101112109

Sustainable and Green Electronics for Circular Economy

Deliverable 3.4

Final prototypes for Gen 3, including validation data and end user engagement

Project Coordinator	Ramon Caanen, Philips Electronics Nederland B.V.		
Start date Project	June 1st, 2023	**Duration**	36 months
Version	1.0		
Status	Final		
Date of issue	30-05-2026		
Dissemination level	Public		

Authors' data

Author	Beneficiary	e-mail
Liisa Hakola	VTT	liisa.hakola@vtt.fi
Pilot#1.1: Robert Hofsink	PMS	robert.hofsink@philips.com
Pilot#1.2: Philip Monsbourgh, Sharina Ligtelijn	PCL	philip.monsbourgh@philips.com, PEN, sharina.ligtelijn@philips.com
Pilot#1.3: Peter Bancken	SIG	peter.bancken@signify.com
Pilot#2.1: Rita Cristovao	PLUX	rcristovao@pluxbiosignals.com
Pilot#2.2: Mikko Paakkolanvaara	SCR	mikko.paakkolanvaara@screentec.com
Pilot#2.3: Axelle Poteaux	FOR	axelle.poteaux@forvia.com
Pilot#3.1a: Elisabeth Hengge	IFAT	elisabeth.hengge@infineon.com
Pilot#3.1b: Alfredo Ongaro	ONA	a.ongaro@onalabs.com
Pilot#3.2: Shabira Abbas, Tilak Lakshmana	ESS	shabira.abbas@essity.com, tilak.lakshmana@essity.com
Pilot#3.3: Moritz Schlagmann	IFAG	moritz.schlagmann@infineon.com
Final editor's address	Ramon Caanen	ramon.caanen@philips.com Philips Electronics Nederland B.V. High Tech Campus 34 – Floor 5 Eindhoven / Netherlands

Management Summary

Within Sustronics, sustainable materials and processes were identified, investigated, and developed aiming at increasing the sustainability in electronics. These solutions were then integrated in WP3 in the three different use cases, which include a total of ten pilots listed below:

Use Case #1: Circular electronic devices

- Pilot#1.1 Green and circular image guided therapy systems
- Pilot#1.2 Sustainable system integration and product design of personal health devices
- Pilot#1.3 Sustainable luminaire

Use Case #2: Sustainable manufacturing for electronics

- Pilot#2.1 Embedded electronics for EEG monitoring
- Pilot#2.2 Wearable health monitoring
- Pilot#2.3 Sustainable dashboard for automotive

Use Case #3: Environmentally compatible single use electronics

- Pilot#3.1a In Vitro Diagnostics
- Pilot#3.1b Smart skin patch
- Pilot#3.2 Smart Hygiene
- Pilot#3.3 Smart wound dressing

This deliverable represents the realisation of Gen 3 prototypes of each pilot. All the pilots have successfully integrated their Gen 3 prototypes with sustainability as the guiding feature. The LCA studies for environmental impact have been used to update some of the pilot descriptions since Gen 1 to better align with decreased environmental footprint. Furthermore, the pilots have specified their end-user engagement and social impact.

List of abbreviations

ADPe	Abiotic Depletion Potential
AI	Artificial Intelligence
AFE	Analog Front End
ASIC	Application-Specific Integrated Circuit
BLE	Bluetooth Low Energy
BLI	Battery Light Indication
BMI	Body Mass Index
BOM	Bill of Materials
CCC	Concordance Correlation Coefficient
CGM	Continuous Glucose Monitoring
CL	Control Line
DPP	Digital Product Passport
ECG	Electrocardiography
Ecotox	Freshwater ecotoxicity
EEG	Electroencephalogram
EoL	End-of-Life
ESG	Environmental, Social, Governance
FAETP	Freshwater Aquatic EcoToxicity Potential
G&B	Grooming & Beauty
GWP	Global Warming Potential
GUI	Graphical User Interface
IC	Integrated Circuit
ICU	Intensive Care Unit
IGTS	Image Guided Therapy System
IME	In-Mold Electronics
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LDS	Laser Direct Structuring
LE	Low End
LED	Light Emitting Diode
LF	Lateral Flow
LFA	Lateral Flow Assay
LFD	Lateral Flow Device
MARD	Mean Absolute Relative Difference
MB	MasterBatch
MSW	Municipal Solid Waste
MQTT	Message Queue Telemetry Transport
NFC	Near Field Communication
OEM	Original Equipment Manufacturer
PC	PolyCarbonate

