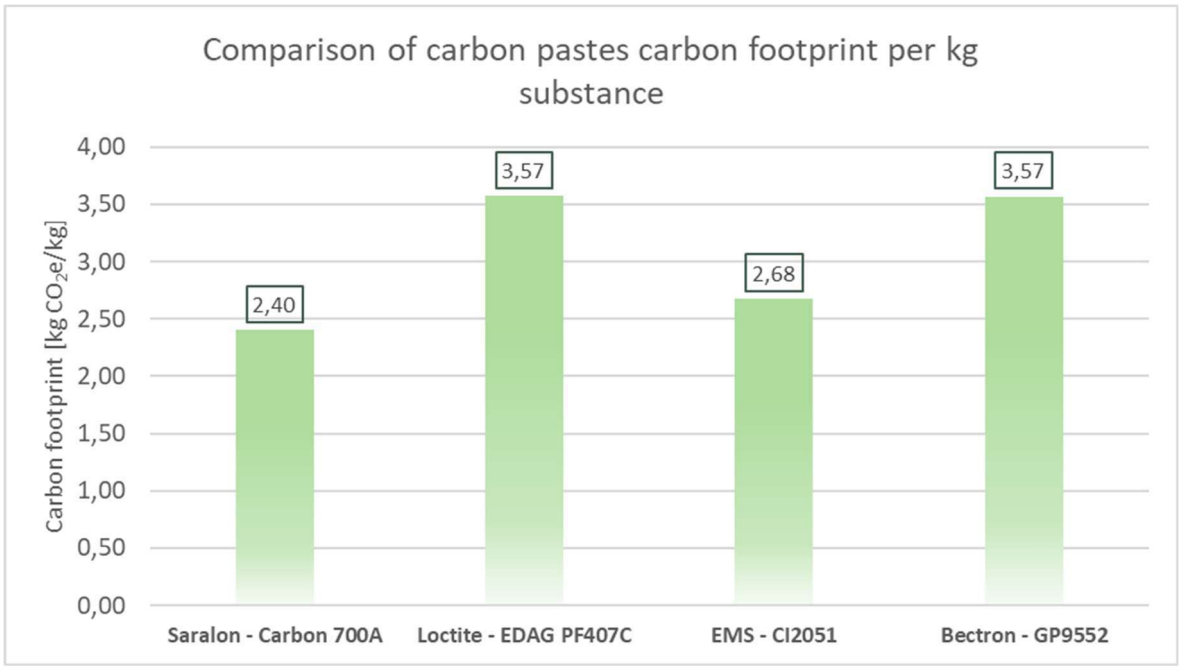


Figure 39. Carbon footprint comparison between carbon inks per kg.

Sustainability of **adhesives** can be addressed by selecting products that are based on sustainable raw materials, such as bio-based or renewable ones. Another approach is to select adhesives that can be processed during component assembly will less energy i.e. that possess lower curing temperatures and/or shorter curing times. Since commercial bio-based adhesives do not exist, the approach here was to find adhesives that consume less energy during assembly. The three adhesive combinations (selected based on component assembly results presented in Section 2.4.1) that are examined in this study were:

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

Case 1 is the state-of-the-art process used in hybrid assembly. Cases 2-3 represent novel alternatives with more sustainable approach. By utilizing calculations for energy density, this study evaluated the efficiency and sustainability of each case within electronic device applications. The findings highlight differences in power consumption for curing process, providing insights for LCA and the selection of adhesives based on energy efficiency and environmental impact. Figure 40 compares cure time and required curing power across three cases evaluated in this study. The Case 2 required the shortest curing time and the least curing power, while Case 1 has the longest curing time and Case 3 requires the most curing power.

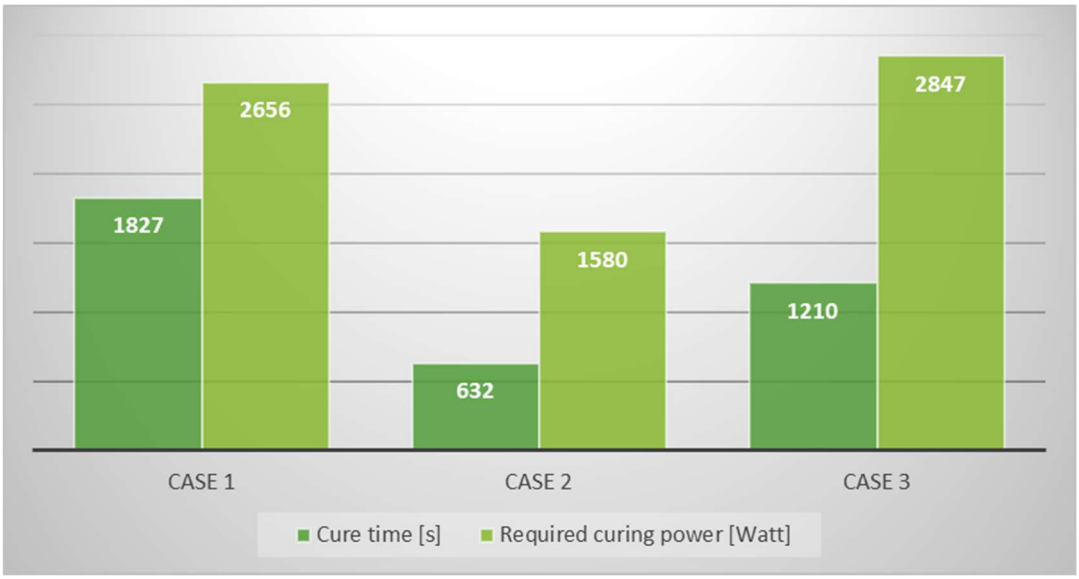


Figure 40. Comparative analysis of cure time and required curing power across the three studied cases.

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

4.1.2 Environmental impact of three pilots

Pilot 2.1 developed a next-generation EEG (Electroencephalogram) monitoring solution combining embedded electronics with sustainable design principles. The objective was to reduce the environmental footprint of EEG systems while maintaining clinical-grade signal quality and usability. The pilot was led by PLUX with contributions from SCR (electrode), PIEP (sensor) and VTT (LCA). The pilot emphasized using eco-friendly materials and integrating energy-efficient designs in healthcare monitoring equipment. This was achieved by creating EEG electrodes and sensor designs (by Laser direct structuring (LDS)) that are environmentally sustainable, minimizing disposable materials and lowering environmental footprint, ensuring signal quality matches or surpasses current clinical standards.

Scope of the LCA was cradle-to-grave with especial focus on cradle to gate for the electrode and sensor as those are the steps that the pilot partners have control over. Use stage was based on estimations by project partners and end of life was also an estimate based on literature and assumed treatment routes. The use case consisted of a two-channel forehead EEG system for daily-use scenarios, where printed electrodes connect to a sensor and signal hardware.

Figure 41 and Figure 42 present the contribution analysis of the EEG electrode during its lifetime and comparison with the non-sustainable baseline electrode, respectively. Figure 41 highlights which components of the electrode's production are most significant in terms of environmental burden, allowing for a clearer understanding of the relative impact of raw materials versus processing steps. Materials cause a big portion of the electrode's lifetime environmental impacts. Other visible impacts arise from the snap button and end-of-life. In comparison with the benchmark electrode, the project electrode shows significant improvements across all environmental impact categories.

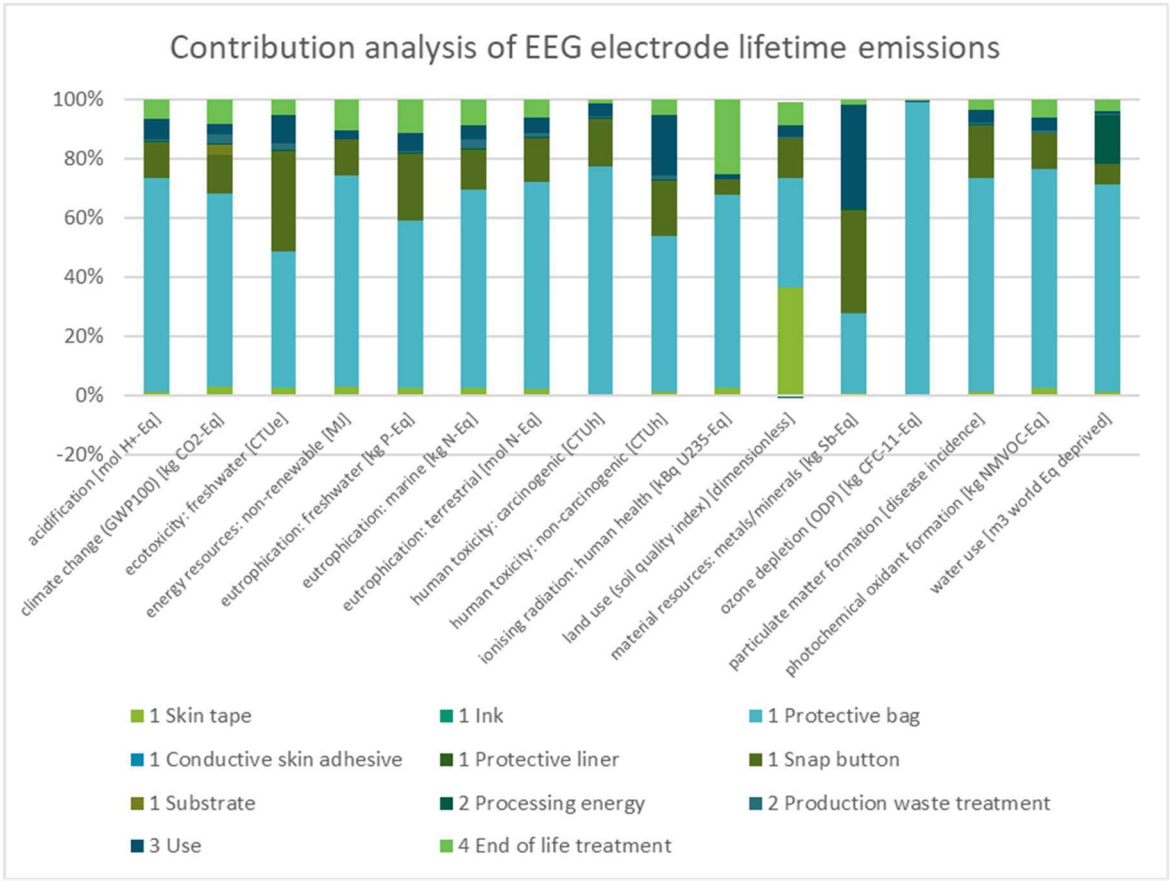


Figure 41. Contribution analysis of EEG electrode lifetime emissions.

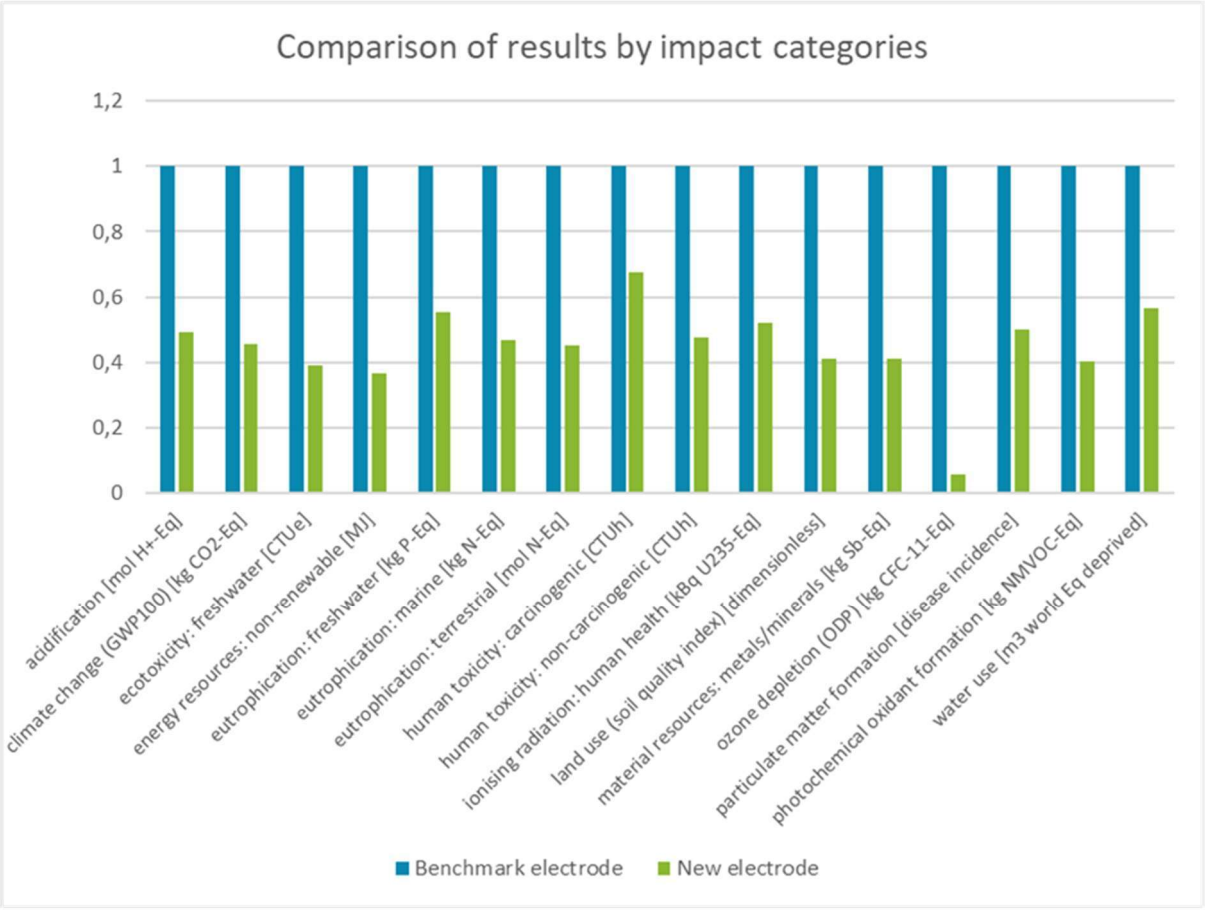


Figure 42. Comparison of baseline electrode and the electrode developed in Sustronics.

Figure 43 and Figure 44 present the contribution analysis of the LDS sensor during its lifetime and comparison with the (non-LDS) baseline sensor, respectively. The different metallization steps are responsible for approximately 80 % of the lifetime environmental impacts of the sensor depending on impact category. Most prominent are the copper and nickel stages. The raw material polycarbonate (PC) is also a cause for some impacts. In this case, 50 % of the PC is post-consumer recycled, and increasing this proportion could further benefit the environment. According to the results, the final prototype LDS sensor has higher environmental impacts in all studied impact categories. Most of these impacts come from the metallization steps.

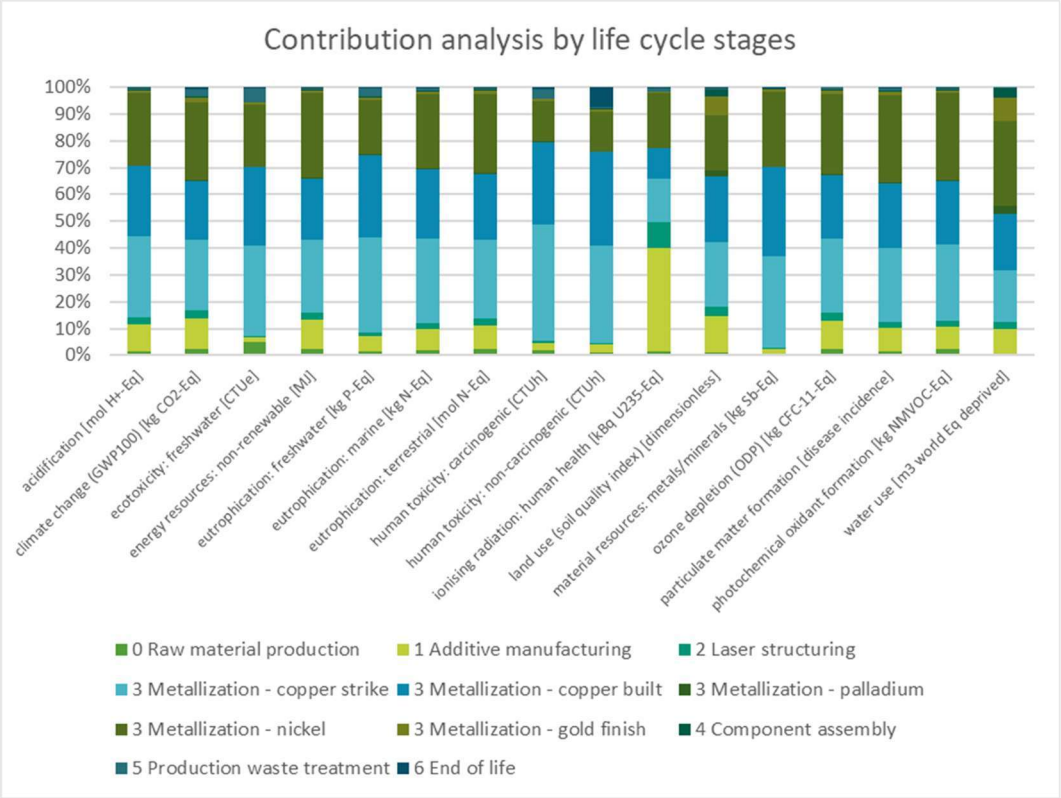


Figure 43. Contribution analysis of LDS sensor lifetime emissions.

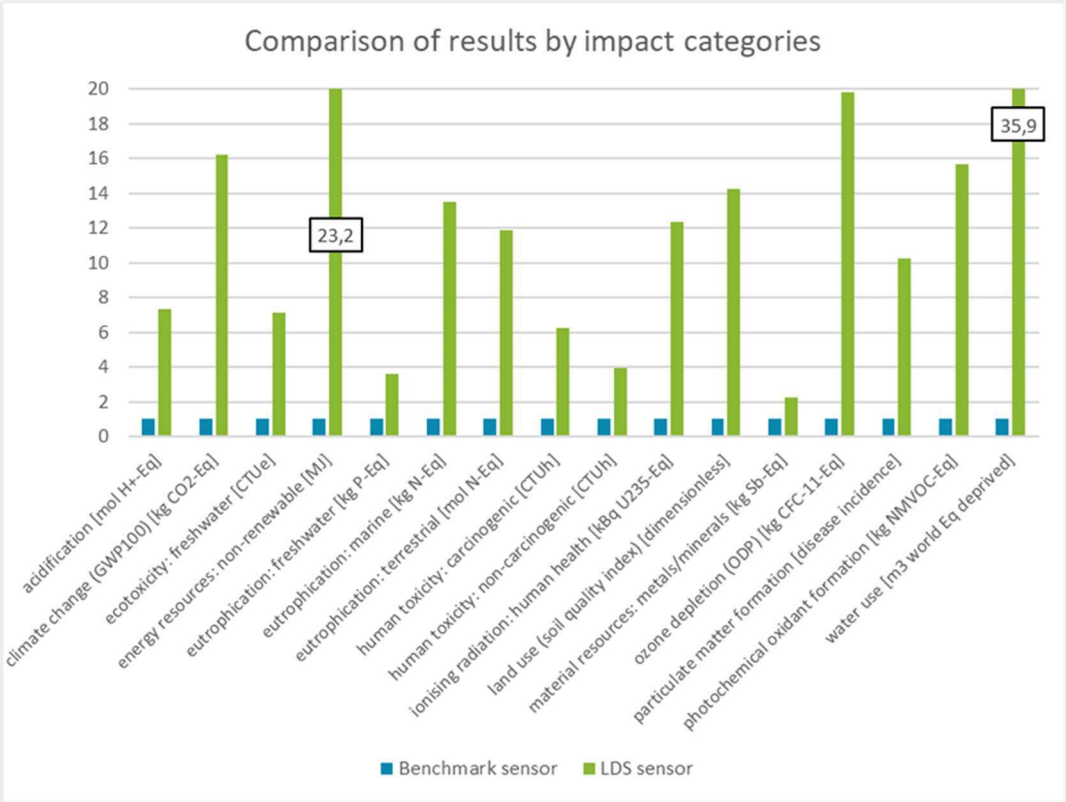


Figure 44. Comparison of baseline sensor and LDS sensor manufacturing. Use and end-of-life are excluded.

Pilot 2.2 aimed to develop wearable health manufacturing devices. It was led by SCR with contributions from MOV, TER, UPM, EDI, TAU and VTT. The target was to demonstrate the developed technologies for more sustainable wearable systems for health monitoring. LCA was used to identify the key environmental impacts of the current prototypes with focus on single use or multi use medical electrodes for ECG (electrocardiography) and bio-impedance monitoring by using more sustainable materials. Scope of the study was cradle-to-grave with special focus on cradle-to-gate for the electrodes as those are the steps that the pilot partners have control over. Use stage was based on estimations by pilot partners and end of life was also an estimate based on literature and assumed treatment routes. The electrodes are used in measuring together with a sensor, but that sensor was not included in this study, only the battery that's used by the sensor.

Figure 45 shows the contribution analysis for the electrode during its life cycle stages. The results demonstrate that while manufacturing remains the primary contributor to environmental impact, use and end-of-life have a measurable impact as well. Conductive adhesive tape is responsible for substantial impacts in almost all impact categories. Silver in the adhesive is responsible for most of these impacts. The protective bag is responsible for the biggest share of impacts in energy resources (non-renewable) and shows high impacts also in climate change, ionising radiation, photochemical oxidant formation and water use. The substrate material, white coated paper, does not show considerable impacts in climate change. Transfer adhesive on the other hand dominates ozone depletion but has minimal impacts elsewhere. Impacts from other materials vary across impact categories.

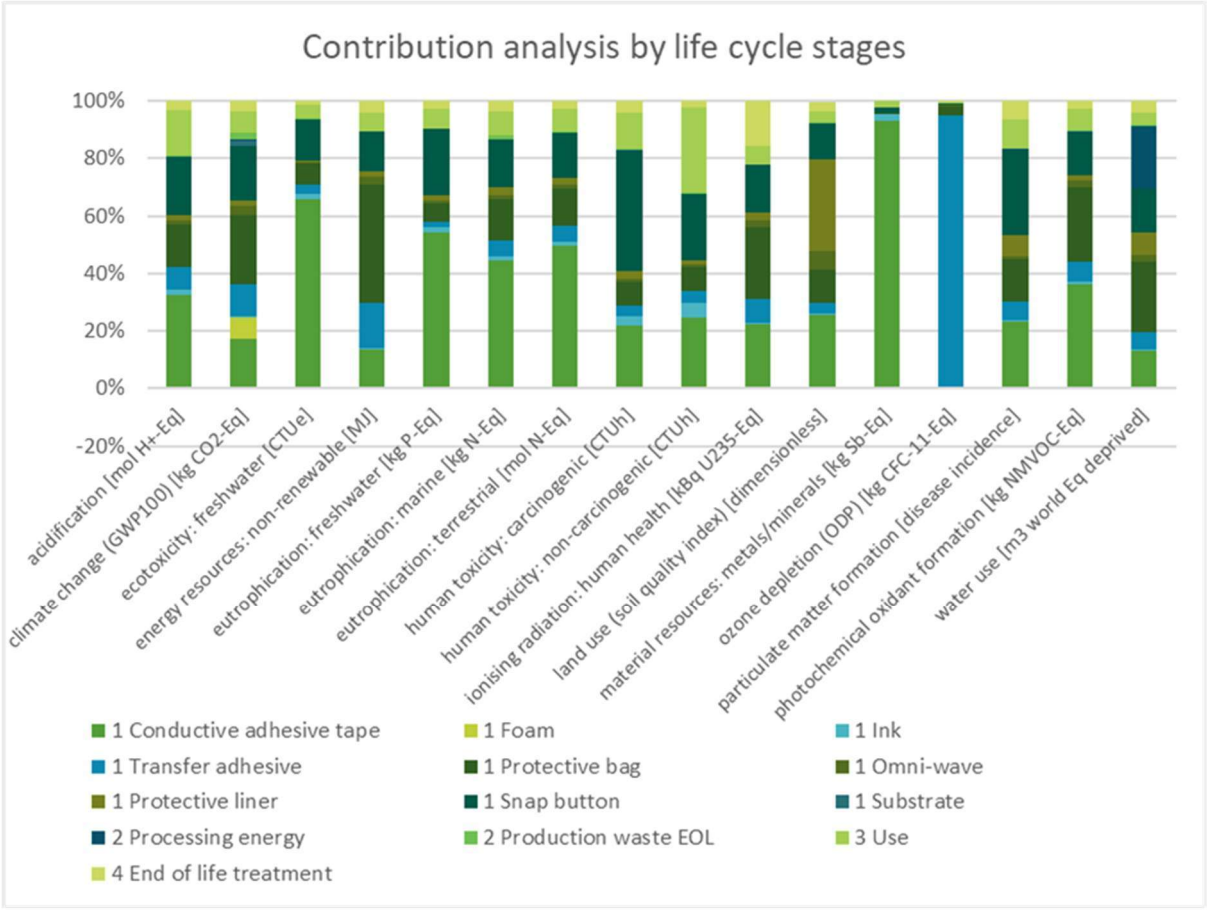


Figure 45. Contribution analysis of single use electrode lifetime emissions.

One of the targets of Pilot 2.2 was to demonstrate single use and multi-use medical electrodes. Sensitivity analysis was implemented to compare the two designs during one year of measurements.

The single use case consisted of 365 electrodes with measurement length 10 h/day powered by a Li-ion battery that lasts 168 h. The multi-use electrode was connected to a belt and a buckle with measurement length 10 h/day powered by a Li-ion battery that lasts 168 h. Electrode, belt and buckle are washed in washing machine using a 30 °C cycle every week. Figure 46 compares these two options. It is evident that the reusable electrode, despite the emissions associated with washing and battery replacement, results in significantly lower overall emissions compared to the single use alternative. The single use electrodes accumulate emissions rapidly due to the manufacturing requirements for each individual unit, whereas the reusable option spreads its environmental impact across multiple uses, making it a more sustainable choice in the long term. The lifetime of multi-use electrode was varied in a sensitivity analysis studying only the climate change impact to see at which point the reusable electrodes becomes better. The reusable electrode with washable belt had higher climate change impact only for the first six measurement cycles. After that, the single use electrode had higher impacts.