PCB	**Printed Circuit Board**
PEF	**PolyEthylene Furanoate**
PET	**PolyEthylene Terephthalate**
PLA	**PolyLactic Acid**
PoC	**Point-of-Care**
PP	**PolyPropylene**
PPG	**PhotoPlethysmoGraphy**
R2R	**Roll-to-Roll**
RMSE	**Root Mean Squared Error**
SMD	**Surface Mounted Device**
SRL	**Sustainability Readiness Level**
SW	**SoftWare**
TL	**Test Line**
TMB	**Tetramethylbenzidine**
TPU	**Thermoplastic Polyurethane**
TRL	**Technology Readiness Level**
UCPCR	**Urine C-Peptide to Creatinine Ratio**
VPC	**Value Proposition Creation**
WE	**Working Electrode**
WEEE	**Waste Electronic and Electric Equipment**

Table of Contents

1. Introduction

1.1. Purpose of the document

The goal of WP3 of Sustronics project is to specify, integrate and validate the use case specific pilots as well as their manufacturing workflows based on technologies coming from WP1-2 (Material and process development & Component and device development), and sustainability analysis from WP4 (Sustainability assessment and eco-design) to guarantee that the pilots are implemented in the most sustainable manner. The system approach for the pilots is closely assisted by questions of sustainability in the whole life cycle and concepts for end-of-life management. This deliverable reports the progress of Gen 3 prototypes of the ten pilots.

Chapter 2 of this document describes Gen 3 demonstrators which have been developed for all pilots, including sustainability considerations. In chapter 3 and 4, respectively, the system specifications, designs and achievements of each pilot Gen 3 prototypes are reported. Chapter 5 describes the social aspects related to each pilot. Chapter 6 summarises the overall conclusions for Gen 3.

The following Technology (TRL) and Sustainability Readiness Levels (SRL) have been used in this document for each pilot to highlight their development status:

TRL

- TRL 1 – Basic principles observed
- TRL 2 – Technology concept formulated
- TRL 3 – Experimental proof of concept
- TRL 4 – Technology validated in lab
- TRL 5 – Technology validated in relevant environment
- TRL 6 – Technology demonstrated in relevant environment
- TRL 7 – System prototype demonstration in operational environment
- TRL 8 – System complete and qualified
- TRL 9 – Actual system proven in operational environment

SRL

- SRL 1 – Basic sustainability requirements observed
- SRL 2 – Sustainability concept formulated
- SRL 3 – Experimental proof of concept for sustainability (e.g. first LCA available)
- SRL 4 – Sustainability approach validated in lab (e.g. testing sustainable materials)
- SRL 5 – Sustainability approach validated in relevant environment
- SRL 6 – Sustainability approach demonstrated in relevant environment
- SRL 7 – Sustainability approach demonstration in operational environment
- SRL 8 – Sustainable system complete and qualified
- SRL 9 – Sustainable system proven in operational environment

1.2. Related documents

D3.4 is an update of D3.3 and presents the Gen 3 final prototypes, including their characterisation as well as updates to the system specification and design (requirements) towards Gen 3.