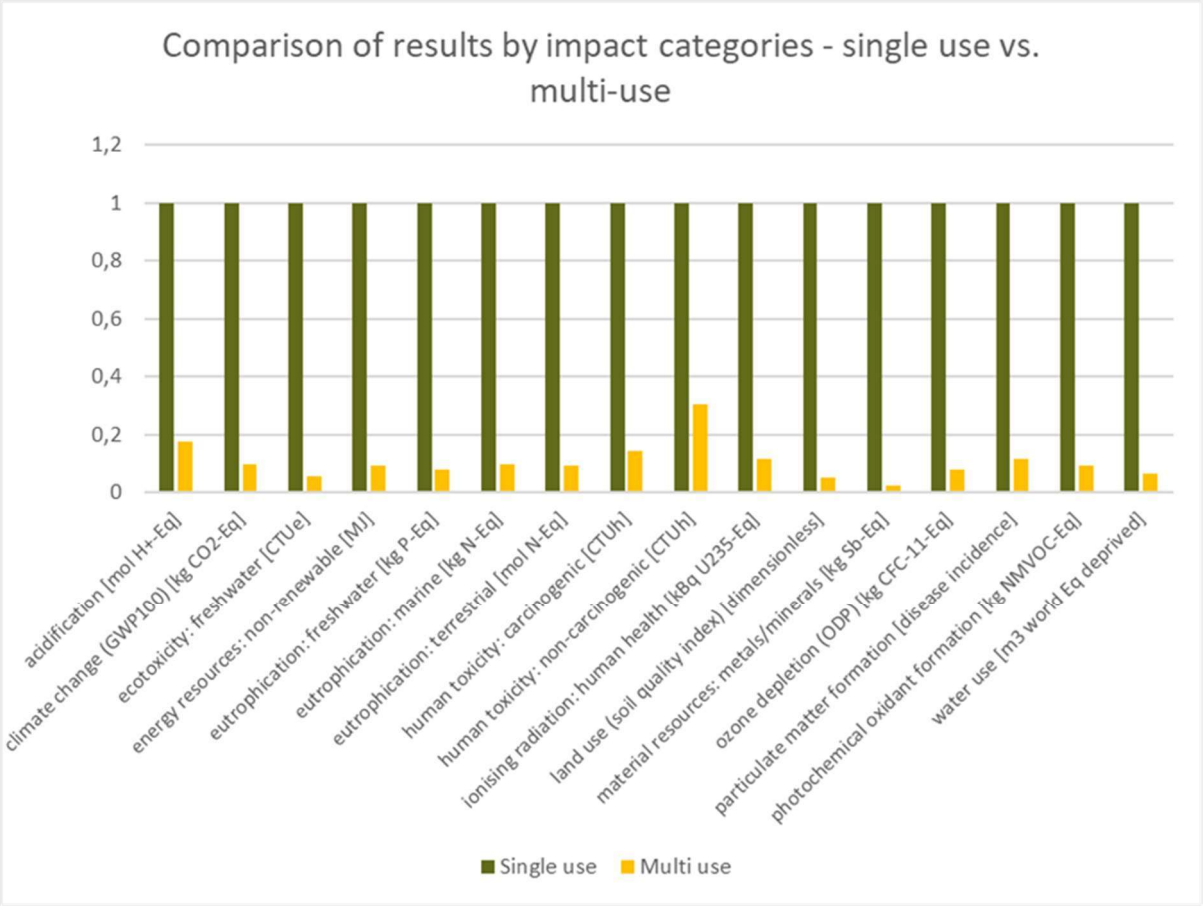


Figure 46. Comparison of single use electrode and reusable electrode lifetime emissions for 1 year.

Pilot 2.3 aimed to develop an innovative automotive dashboard offering a more comfortable and pleasant user experience for drivers, while answering the need for a green and circular approach. It was led by Forvia with contributions from CEA, Symbiose, Avantium, RISE, Mirec and VTT. The dashboard was based on the combination of In-Mold Electronics, as an alternative to conventional PCBs, and bio-based substrates. LCA was cradle-to-grave, covering all relevant life cycle phases from raw materials acquisition to end-of-life. The main focus of the analysis was on the production phase, since it's the phase that Forvia has the most control over and where the dashboards design has the biggest effect. However, the scope was set at cradle-to-grave to also include potential end-

of-life routes. The automotive dashboard was composed of three parts: decorative film, electronic/technical film and housing.

Figure 47 and Figure 48 show the contribution analysis for the manufacturing emissions when using PEF and bio-based PC, respectively. The impacts are similar for both materials, with the electronic film causing the bulk of impacts in most categories followed by the decorative film and the housing. The electronic film has many components like LEDs and capacitors which have high environmental impacts. It seems that PEF has a significant impact on ozone depletion and land use as well as marine eutrophication while bio-PC shows lesser impacts in those categories. Although, it is possible that the bio-PC impacts are not representative due to the underlaying LCI data for fossil production, so comparison is not advised.

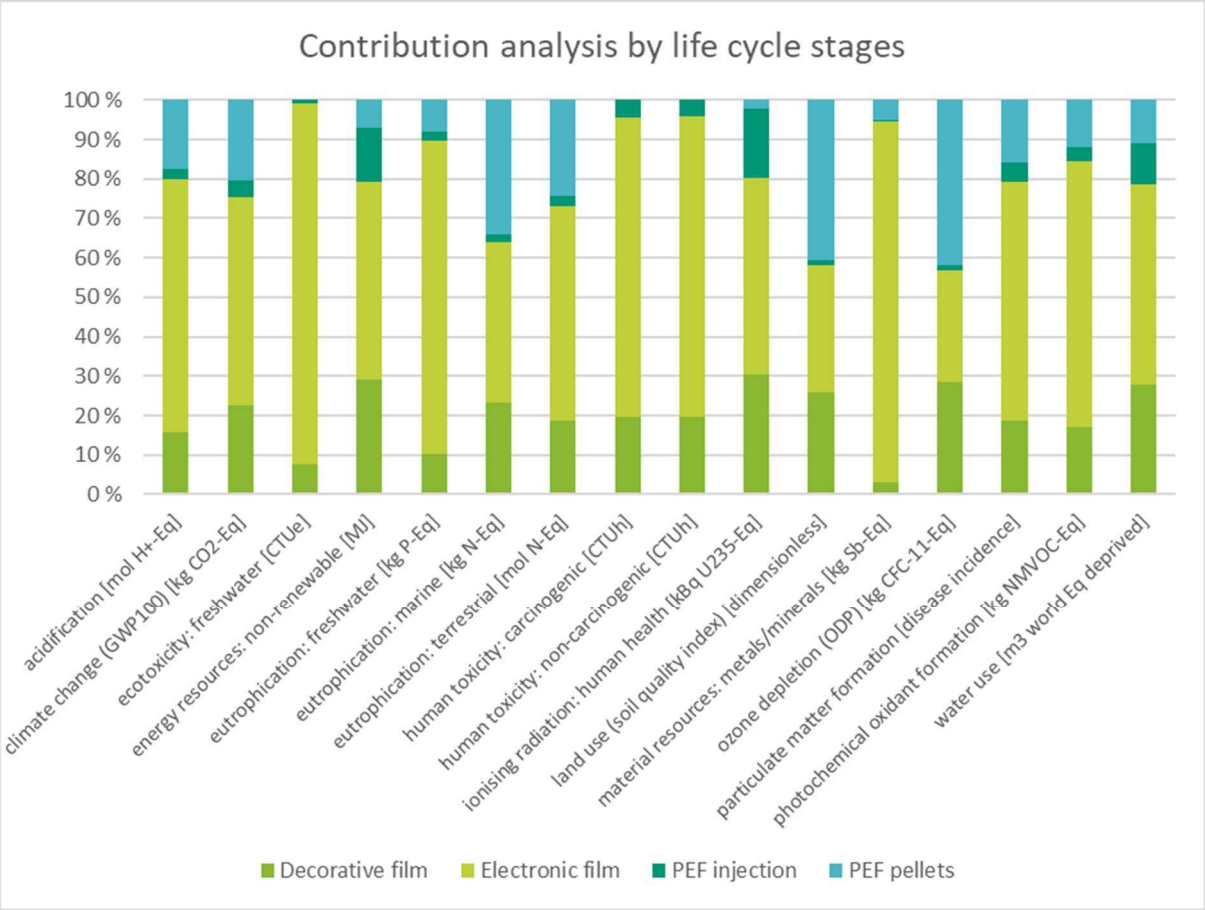


Figure 47. Contribution analysis of automotive dashboard manufacturing emissions using PEF.

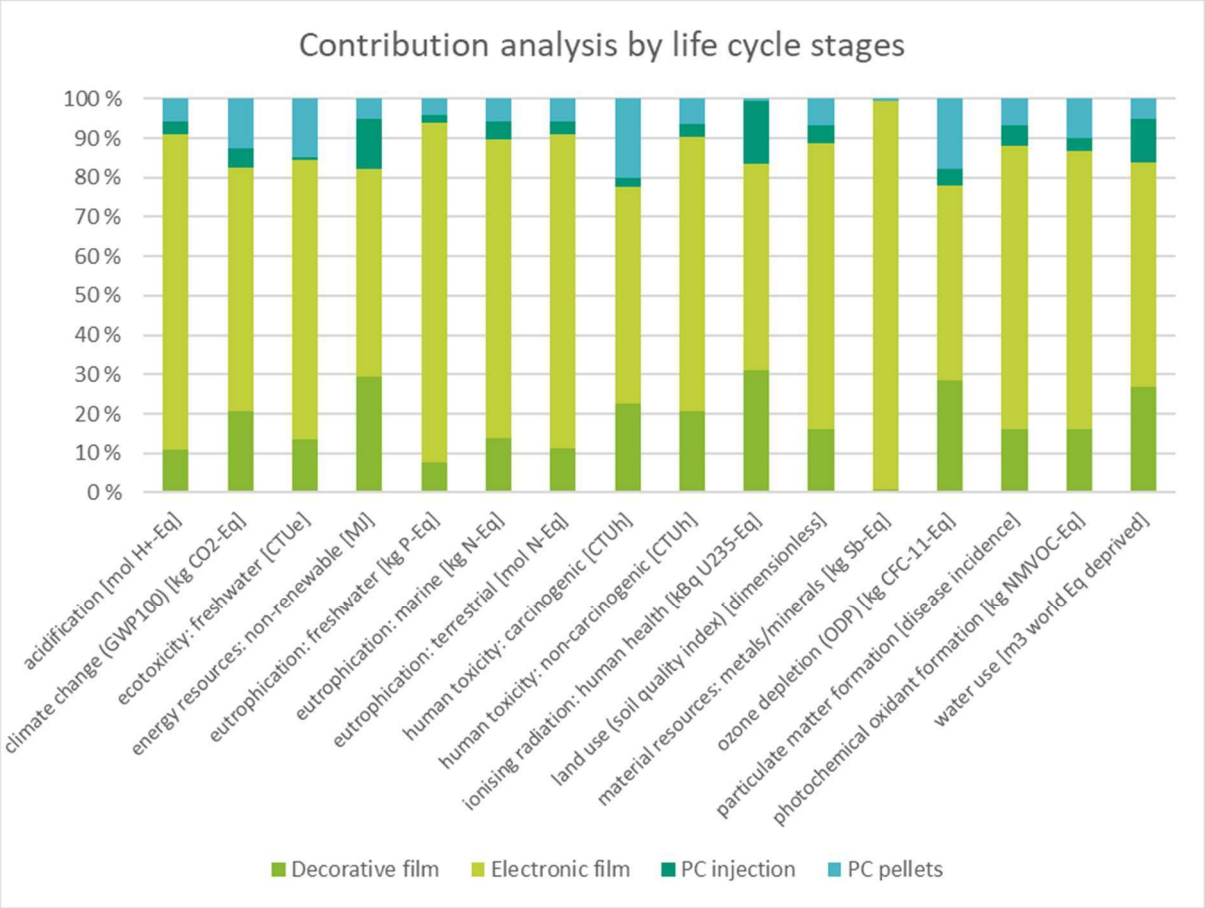


Figure 48. Contribution analysis of automobile dashboard manufacturing emissions using bio-PC.

Two alternative end-of-life routes were studied for the bio-PC and PEF dashboards:

1. Incineration. Includes incineration as municipal solid waste, treatment of incineration residues, separation of aluminium and copper from the bottom ash and preparing them for recycling. Credits are gained from energy substitution.
2. WEEE recycling. Includes shredding and sorting of materials, recycling of plastics and metals. Credits are gained from material substitution.

Incinerating the dashboard at end-of-life results in low impacts to climate change. The potential credits from material and energy substitution almost offset those impacts. Credits arise from replacing market energy by energy generated through incineration, and primary copper by the recovered materials. Recycling the dashboard at end-of-life results in mixed impacts to climate change for bio-PC and PEF. In this case, credits arise from replacing primary plastic materials. Since the recycling processes differ for bio-PC (chemical recycling) and PEF (mechanical recycling), the two are not completely comparable.