The Gen 3 prototypes, together with their more detailed life cycle assessment (LCA) and the development of circular business models, are further documented in the following deliverables:

- D4.6 Life cycle assessment and handprint study results for select case studies (FHG, M35)
- D4.7 Review on the design and implementation of prototypes of circular business models in Sustronics (PMS, M36)

All requirement-related deliverables from WP1 are linked to and provide input for this document:

- D1.1 – Materials specifications and initial testing plan
- D1.2 – Processes specifications and initial testing plan
- D1.3 – Validation and testing plan
- D1.4 – Sustainable materials and their characteristics
- D1.5 – Sustainable processes and their characteristics
- D1.6 – Material and process validation and testing results

All component and device development deliverables from WP2 are also related to this document and contribute to the overall system design and implementation:

- D2.1 – Requirements specification for components and devices
- D2.2 – Report on sensors and transducers
- D2.3 – Report on energy storage and energy management
- D2.4 – Report on communication and energy harvesting hardware and protocols
- D2.5 – Report on ASIC development
- D2.6 – Report on hybrid and integrated components
- D2.7 – Report on software functionalities

All use-case-related deliverables from WP3 are directly linked to this document and describe the evolution of the pilot systems across generations:

- D3.1 – Initial system specification and design for pilots, including circularity aspects
- D3.2 – Gen 1 prototypes, including characterisation and updates to system specification and design for Gen 2
- D3.3 – Gen 2 prototypes, including characterisation and updates to system specification and design for Gen 3

All sustainability assessment and eco-design deliverables from WP4 are connected to this document and support the evaluation of environmental impact and circularity aspects:

- D4.1 – Guideline, framework and KPIs to LCI management and circular business models
- D4.2 – Analysis of life cycle-based environmental impacts and end-of-life processes of sustainable materials in electronics
- D4.3 – Digital product passport concept definition
- D4.4 – End-of-life concepts and new processes for sustainable electronics
- D4.5 – Final description of the e-co_2-design framework
- D4.6 – Life cycle assessment and handprint study results for select case studies
- D4.7 – Review on the design and implementation of prototypes of circular business models in Sustronics

2. Description of Pilot Status Gen 3

2.1. Use Case #1 Circular electronic devices

Use Case 1 Leader: PEN (Ramon Caanen)

Use case 1 consists of three pilots:

- Pilot#1.1 Green and circular image guided therapy systems (PMS)
- Pilot#1.2 Sustainable system integration and product design of personals health products (PCL)
- Pilot#1.3 Sustainable luminaire (SIG)

The objective of UC#1 is to design electronic devices to be compatible with specified circularity strategies, such as remanufacture, repair, recycle, while benefiting also from additive manufacturing technologies and bio-based materials. The three pilots will, thus, redesign existing products in line with circularity and sustainability requirements.

2.1.1. Pilot#1.1 Green and circular image guided therapy systems

Pilot Leader: PMS (Stefan Schalk)

The goal of this pilot is to minimize the environmental footprint of Philips' image guided therapy systems (IGTS), particularly the Azurion (Figure 1), underpinned by LCAs to facilitate sustainability claims. The Azurion is an interventional X-ray system that is used in minimally invasive treatment. As such it must adhere to strict regulations on the design process and changes that may affect functional effectiveness or patient safety. For this reason, making changes to the product is costly and any circular design decision is best introduced early in the design process.

Figure 1: Philips Azurion X-ray imaging system

The lifetime of an Azurion is typically 10 years, which can be extended by another 4 years of service. Given this long lifetime, the use phase (i.e., energy consumption) is an important factor in the Azurion's environmental footprint.

This pilot focuses on the following aspects:

- Reducing energy consumption: disabling components when they are not needed
- Reusing installation frames (remanufacturing explored in Gen 1)
- New lightweight, modular geometry design
- Embedding LCAs and environmental considerations in the R&D process

Updated Pilot Description for Gen 3:

Gen 2 and Gen 3 will not contain updated demonstrators of parts reused from Allura into Azurion imaging systems. Due to a re-evaluation of the certification strategy for component lifetime extensions, a remanufacturing solution will not be in time for the timeframe in which Allura systems will return from the field. Although this remanufacturing pilot is discontinued, learnings can be transferred to future releases outside the scope of Sustronics. Meanwhile, the reuse of metal installation frames (now only used a single time and then recycled) has been investigated and a pilot has started to make this possible for Azurions. Installation frames of the Azurion imaging system are currently only used once for the deployment at customer sites, after which they are scrapped. As part of reducing the material usage an investigation has started into the reuse of such installation frames, leading to a reduction of steel and wood as pictured in Figure 2.