4.2 Circular business model development

TAU focused on translating circular economy principles into business model configurations for future deployment. As part of this work, TAU created a “Circular Business Model (CBM) Design Template” to structure the analysis of pilot-level business models. The template connected circular design strategies with customer needs, service delivery, stakeholder collaboration, revenue creation, cost

structures, and sustainability benefits. It also enabled consistent comparison across pilots and supported the identification of general CBM archetypes.

The work was based on qualitative data collected through interviews and workshops with project partners. The analysis focused on four circular business model value dimensions: value proposition, value delivery, value creation, and value capture. These dimensions were linked to circular economy design strategies, including extending, cycling, and intensifying.

4.2.1 Methodological approach

The "CBM design template" development followed five main phases, from interview design to archetype development. Table 10 summarises the methodological steps applied in this work.

Table 10. Methodological and project implementation framework.

Phase	Activity	Output
1	Design of interview questions based on identified research gaps in the health technology sector related to LCA integration into CBMs	Interview questions
2	Semi-structured interviews (22 interviews with project partners)	Interview transcripts for qualitative analysis
3	Analysis of interview material and development of the "CBM Design Template"	CBM Design Template
4	Focus group workshops using the "CBM Design Template" with pilot partners	Completed CBM Design Templates from 10 pilot projects
5	Qualitative coding and analysis of completed "CBM Design Templates"	CBM archetypes and circular economy design strategies mapping

The development process enabled a consistent analysis of CBM elements across different pilot contexts. It also linked interview findings and workshop-based inputs to the identification of CBM archetypes.

4.2.4 Circular Business Model Design Template

TAU applied the "CBM Design Template" as the analytical tool for collecting and comparing pilot-level CBM data. The template structured the analysis according to product and service value, delivery processes, partner roles, value creation activities, revenue sources, cost implications, and circular economy design strategies (see Figure 49).

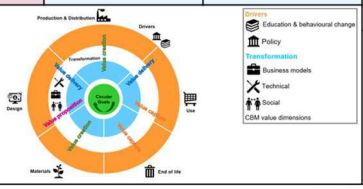
Circular Business Model (CBM) Design Template Including Guiding Questions

- **Product life time:**_____
- **Times of use:**_____
- **Application field:**_____
- **Cost of the product (Approx.):**_____

Circular Business Model (CBM) Dimensions

Value proposition		Value Delivery		Value Creation		Value Capture	
Products	**Services**	**Target customer & users**	**Value delivery processes**	**Key partners and stakeholders**	**Value creation processes**	**Revenues**	**Cost**
What product features make them sustainable or circular (e.g., design for reuse, recyclability, durability, modularity)? How do they address environmental challenges or customer needs?	What services can be offered to the complement the product lifecycle (e.g., repair, refurbishment)? How can these services enhance/improve the value proposition of the circular product?	Who are the key customer segments that would benefit from circular products and services? What specific needs or challenges are they facing regarding sustainability?	How do you ensure that your products or services are delivered in a way that supports circularity (e.g., through sustainable materials, packaging, distribution)? What steps can be taken to improve the delivery process to reduce waste and ensure products can be easily returned, repaired, or reused? (e.g., localisation of waste management)	Who are the main partners (e.g., suppliers, stakeholders, collaborators, waste management) that help make the circular business model possible? What roles are they required to have to create value in a circular economy?	What processes are crucial for creating value within a circular business model (e.g., remanufacturing, closed-loop supply chain) at your company or organization? How can these processes help to reduce waste and increase resource efficiency?	How can new revenue streams be created through circular models (e.g., product-as-a-service, leasing, or subscription models)? What are the opportunities for capturing value from used/recycled products or materials?	What cost drivers or factors are impacted when transitioning to a circular business model (e.g., initial investment in remanufacturing or other CE strategies)? How can circularity help reduce costs in the long-term vision?

Product life cycle stages:
1. Raw material extraction
2. Processing
3. Design
4. Manufacturing
5. Transportation / Retail
6. Use
7. End of life (EOL)
8. Disposal



Circular economy design strategies

Cycling (C)	Extending (E)	Intensifying (I)
• Refurbishing • Repair • Remanufacturing • Recycling • Reuse • Design for modularity	• Long-lasting products • Upgradability • Timeless design • Marketing and consumer education • Maintenance services • Product support/Customer service	• Rental/Leasing • Product as a service • Digital capabilites developed (e.g. tracking) • Contract management and pricing per unit of service

1. Geissdoerfer, M., Pieroni, M.P.P., Pigosso, D.C.A., Soufani, K., 2020. Circular business models: A review. Journal of Cleaner Production 277, 123741. https://doi.org/10.1016/j.jclepro.2020.123741
2. Osterwalder, A., Pigneur, Y., 2010. Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers. John Wiley & Sons.
3. Nußholz, J.L.K., 2018. A circular business model mapping tool for creating value from prolonged product lifetime and closed material loops. Journal of Cleaner Production 197, 185–194. https://doi.org/10.1016/j.jclepro.2018.06.112
4. Figure Source: OECD (2018) Business Models for the Circular Economy – Opportunities and Challenges from a Policy Perspective, RE-Circle Policy Highlight, October 2028.

Figure 49. The CBM Design Template developed for the project including guiding questions.

This template made it possible to compare pilots with different product lifetimes, user groups, service needs, and end-of-life treatments. It also allowed to make generalizations and find some similarities within the pilots to further develop CBM archetypes (see section 4.2.4).

4.2.2 Pilot scope and product categories

Table 11 shows the product categories (PCs) and corresponding pilot projects used for CBM archetype development.

Table 11. Product categories and corresponding pilot project titles for CBM archetype development

Item	PC	Pilot project
1	Durable systems and devices	• Pilot 1.1: Image-guided therapy systems (IGTS) • Pilot 1.2: Personal grooming devices
2	Wearable medical/health devices	• Pilot 2.1: Embedded electronics for monitoring • Pilot 2.2: Wearable health monitoring • Pilot 3.1b: Smart patch • Pilot 3.2: Hygiene products • Pilot 3.3: Wound dressings
3	Diagnostic medical device	• Pilot 3.1a: Diagnostics tool

The development of general circular business model archetypes was based on eight health technology pilots grouped into three product categories. The categorization reflects shared product architecture, use context, and circular design conditions.

- **Durable systems and devices (PC-1):** This category comprises complex electronic systems and consumer devices characterized by repeated use, modular electronic components, and defined return or service pathways.
- **Wearable medical/health devices (PC-2):** This category comprises body-worn devices that integrate electronic components with hygiene-sensitive, disposable, or replaceable elements. It includes embedded electronics for monitoring (Pilot 2.1), wearable health monitoring devices (Pilot 2.2), smart patches (Pilot 3.1b), smart hygiene products (Pilot 3.2), and wound dressings (Pilot 3.3).
- **Diagnostic medical devices (PC-3):** This category includes diagnostic solutions that combine reusable electronic parts with single-use or consumable components, represented by the diagnostics tool pilot (Pilot 3.1a).

Two pilots (Pilot 1.3 and Pilot 2.3) were not included in the development of the general CBM archetypes, as their application contexts and circularity requirements differ from those of the health technology pilots.

4.2.3 General circular business model archetypes

The analysis of the completed "CBM Design Templates" (Figure 49) resulted in four general circular business model archetypes. These archetypes were developed from the health technology pilots listed in Table 12. Each archetype reflects shared CBM patterns across specific pilots rather than a single pilot case [Abedi et al., Manuscript under review].

Table 12. General overview of CBM archetypes identified across the pilots (Based on Abedi et al., Manuscript under review).

Product category	Associated pilots	General CBM archetype	CE strategy	Main circular focus
PC-1	Pilot 1.1, 1,2	**Prolonging product life**	Extending	Modular design, repair, upgrade, refurbishment, and longer use periods
		Return and material circularity	Cycling	Take back program, component recovery, refurbishment, and material recovery
PC-2	Pilot 2.1, 2.2, 3.1b, 3.2, 3.3	**Device as a service platform**	Cycling; Intensifying	Reusable electronics, service-based access, digital monitoring, take back, and safe separation of single-use components
PC-3	Pilot 3.1a	**Sustainable materials and energy-efficient digital access**	Cycling; Extending; Intensifying	Biodegradable disposable components, reusable digital readers/transmitters, home-based testing, and energy-efficient logistics

For PC-1 (Pilot 1.1 Image-guided therapy systems and Pilot 1.2 Personal grooming devices), two archetypes were identified: 1) Prolonging product life and 2) Return and material circularity. These pilots involve durable systems and devices with repeated use, modular components, and defined service or return pathways. Circularity is therefore developed through repair, upgrades, refurbishment, take back, component recovery, and material recovery.

For PC-2, wearable medical and health devices, which includes five pilots, the general archetype was identified as Device as a service platform. This product category combines reusable electronic

components with wearable, disposable, or hygiene-sensitive elements. The archetype focuses on service-based access, digital monitoring, reuse of durable electronics, take back processes, and safe separation of single-use components.

For PC-3 (Pilot 3.1a Diagnostics tool), the general archetype was identified as Sustainable materials and energy-efficient digital access. This pilot concerns a diagnostic medical device with single-use sampling components and reusable digital access through a smartphone or reader. Circularity is therefore addressed through biodegradable disposable components, home-based testing, energy-efficient logistics, and reduced need for dedicated electronic readers.

4.2.4 Sustainability benefits

The identified CBM archetypes contribute to environmental, economic, and social sustainability. Table 13 shows the main sustainability benefits per archetype.

Table 13. Sustainability benefits per CBM archetype. (Based on Abedi et al., Manuscript under review).

General CBM archetype	Environmental benefits	Economic benefits	Social benefits
Prolonging product life	Reduced material use, lower waste, longer product use	Lower replacement needs, service revenues, reduced material costs	Improved product reliability and user support
Return and material circularity	Component recovery, material recovery, reduced virgin material use	Revenues from refurbished parts and products, lower material costs	Safer and more traceable return systems
Device as a service platform	Reuse of durable electronics, controlled recovery, reduced visits	Subscription and leasing revenues, improved asset use, lower logistics needs	Remote monitoring, improved access to care, safe separation of hygiene-sensitive parts
Sustainable materials and energy-efficient digital access	Biodegradable components, reduced packaging, reduced travel	Lower distribution costs, subscription-based services, reduced reader production	Home-based testing, improved diagnostic access, reduced burden on healthcare settings

The sustainability benefits vary according to product type and use context. Durable systems mainly support circularity through longer use and material recovery. Wearable medical and health devices support circularity through service-based access and reuse of durable electronics. Diagnostic devices support circularity through sustainable materials, reusable digital interfaces, and home-based service delivery.

The CBM outcomes were assessed using early-stage circular design indicators derived from the “CBM Design Template”. Since the pilots were mainly positioned at prototype or early development stages, the assessment focused on the extent to which circular and eco-design principles were

addressed in product and service development. This approach was appropriate because the pilot cases were unique and focused on different aspects of sustainable circular design.

The assessment covered five main areas: circular product design, circular service design, value delivery, value creation, and value capture. Table 14 summarises the main KPI areas used in the assessment.

Table 14. Main KPI areas used in the circular business model assessment. (Based on Sustronics D 4.7.)

KPI	Main indicators
Circular product design	Sustainable materials, reduced material use, reduced packaging, durability, modularity, repairability, recyclability
Circular service design	Repair services, replacement of critical parts, refurbishment, take back, leasing, digital services, remote tracking
Value delivery	Packaging, logistics, reverse supply chain, reduced travel, remote access, facilitated returns and repairs
Value creation	Closed-loop supply chains, material reuse, component reuse, refurbishment, remanufacturing, patient-specific reuse
Value capture	Service contracts, subscriptions, leasing, refurbished product sales, lower material and replacement costs

The assessment showed that the pilots covered a broad set of circular design indicators. For circular product design, the main achievements related to the use of sustainable materials, reduction of packaging materials, and product durability. For circular service design, refurbishment services were one of the areas where multiple pilots reached results. Digital services via applications, remote tracking, repair services, and replacement of critical components were also addressed by several pilots.

For value delivery, packaging offered the opportunity to reduce waste and create savings. Logistics was also identified as a relevant area for sustainable value creation, especially by reducing travel needs, for example for patients visiting healthcare or hospital facilities. For value creation, several pilots identified material reuse processes, component reuse, refurbishment, remanufacturing, and closed-loop supply chains. Some pilots also identified modular design to support product lifetime and upgradability.

Figure 50 illustrates the number of circular design KPI areas applied in each pilot. The figure shows that the pilots differed in the number of circular design areas covered, reflecting their different product types, technology readiness levels, hygiene requirements, and reuse possibilities.

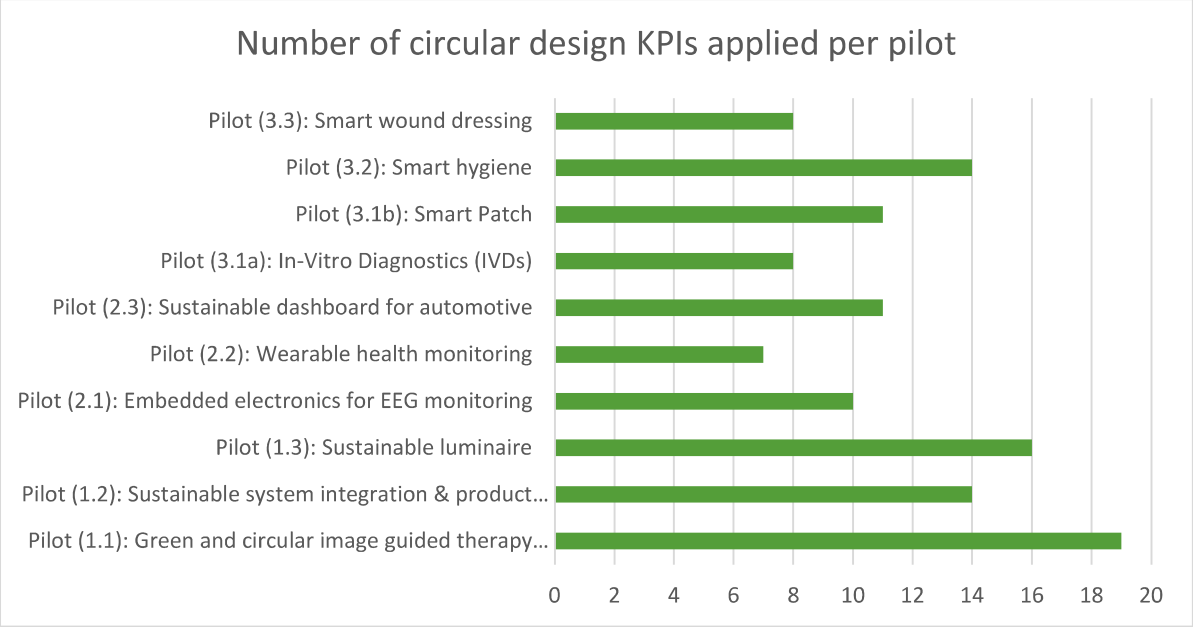


Figure 50. Circular design coverage per pilot. (detailed in Sustronics deliverable D4.7.)

Durable systems and devices covered a wider set of circular design indicators because they offered stronger possibilities for repair, refurbishment, service contracts, and material recovery. Single-use or hygiene-sensitive applications covered fewer indicators but still contributed through sustainable materials, reduced packaging, digital services, and safe end-of-life considerations. The assessment indicates that CBM design was reflected in product features, service elements, delivery processes, and value creation activities across the pilots. The results also show that evaluation at early technology readiness levels should focus on the integration of circular and eco-design principles into product and service configurations, rather than on market-level circular performance.

4.2.5 Main outcomes

TAU's CBM development produced three main outcomes. First, the "CBM Design Template" was developed and applied as a structured tool for analysing circular business models across the pilots. Second, pilot-level data were used to identify general circular business model archetypes for health technology product categories. Third, the circular business models were reviewed using early-stage circular design KPI indicators suited to prototype development. The work shows that CBMs must be adapted to product type and use context. Durable systems can focus on longer use, repair, refurbishment, and return. Wearable medical and health devices can combine reusable electronics with service-based access and safe handling of single-use parts. Diagnostic devices can use sustainable disposable materials, reusable digital readers, and home-based service delivery.

These outcomes provide a practical basis for developing CBMs in health technology and related electronics sectors. They also support future exploitation by helping companies identify circular value propositions, service models, partner roles, revenue opportunities, and cost implications at an early stage of product and service development.

4.3 Consumer and stakeholder engagement

Activities related to consumer and stakeholder engagement analysed how consumers, companies, and other relevant stakeholders perceive sustainable and circular electronics, with particular attention to barriers, enablers, and the conditions under which more sustainable solutions are likely

to be accepted, adopted, and scaled. The purpose was to translate these findings into practical implications for communication, exploitation, standardisation, and future community-building activities. The activities were implemented by VTT with TAU supporting in analysis of results. The work consisted of a cross-country consumer study, two complementary B2B surveys, qualitative stakeholder interviews, and three exploratory industry workshops. The consumer study was analysed using descriptive comparison, PLS-SEM, and multi-group analysis across countries. The B2B survey was analysed descriptively and interpretively, with attention to readiness, trade-offs, and organisational profiles. The interviews were analysed thematically to identify recurring barriers and enablers of uptake. The workshop outputs were synthesised qualitatively to identify exploratory themes and ecosystem-level concerns.

4.3.1 Consumer study

The aim of the consumer study was to investigate how consumers perceive sustainable electronics, repairability, and the types of information that support more sustainable choices. The consumer study covered Austria, Finland, Germany, Portugal, and Spain, with 200 respondents per country, resulting in a total sample of 1,000 participants. Across these five countries, the results showed that consumers are not uniformly resistant to sustainable electronics. Instead, their attitudes and intentions are shaped by differences in sustainability-related knowledge, behavioural habits, perceived barriers, and the usefulness of product information.

The descriptive results showed that consumers are especially responsive to sustainability when it is linked to product longevity, repairability, maintenance support, and other concrete use-related benefits. Repairability and durability appeared easier to mobilise than environmentally friendly materials in the abstract. This suggests that sustainable electronics are more likely to gain traction when sustainability is translated into understandable user benefits, such as longer product lifetime, easier maintenance, better value retention, and lower replacement frequency, rather than being framed only as a general ecological concern.

The descriptive material also indicated that Digital Product Passport (DPP) information is valued most when it supports practical decision-making. The most desired information categories include durability, supply-chain transparency, safety and compliance information, repair and maintenance guidance, and end-of-life or recycling information. These preferences suggest that consumers do not view sustainability information as an end in itself. Rather, they value it when it helps them assess whether a product is durable, repairable, safe, and worth choosing.

The country comparison indicated that a common European intervention logic is possible, but its implementation is likely to benefit from some context-sensitive emphasis. Across all five countries, sustainability literacy and practical knowledge were a robust driver of intention to repair or maintain devices, with strong and statistically significant effects throughout. Habit and automaticity in sustainable behaviour also positively predicted repair intention across countries, with particularly strong effects in Finland and Germany. These results indicated that the core behavioural architecture of sustainable electronics adoption is shared, even though some predictors vary in strength across contexts.

4.3.2 B2B surveys

The B2B analysis focused on organisational actors operating in medtech, wearable health, and applied research contexts, where sustainability ambitions must be balanced against technical performance, compliance requirements, and market realities. Across these contexts, the evidence points to a consistent pattern: firms were generally interested in sustainability and open to more sustainable electronics and electrode materials, but adoption depends on whether change can occur without undermining performance, regulatory compliance, user trust, or operational workflow. Two

complementary evidence streams were used: two B2B surveys conducted at different points in the value chain and a set of qualitative stakeholder interviews. The first survey was circulated through an electrode material producer to its customer network and focused on how firms evaluate sustainable electrode materials under real decision conditions. The second survey was circulated through a more downstream electrode solution company that builds on such materials in its own product offering and gathered the perspectives of its own customers and relevant market contacts.

The B2B survey and interview findings indicated that uptake depends less on whether greener materials exist in principle, and more on whether they can be shown to be performance-equivalent, certifiable, traceable, and workable within procurement and disposal systems. Sustainable electronics adoption in medtech and adjacent sectors is therefore not primarily blocked by negative attitudes. Instead, it is constrained by the interaction of performance risk, regulatory burden, weak market pull, supplier uncertainty, and underdeveloped end-of-life pathways.

The combined B2B evidence is especially valuable because it captures sustainability adoption from more than one position in the value chain. The upstream survey provides stronger visibility into procurement-adjacent material decisions, where performance, certification, and supplier transparency are central. The downstream survey adds perspective on solution offering, market fit, customer-facing needs, and price pragmatism. Together, these findings show that adoption conditions are not identical across the market: what matters at the level of material sourcing may differ from what matters in downstream product and solution contexts.

The interview findings deepened this interpretation by showing why sustainability often remains difficult to implement even when interest exists. Firms are more likely to act when sustainability can be framed not simply as environmentally preferable, but as validated, compliant, transparent, and operationally safe. This means that the path to adoption is shaped by innovation in materials and product design, supported by credible validation pathways, traceability, lifecycle value, and confidence in implementation.

Overall, the stakeholder and market findings suggest that sustainable electronics adoption is best understood as a value-chain coordination challenge rather than as a simple attitude problem.

4.3.3 Industry workshops

Sustronics project organised three industry workshops, of which two were led by VTT and TAU: PrintoCent workshop in Oulu (June 2024) and the IEEE FLEPS 2024 workshop in Tampere (July 2024). The workshop discussions broadly confirmed the patterns identified in the surveys and interviews. Participants emphasised that sustainability is widely recognised as important, while adoption depends on whether it can be implemented with strong performance, credible validation, and practical fit within existing systems. Performance and risk remained central, validation and proof were repeatedly highlighted as prerequisites for uptake, and supply-chain transparency was seen as necessary for stronger trust and traceability. Participants also emphasised the continued weakness of market pull and the need for circularity solutions that are supported by wider coordination across design, logistics, regulation, and business models.

4.3.4 Conclusions

Based on integrative analysis of the outcomes the main mechanisms through which sustainable electronics adoption can be strengthened were identified. Across the consumer study, the two B2B surveys, the interview findings, and the workshop insights, a consistent conclusion emerges: sustainability gains traction when it is translated into solutions that are understandable, workable, and credible for the actors expected to adopt them. The most effective mechanisms reduce uncertainty, lower friction, and align sustainability goals with practical decision-making across the value chain. Figure 51 summarises the overall mechanism logic and shows how design, validation,

market, behavioural, and policy mechanisms work together to reduce uncertainty and strengthen adoption across the value chain.

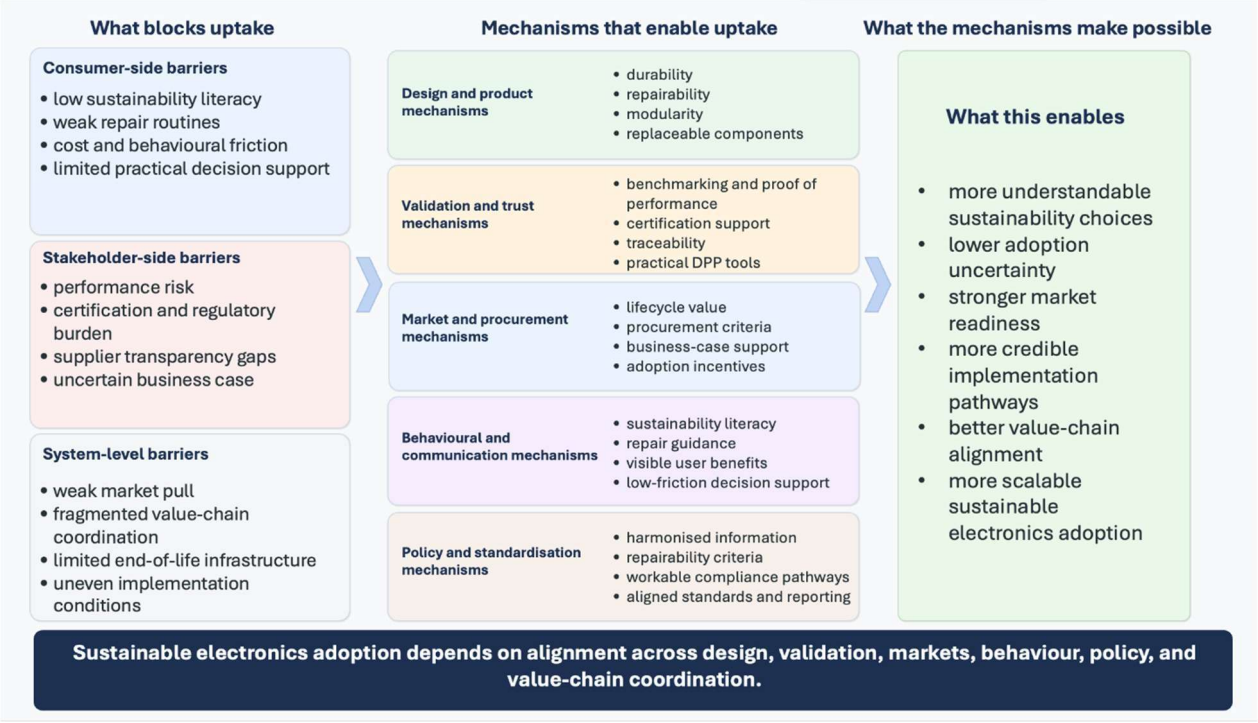


Figure 51. Integrated mechanism framework for sustainable electronics adoption.

4.4 Digital product passport concept development

VTT collaborated with UPC in specification and development of the DPP concept for sustainable and circular electronics products. The activities carried out by VTT included (i) literature survey on DPP principles, regulatory framework and existing DPP prototypes; (ii) survey on data requirements within the ten project pilots; and (iii) survey on consumer attitudes on DPP (reported in Section 4.3.1).

4.4.1 Literature findings

According to the literature survey, DPPs support the implementation of circular economy principles in the electronics sector. They include data on product composition, maintenance, environmental performance, and end-of-life processes. The availability of this information enhances transparency, enables traceability, and reinforces sustainability throughout the product lifecycle, facilitating informed decisions in design, use, and disposal [Adisorn et al, 2021], [Hakola et al, 2025], [Wicaksono et al, 2025].