Figure 2: Installation frames for Azurion imaging system

Additionally, an alternative pilot about the design of a lightweight, modular geometry has been included to replace remanufacturing in Gen 2 and Gen 3 of Pilot 1.1, potentially strongly reducing the footprint of Azurion (and successors) in the future (to be assessed by LCA). This case will also be used to investigate the potential in embedding sustainability in the standard value proposition creation process, for which the conclusions are presented with Gen 3.

The state-of-the-art imaging system holds a heavy C-arm shaped geometry which significantly adds to the material footprint of the overall system. In the context of Sustronics, Pilot 1.1 is working on a lighter weight, modular system, which at the same time offers more flexibility in its imaging capabilities.

Technologies involved and role of project partners in Gen 3:

- Software for saving energy (PMS)
    - Control software to activate/deactivate energy mode
    - AI models to detect patient
- LCA tooling and infrastructure:
    - Obtaining the data and evaluating the quality of the data (PEN)
    - Performing LCAs and identifying hotspots in the design (PEN)
    - Assessing the use of LCAs and identifying opportunities for use of LCAs to enable circular models (TAU)
    - Recommendations on requirements and a process for making sustainability part of the design process (FHG)
    - Embedding sustainability and LCAs into the Value Proposition Creation process (PMS, TAU)
- Light-weight modular system
    - Robotic arm and motion control technology (PMS)
    - Modular end-effector (PMS)

Technical layout and characterisation of Gen 3:

The Gen 3 prototype consists of the progress in the identified elements for sustainability improvement: energy saving, new geometry design, and the supporting LCA/LCI tooling. Gen 2 already contained a prototype process for frame reuse and has not been further developed in Gen 3.

Reuse of installation frames

This is the pilot as developed for Gen 2, in which installation frames were collected back after use, instead of being sent to the recycler (Figure 3). Next to this, we conducted simulations of the stress on the frames because of vibrations during truck transport (Figure 4). Conclusions were that frames could be reused up to five times, and now single reuse of the frames has been certified (to be extended to five times reuse in the future). The reuse of frames is expected to bring a positive case as well as a reduction in footprint.