DPPs enhance environmental performance and support the alignment of product development to regulatory requirements and evolving market expectations. Their implementation in the electronics sector is particularly valuable due to the industry's complexity, short product life cycles, and the value of critical raw materials involved. However, the adoption of DPPs also presents multiple technical, organisational, and regulatory challenges. Table 15 summarises the benefits and challenges associated with DPPs in the electronics sector [Abedi et al, 2024]. While the benefits presented by DPPs are notable, their realisation requires coordinated efforts across the technological, organizational, and regulatory domains. Standardisation, stakeholder collaboration, and targeted

policy interventions will be important for addressing existing challenges and supporting the role of DPPs in promoting circular transformation in electronics.

Table 15: Benefits and challenges of DPPs in the electronics sector.

Benefits	Challenges
Enhances lifecycle transparency and traceability.	Lack of data standards and limited system compatibility reduce effective collaboration among stakeholders.
Supports informed reuse, repair, remanufacture, and recycling decisions.	Ensuring data accuracy, reliability, and quality is complex.
Promote sustainable business models in electronics manufacturing.	Technical complexity and high implementation costs are significant barriers, especially for SMEs.
Enables real-time data access via IoT and smart tags.	A lack of digital infrastructure makes it difficult to adopt.
Enables consumers to make sustainable choices.	Concerns about cost and effort required for sensor-based data collection.
Creates possibilities for 3rd party developers, business and services	Standards or documented interfaces, data sharing

There are many on-going activities related to development of DPP platforms or key functionalities. For example, CIRPASS project has listed 98 initiatives related to DPP development [CIRPASS project, 2025]. It should be noted that development of the electronics industry specific DPP platforms is limited, while textile industry specific platforms are widely available. There is active development for the DPPs for the batteries.

4.4.2 Pilot surveys

The pilot survey was implemented as a questionnaire targeted for the pilot leaders that were allowed to fill the questionnaire with the other pilot partners, when feasible, at M9. A detailed analysis of the results is also reported in [Hakola et al, 2025]. The questionnaire consisted of a list of the value chain actors that the pilots were asked to identify either as relevant or non-relevant for their value chain during Sustronics project. The pilots were also asked to identify what type of data is needed from each actor, what kind of data is available from each actor and in which format, what are the existing data gaps, and is there a need for lifecycle monitoring. The results were analysed qualitatively.

Based on the pilot survey, the most relevant value chain actors were the material and component providers, software developers, as well as hardware and system integrators. The importance of end-of-life and circularity operators was also highlighted. The product life cycle data was currently seen to be scattered across multiple locations and documents, with a lack of information related to sustainability, environmental impact, and end-of-life management. A detailed list of all components and sub-assemblies, including their characteristics, was also missing. Lifecycle monitoring was particularly needed to ensure that components and devices can tolerate storage. These are all aspects that DPPs can help address.

Two pilots were identified as potential test cases for the DPP platform to be demonstrated in Sustronics project. The specific needs of these pilots were specified at M17 to help Upcode in development of pilot-specific DPPs for Pilot 1.2 (Sustainable system integration and product design of personal health devices led by Philips) and Pilot 2.1 (Embedded electronics for EEG monitoring led by PLUX). The identification resulted in a list of key stakeholders with their specific data needs.

5 Dissemination, communication and exploitation

5.1 Communication

5.1.1 Press releases

Press release highlighting the Finnish consortium published by VTT 14.11.23, “Finnish consortium led by VTT joins 40-million-euro EU project to address global challenges of e-waste and finite electronic materials with sustainable solutions”: https://www.vttresearch.com/en/news-and-ideas/finnish-consortium-led-vtt-joins-40-million-euro-eu-project-address-global

Press release by TAU 6.3.24, “Tampere University joins efforts to support the transition to sustainability across the electronics industry”: https://www.tuni.fi/en/news/tampere-university-joins-efforts-support-transition-sustainability-across-electronics-industry

Preparation of LinkedIn posts to project LinkedIn site and reposting.

5.2 Dissemination

5.2.1 Journal articles

Fatemeh Abedi, Max Marwede, Stefan Schalk, Ulla A. Saari, (2025) Health-Technology Industry Transitioning to the Circular Economy - Development of Circular Business Model Archetypes. Journal of Business Strategy and the Environment. [Manuscript under review]

Fatemeh Abedi, Ulla A. Saari, Marko Seppänen, (2026 accepted for publication). Sustainable electronics in health technology - Using environmental life cycle assessments for circular business models. Journal of Cleaner Environmental Systems.

Liisa Hakola, Fatemeh Abedi, Sirpa Nordman, Maria Smolander, Jouni Paltakari. “Smart Tags as Enablers for Digital Product Passports in Circular Electronics Value Chains,” Circ. Econ. Sustain., 2025, doi: 10.1007/s43615-025-00500-y. (VTT)

Tapio Mäkelä et al. “Novel diffuser for illumination applications" (in process, to be submitted post-project). (VTT)

Kirsi Immonen et al. “Roll-to-roll vs. sheet printing process on printability of polylactide type bio-based substrates”, submitted to IoP Publishing. (VTT with TNO)

Minna Vikman et al. “The influence of conductive inks on biodegradability of paper in industrial composting conditions”, submitted to (VTT with TNO) Resources, Conservation and Recycling

Juuso Puutio, Katja Laine, Hamed Pourkheirollah and Matti Mäntysalo, Electromechanical characterization of flexible screen-printed tracks, *Flex. Print. Electron.* 11 015004, DOI 10.1088/2058-8585/ae383

Aapo Kattainen et al., “Low-leakage-current deep eutectic solvent based supercapacitor for disposable, flexible, and ultra-low-power electronics”, submitted to Journal of Energy Storage; under review

Aapo Kattainen, et al., “Vacuum heat treatment of choline chloride/glycerol deep eutectic solvent for enhanced supercapacitor performance”, planned publication.

Katja Laine, et al., “Reliability and Failure Mode Analysis of Screen-Printed Carbon and Copper Conductors on Sustainable Flexible Substrates”, planned publication.

5.2.2 Conference papers, posters and presentations

Liisa Hakola, Maria Smolander, Taina Rauhala, Marja Vilkman (VTT). “Eco-design and circularity guidelines for printed flexible electronic devices based on a holistic and streamlined sustainability assessment”, Electronics Goes Green 2024, 18.-20.6.24, Berlin, Germany.

Lotta Hepo-oja (VTT). “Life Cycle Assessment Of Printed Electronics - A Case Study Of Three Pilot Applications”, SETAC Europe 26th LCA Symposium, 21.-23.10.24, Gothenburg, Sweden

Liisa Hakola (VTT): “'Roadmap Towards Sustainable and Circular Electronics - Recommendations from Sustronics Research Project”, MIKON 2026 conference, 18.-21.5.26, Krakow, Poland.

Lotta Hepo-oja (VTT): “Normalization And Weighting As Tools For Product Development – A Case Study Of An Electrode”, SETAC Europe Annual Meeting, 17.-21.5.26, Maastricht, the Netherlands.

Fatemeh Abedi, Ulla A. Saari, Liisa Hakola “Implementation and Adoption of Digital Product Passports: A Systematic Literature Review” 2024 IEEE International Conference on Engineering, Technology, and Innovation (ICE/ITMC), Funchal, Portugal, 2024, pp. 1-9. [Link]

Katja Laine, Hamed Pourkheirollah, Matti Mäntysalo, “Electromechanical Reliability Study of Screen-Printed Copper Conductors on Flexible Substrates”, to be published in IEEE ESTC 2026, Sept, Helsinki

Fatemeh Abedi (TAU/VTT): Circular business model types for the health-technology industry. Poster pitch and poster presentation for LOPEC - Exhibition and Conference for the Printed Electronics, Munich, Germany, 24-26 February 2026.

Kattainen Aapo (TAU): Electromechanical characterization for wearable electronics. Poster presentation for LOPEC - Exhibition and Conference for the Printed Electronics, Munich, Germany, 24-26 February 2026.

Mäntysalo Matti (TAU): Deep eutectic solvent electrolytes for disposable printed supercapacitors. Poster presentation for LOPEC - Exhibition and Conference for the Printed Electronics, Munich, Germany, February 2025.

5.2.3 Other peer-reviewed publications

Fatemeh Abedi, Ulla A. Saari, Maria Smolander, Liisa Hakola, Tilak Lakshmana and Thomas Kraft, (2025). Circular Sustainable Electronics from Design and Manufacturing to Business Models. pp.252-277. [Link]

5.2.4 Other presentations

Liisa Hakola (VTT). “Business opportunities from sustainable electronics – case Sustronics”. PRINSE’24 seminar 25.1.2024, Oulu, Finland.

Liisa Hakola (VTT). “Opportunities for improving sustainability and circularity for electronics”, Techblick - The Future of Electronics RESHAPED 2024 Berlin, Masterclass, 22.10.24, Berlin, Germany

Liisa Hakola (VTT). “Opportunities for improving sustainability and circularity for electronics”, KOTEL ekodesign seminar, 14.5.2025, Helsinki, Finland.

Liisa Hakola (VTT). “Printed electronics on bio-based and cellulose based substrates”, NMG Lunchtime Seminar Series: Focus on Paper Science, 22.5.25, online.

Liisa Hakola (VTT). “Sustainable and green electronics for circular economy”, INTERIZON DAY 2025, 24.9.25, Online/Poland.

Maria Smolander (VTT): “Sustainable and circular flexible electronics”, workshop “Re-Thinking Electronics – Is Greentech Too Good to Be True?”, AMIRES 22.10.25, Prague, Czech Republic.

Liisa Hakola (VTT). “Sustainability in electronics manufacturing”, EIPC webinar, 28.10.25, Online.

Liisa Hakola (VTT). “Sustainability and circularity in electronics manufacturing”, International conference, exhibition on semiconductor products and materials, 30.10.25, Online/Vietnam.

Liisa Hakola (VTT): “Safer and more sustainable materials for electronics manufacturing“, Advancing sustainable and circular electronics workshop, 24.4.26, Brussels, Belgium.

Ulla Saari (TAU): General presentation on the “main outcomes from the Sustronics project, focusing on the work conducted at Tampere University”. Workshop on sustainable electronics planned for May 27th at the Institut Français in Helsinki, arranged by the Embassy of France in Finland.

Ulla Saari (TAU): “Measuring circular economy transformation: Finding the relevant key performance indicators”, Strategic Technology & Innovation at Management (STIM) Consortium Workshop, the University of Cambridge, 18.3.2026, Cambridge, UK.

5.2.5 Participation in other events

Organisation of project booth at CHIPS JU Launch event, 3.-4.12.23, Brussels, Belgium (VTT).

Poster at Smart Packaging Summit in Research Hub, 10.-12.11.25, Amsterdam: “Sustainable smart tags and smart labels” (VTT).

Organisation of project booth at EFECS 2025, 3.-4.12.25, Malta (VTT).

Poster and pilot samples at booth at PRINSE’26 seminar, 28.-29.1.26, Oulu, Finland (VTT).

Liisa Hakola (VTT), chairing project public webinar, and presentation from Ulla Saari (TAU) on circular business models, 21.4.26, Barcelona/online. https://www.youtube.com/watch?v=4j4e-LLxUes&t=2463s

5.2.6 Thesis

Liisa Hakola (VTT). “Sustainability and technical feasibility of smart tags as data carriers for intelligent packaging and digital product passports”, Doctoral Thesis, Aalto University, 2026, https://urn.fi/URN:ISBN:978-952-64-2910-6

Fatemeh Abedi (TAU). “Development of Circular Business Models for Health Technology Products and Services” Doctoral Thesis, Tampere University, 2026 [Thesis to be sent for pre-examination].

Reetta Tulkki (TAU). “Designing for circularity: Integrating sustainability into new product development: Case study in the health-technology industry”, Master’s Thesis, Tampere University, 2026, https://urn.fi/URN:NBN:fi:tuni-202604103829

Puutio Juuso (TAU). “Electromechanical characterization for wearable electronics”, Master’s Thesis, Tampere University, 2025, https://urn.fi/URN:NBN:fi:tuni-202501061100

Kattainen Aapo (TAU), “Deep-eutectic-solvent-based supercapacitor for single-use medical diagnostics”, Master’s Thesis, Tampere University, 2025, https://urn.fi/URN:NBN:fi:tuni-202506066891

5.2.7 Workshops

SUSTRONICS – PrintoCent workshop, 3.6.2024, Oulu, Finland (organised and facilitated by VTT)

IEEE FLEPS workshop on circular and sustainable electronics, 1.7.2024, Tampere, Finland (organised by VTT, facilitated by TAU)

5.2.8 Other dissemination

Liisa Hakola, Ulla Saari, et al. “Recommendations for sustainable and circular electronics from Sustronics project”, project whitepaper, 2026. (VTT and TAU with partners)

5.3 Exploitation

5.3.1 Education

The main findings of Sustronics will be used in the development of a new course at Unit of Industrial Engineering and Management at TAU by Assoc. Prof. Ulla Saari and Doctoral researcher Fatemeh Abedi. The course is called “Sustainable Systems Management”, and it will start in the academic year 2027-2028 under a new major called “Riskien, kestävyyden ja turvallisuuden johtaminen” (Risk, sustainability and safety management).

5.3.2 Workshops

VTT, with support from TAU, organised a series of workshops for the Sustronics consortium to develop proposals for standardisation work and to specify the desired future for sustainable and circular electronics and the steps to reach this specified future. During the workshops regulations and policies were identified as the primary drivers for accelerating the development and growth of the markets for sustainable and circular electronic products. These outcomes set the framework that the companies are recommended to follow, influencing both the development of sustainable circular product based on eco-design principles and circular sustainable manufacturing. Figure 52 shows a hierarchical prioritisation of actions supporting product eco-design and lifetime extension. It shows that progress towards product eco-design and lifetime extension depends on consistency between EU policy and standards, traceability tools, product design choices, technological solutions and social conditions.

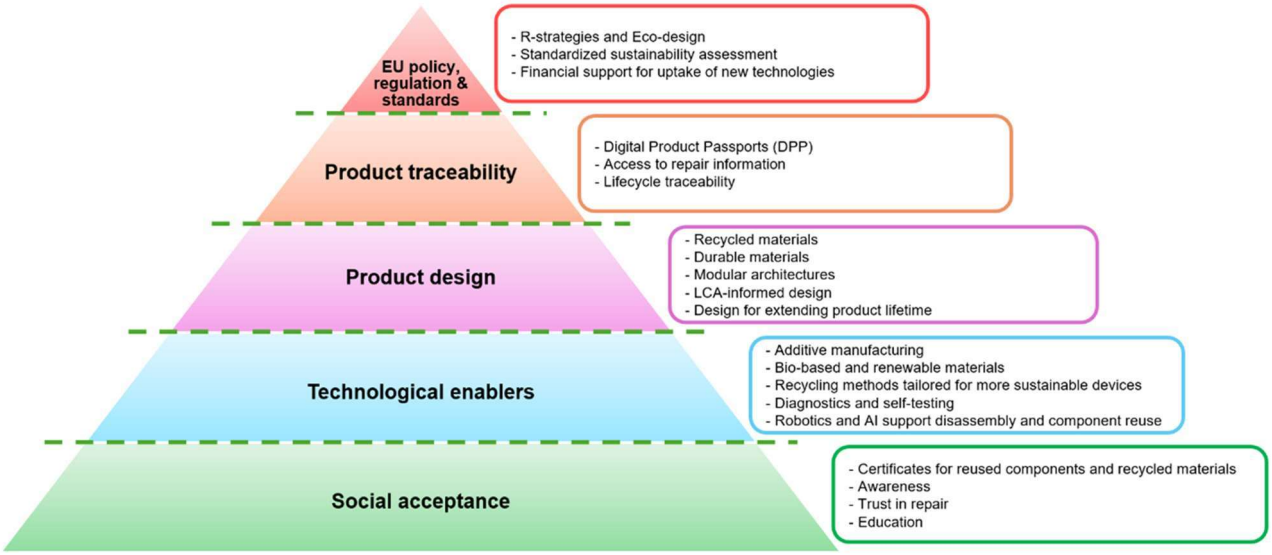


Figure 52. Hierarchy of priorities supporting product eco-design and lifetime extension.

5.3.3 Standardisation proposals

Two standardisation workshops were designed and led by VTT with all partners participating during two General Assembly meetings. The tasks included listing of standards and regulations relevant for the partners, identification of standardisation challenges and gaps as well as development of standardisation needs and ways to influence those. Based on the results five standardisation proposals were developed:

1. Environmental impact: There is a need for harmonised and standardised data formats, databases and methods for LCA, including how to assess end-of-life and software. Furthermore, guidelines for recyclability assessment are needed. Sustainability readiness level and LCA-based labels are proposed as one solution.
2. Printed electronics manufacturing: Standardisation is needed for use of sustainable and processable materials for printed electronics as well as how to recycle printed electronics devices within existing e-waste management systems or in new ones.
3. Sustainable materials: LCA data on new materials is not existing in databases to a full extent, thus linking with environmental impact. Reporting guidelines for recycled content, use of bio-based plastics and clear definitions (e.g. bio-based and biodegradable) are required.
4. End-of-life: Standards and guidelines for dismantling, sorting and recycling are required to ensure that sustainable electronics are handled in a proper manner. New end-of-life approaches, such as biocompostability and reuse of medical devices, need standards and rules.
5. Data: AI needs more standards, for example, focusing on privacy-preservation and machine-learning to guide device energy use. Use and production of synthetic data in training algorithms and in product development should be standardised.

5.3.4 Future roadmaps

The methodology for the future oriented workshops consisted of (i) development of future narratives based on existing public vision reports and with help of AI; (ii) collection of comments from the

research partners to further develop and finetune the narratives; (iii) specification of critical events relevant for realisation of the different future narratives through workshopping with the full consortium; (iv) development of transitions paths; and (v) development of a policy brief.

First, three future narratives were developed:

1. Regenerative Intelligence – Eco-Designing Electronics for a Sustainable Future
2. Circular Continuum – Lifetime Extension and Resilience in Electronics
3. Conscious Computation – Embedding Intelligence into Sustainable Electronics to Monitor and Manage Operation and Energy Consumption

The workshop participants were asked to define positive (desired) and negative (to be avoided) events that would influence the narratives based on the PESTE framework that includes the Political (P), Economic (Ec), Social (S), Technological (T), and Environmental (E) dimensions. The events were also placed on a timeline. Based on the workshop results VTT and TAU developed three roadmaps – one for each future narrative (Figure 53-Figure 55, respectively).

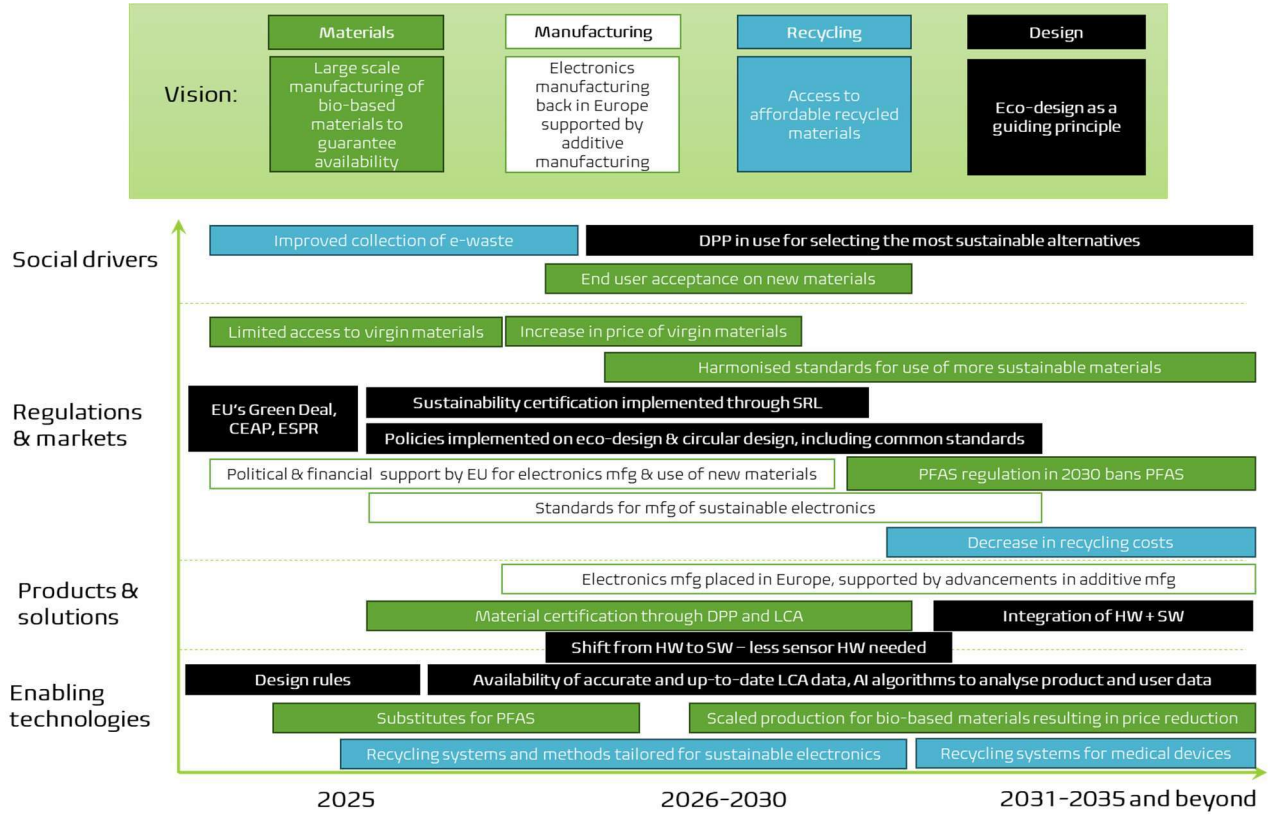


Figure 53. Narrative 1 roadmap illustrating key developments influencing the transition toward eco-designed electronics and the long-term vision. (mfg = manufacturing, HW = hardware, SW = software)

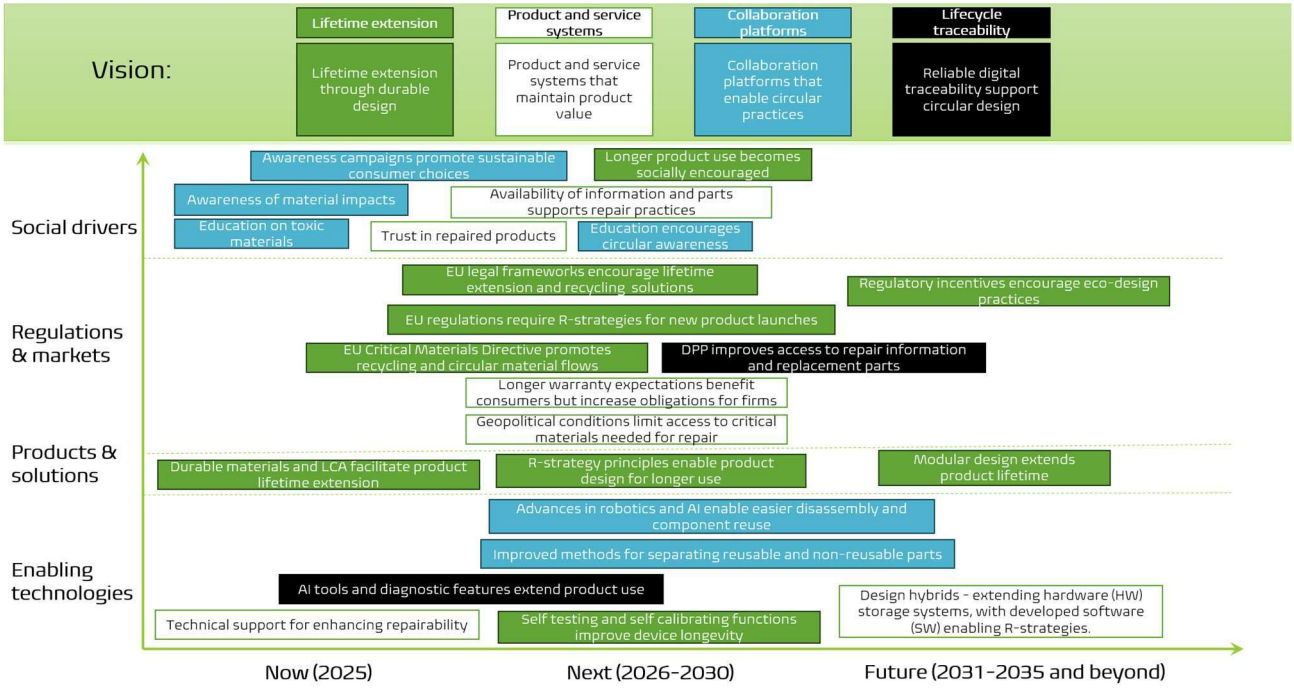


Figure 54. Narrative 2 roadmap illustrating key developments influencing the transition toward circular electronics and the long-term vision.

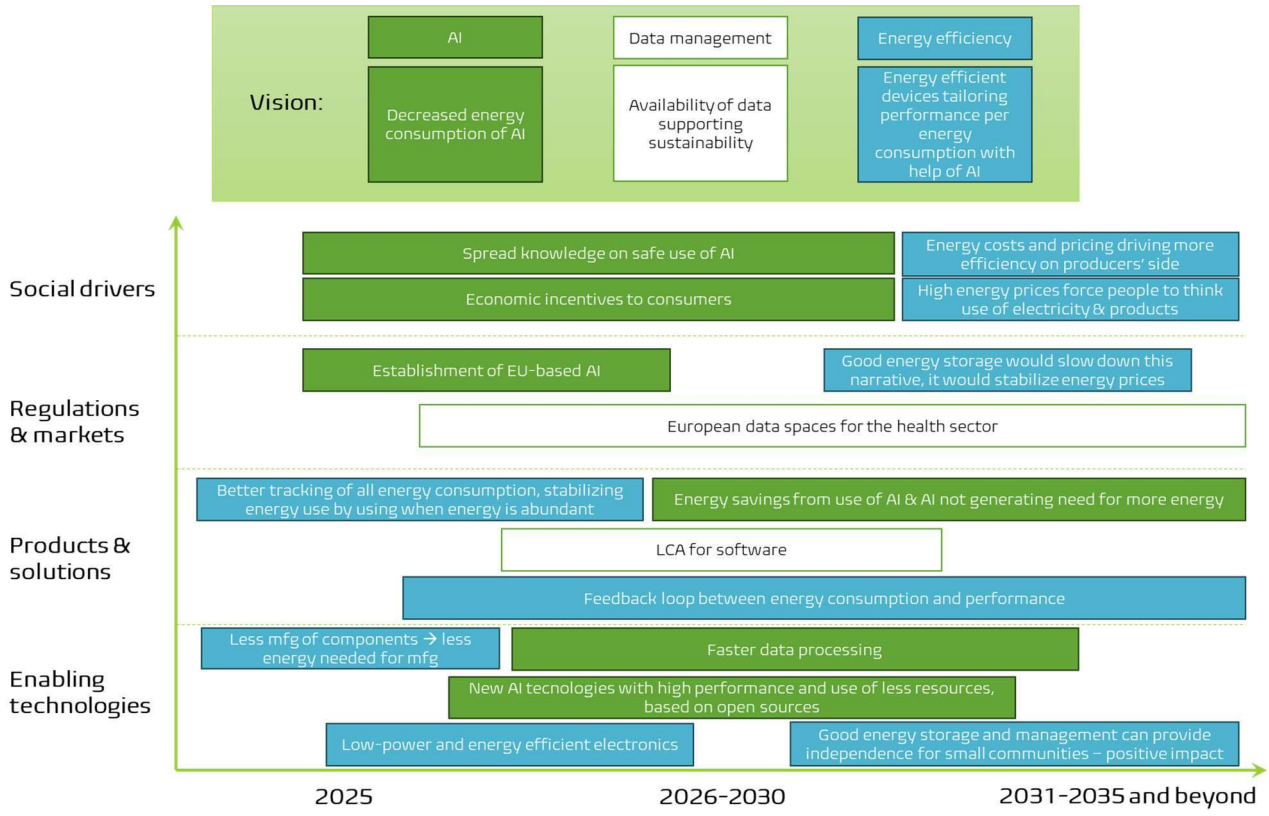


Figure 55. Narrative 3 roadmap illustrating key developments influencing the transition toward conscious computation and the long-term vision.

In the roadmaps regulations and policies are identified as the primary drivers for accelerating sustainable and circular electronic products. They set the framework companies must follow, influencing both design and manufacturing. To support this shift, standards for sustainability assessment are needed—covering consistent methods for evaluating environmental impact, use of recycled materials, and applying eco-design principles. Scaling up additive manufacturing and production of renewable, bio-based materials is expected to reduce environmental impact but requires financial and policy support to meet industrial needs for quality, cost, and production volume. Recycling of printed electronics requires new approaches, as current systems are not fully compatible. Compostable or biodegradable substrates could further enable innovative recovery methods.

Extending product lifetimes is seen as an effective route to reduce material consumption, electronic waste, and the use of critical raw materials. Success relies on coordinated progress across societal, regulatory, technological, and design domains. Social factors — such as awareness of material impacts, education, and trust in repaired products — play a key role in user acceptance. At the regulatory level, EU policies (e.g., Ecodesign, repairability requirements, Critical Raw Materials Directive) strongly influence the adoption of reuse, repair, refurbishment, and recycling practices. Warranty regulations support consumers while increasing responsibilities for manufacturers. From a product perspective, durable materials, modular architecture, and lifecycle-informed design support prolonged use. Enabling technologies include diagnostics, self-testing functions, repair support tools, robotics-enabled disassembly, and advanced sorting for reusable parts.

6 Summary of work carried out by companies involved

6.1 Canatu

CANATU provides a sustainable carbon nanotube (CNT)-based sensing platform for developing electrochemical biosensors to detect type 2 diabetes biomarkers, specifically C-peptide, in urine (Pilot 3.1a). The project successfully demonstrated the feasibility of functionalizing CNTs for the immobilization of biomolecules, such as C-peptide and its corresponding antibodies, enabling targeted biosensing applications. This confirmed the strong potential of CNT-based materials in biotechnology and medical diagnostics, particularly in biosensor development.

During the initial phases of the project, the focus was on developing an electrochemical immunosensor for C-peptide detection and evaluating paper as a sustainable substrate for CNT integration. The work progressed in line with the planned structure, with a clear focus on advancing sensor functionality and exploring sustainable material solutions. The key work packages included the development of a biosensor capable of detecting clinically relevant C-peptide concentrations and the integration of CNT films onto paper-based substrates.

Throughout the project, the implementation of these work packages was continuously assessed against the original objectives, ensuring alignment with the approved plan. This iterative evaluation enabled necessary refinements and supported steady progress toward the project goals.

The project achieved successful immobilization of sensing probes onto the CNT platform and demonstrated functional biosensing capability within clinically relevant ranges. Two assay formats, sandwich and competitive assays, were developed and validated as part of the work. These assays relied on enzymatic reactions and electrochemical readout principles, forming a solid basis for further development. As the project progressed, the assay format and workflow were refined to improve robustness and reproducibility.

In the later stages of the project, the integration of CANATU's carbon nanotube material into a lateral flow–type system was demonstrated as a key step toward a practical diagnostic solution. The results confirmed that CNT materials could be successfully combined with paper-based substrates, supporting the feasibility of a scalable and user-friendly platform. This marked an important transition from component-level development toward a more complete diagnostic concept.

In conclusion, the project demonstrated that CANATU's carbon nanomaterial is a viable platform for advanced biosensing applications. The ability to functionalize CNTs and achieve reliable detection in relevant conditions was successfully shown. In addition, the integration of CNT materials with sustainable substrates was validated, supporting the development of practical diagnostic solutions. Overall, the project reached its objectives and delivered a solid foundation for further development and future commercialization.

6.2 Movesense

Movesense's main focus has been on the joint development and real-life testing of several generations of more sustainable ECG patch samples in Pilot 2.2. Several generations of various substrate, adhesive and ink combinations were evaluated in practical use. Being the first element in the electrocardiogram registration signal path, the ECG patch electrode performance plays crucial role in capturing true and continuous ECG data, that can then be reliably digitized and processed further – eventually leading to diagnostic end use and clinical decision making.

The ECG patch testing included quantitative raw electrocardiogram signal registration, as well as subjective performance evaluation. Subjective evaluation consisted of gathering verbal feedback

from the test users on each sample patches' comfort, durability, adhesion throughout the tests and practical suitability for long term ECG registration. Software tools were developed to assist in scalable data collection and analysis process.

Data analysis was based on raw ECG signal quality inspection throughout the timespan each test specimen was worn. The testing showed clear differences in both measurement performance, but also surprisingly large differences in the end user comfort. Greatest differences between material stack combinations came from moisture tolerance of the substrates and electrical performance of the inks used for printing the conductive traces on the substrates.

Movesense looks forward to continuing the work, aiming to eventually bring more sustainable material combinations into commercial use.

6.3 Screentec

Together with support of other project members Screentec has selected several more sustainable materials to be used in Screen-printing process in order to manufacture functional and more sustainable printed electronics. 12 different substrates and 10 different pastes were used to make screen-printing tests, to find the most suitable materials and material combinations for different pilots of the project. Most of these materials were new to Screentec and we gained valuable information about how they behave in different process steps. Based on these prints VTT made basic characterization to determine the electrical and physical boundaries for the materials and Tampere University made electro-mechanical testing to find out the durability of the conductive materials on different substrates. In addition to the screen-printing process also component pick-and-place process was tested for one pilot, #1.3.

From the most promising materials Screentec manufactured demonstrators for total 5 different pilots and from most demonstrators also 2-4 different generations. Outcome of the different pilots were very satisfatory and educational for Screentec. Test with different demonstrators showed also that they were all functional as planned and also more sustainable the reference.

1. Sustainable luminaire (Pilot 1.3) – Copper printed conductive patterns on paper with surface mounted LED's applied on it. Pilot owner Signify, NL.
2. Sustainable EEG electrodes (Pilot 2.1) – Copper printed conductive patterns on paper made to EEG electrodes by combining prints with snap buttons, skin adhesive etc.
3. Sustainable ECG electrodes (Pilot 2.2) – Carbon printed conductive patterns on paper made to ECG electrodes by combining prints with snap buttons, foam, skin adhesive etc.
4. Sustainable bio-impedance electrodes (Pilot 2.2) – Copper and carbon printed conductive patterns on paper made to bio-impedance electrodes with snap buttons, skin adhesive etc.
5. Sustainable electrochemical sensor (Pilot 3.1a) – copper, carbon and dielectric printed circuit on paper to make electrochmical sensor for C-peptide.

As a conclusion Screentec managed to make many succesful more sustainable demonstrators in this project. Processing, tests and demonstrators increased a lot company's capability and knowledge to process more sustainable materials for different kind of printed electronics products. As a result of the project Screentec has already made commercial sales abroad based on new offering generated by the project. Screentec will continue the promising use and testing of these more sustainable materials also in future projects and assignments.

6.4 Tervakoski

Tervakoski has developed and supplied cellulose based substrates for two main purposes in this project;

1) Substrates for printed electronics
2) Material for fluid transportation in analytical devices.

The focus of our work has been in finding optimal paper grades from existing portfolio and testing them at our partner sites for several end-uses/pilot cases (5 out of 10). In addition, we conducted extensive pilot manufacturing trials to improve certain critical material properties for the papers.

The results show that cellulose based materials, especially designed for optimal porosity and smoothness can be used in various applications to improve the sustainability of electronic devices and components. With certain fine tuning of material properties and product design, the challenges related to processability / print quality could be addressed to facilitate the wider use of cellulose based substrates in the electronics industry.

At the end of the project, our ambition is to identify the most potential routes for commercializing the solutions and support the sustainable transformation of the electronics industry.

6.5 UpCode

UpCode has been developing their own DPP platform and various smart tags in the project. During the project UpCode has participated in pilots that relate the needs of other companies within consortium. What UpCode has learned in the project:

1) There is need for two types of SmartTags, temperature sensing (various thresholds) and humidity sensing.
2) Track and trace of individual items is feature that will be needed in the future when it comes to consumer electronics

To enchance its future business potential, UpCode has developed its private DPP platform that can maintain database of companies, products and items. This data is enriched with locations of recycle and repair centers as well as it has potential to include additional features like C2C discussion platform. For each product and its batch documentation can be uploaded to platform, this documentation can include service manuals, user manuals, certifications and so other data. Also trough the platform consumer can connect services under their interest.

For SmartTags UpCode has piloted new humidity tags that can tell service personnel if device has been altered to water and by so is not anymore under warranty or that specific parts needs to replaced. Also UpCode has developed new datamatrix based UpCode SmartTags which can now include unique item identifiers as well as three individual sensors.

6.6 UPM Raflatac

UPM Raflatac has developed and supplied sustainable pressure-sensitive material solutions for the project, supporting emerging skin-contact and printed electronics applications. This includes advanced laminate constructions for single-use sensor labels, ensuring compatibility with roll-to-roll printing, reliable adhesion and durability in medical and hygiene applications. (Pilot 2.2., Pilot 3.2)

In addition, UPM Raflatac (with support by UPM Biocomposites and later KCL) has supplied and developed Formi 3D filaments to be utilized in luminaire housing (Pilot 1.3).

The work covers the introduction of alternative raw materials, exploration of new adhesive concepts, and execution of compatibility and adhesion testing, while also strengthening testing and pilot-scale production capabilities for future development in advanced adhesive materials.

7 Conclusions

Finnish partners' part of the Sustronics project was implemented successfully without major deviations. All activities were completed according to the plan on planned schedule.

The Sustronics project has demonstrated that sustainable and circular approaches can be advanced in electronics development, specifically printed and hybrid electronics, through coordinated work on materials, processes, components, system integration and business models. The Finnish consortium generated significant results in biopolymer and paper-based substrates, printability, biodegradability, component assembly, electromechanical reliability, light-guiding films, paper fluidics and sustainable energy storage. The results show that several bio-based, recyclable and biodegradable material solutions can already provide technically relevant performance, while also revealing the practical limitations that still need to be addressed in areas such as thermal stability, processability, bonding reliability, conductivity and end-of-life treatment.

The work on sustainability and circularity showed that environmental improvements in electronics require action across the whole value chain. The life cycle assessments highlighted that material choices, assembly approaches, use patterns and end-of-life scenarios strongly influence the overall environmental impact of electronic products. In several cases, the project solutions showed clear potential to reduce impacts compared with conventional alternatives, especially when product lifetime is extended, reusable elements are introduced, or lower-impact materials and processes are applied. In parallel, the circular business model work, stakeholder studies, and DPP activities demonstrated that technical innovation alone is not sufficient. Adoption of sustainable electronics depends on clear value propositions, validation, traceability, service models and collaboration between manufacturers, technology providers, customers and end-of-life actors.

Overall, the Finnish activities in Sustronics created a strong basis for future research, industrial exploitation and ecosystem development in sustainable electronics. The project strengthened scientific understanding, produced practical pilot-level demonstrations, supported dissemination through publications and events and provided recommendations for standardisation, policy development and future roadmaps. The findings indicate that the transition towards sustainable and circular electronics is feasible, but it requires continued development of materials, scalable manufacturing solutions, circular design practices, assessment methods, and market mechanisms. The results presented in this report therefore form an important contribution to the wider European effort to reduce the environmental burden of electronics while enabling new functionalities, products and business opportunities.

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