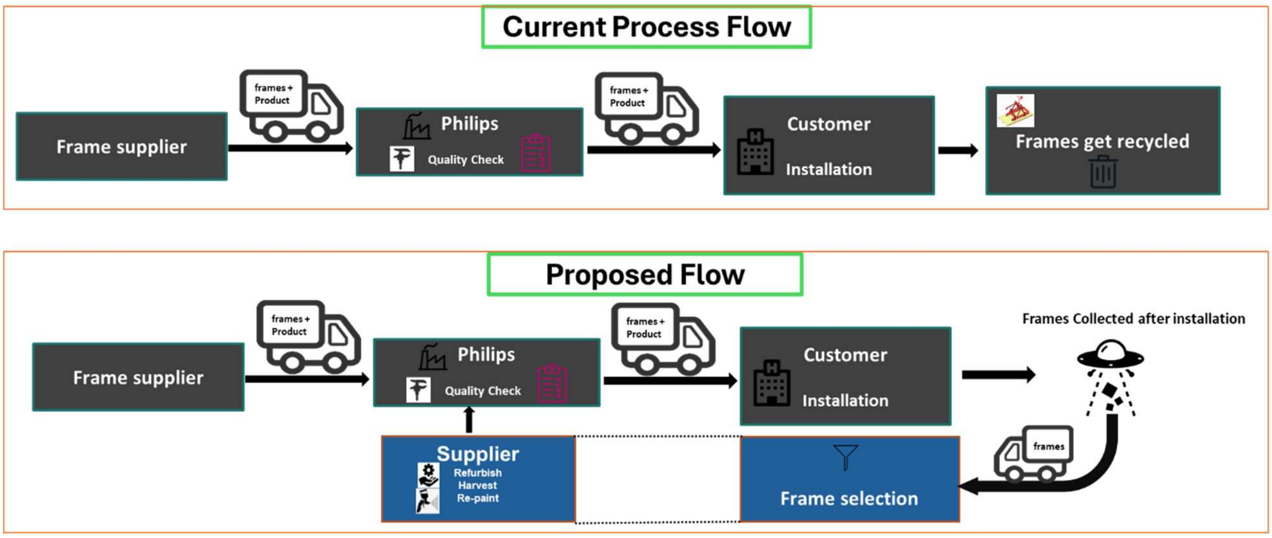


Figure 3. Improved process for reuse of installation frames. Instead of recycling the steel from collected frames, the frames will be selected based on visual inspection and returned to Philips for a quality check and reuse.

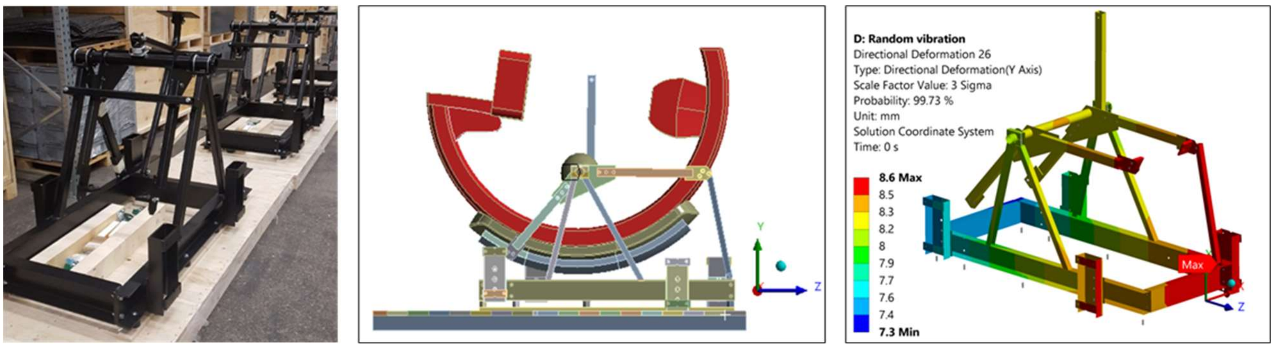


Figure 4. Left: Picture of installation frames. Middle: Schematic of C-arc carried by the installation frame. Right: Example of dynamic analysis conducted on frame.

Energy saving

In Gen 1 a first analysis of the suitability of Azurion components for energy saving has been conducted. In Gen 2 a further refinement of an energy saving feature has been made in which it has been split into a part suitable for fast deployment (within 1-2 years after the project) and a part for a release further down the roadmap. The first part (eco-mode light) contains the features with more straightforward implementations: automatic shutdown functionality and support of display standby. The second part (full eco-mode) will also contain tube standby (disabling the image chain) in between procedures. In Gen 3, automatic triggers to enable and disable eco-mode based on the presence of a patient have been developed.

Expected energy saving for the different implementations have been analysed for three different use scenarios:

- Scenario 1: Environmentally conscious user that already switches off the system manually every day. Energy is only saved by display stand-by and disabling the image chain in between procedures.
- Scenario 2: User does not want to switch off the system overnight but can still save energy by putting displays in standby and disabling the imaging chain.
- Scenario 3: User did not switch off the system at the end of the day but now used the automatic shutdown feature.

The main benefit of full eco-mode is expected to come from scenario 2, in which a user does not want to switch off the system completely but is willing to switch off the imaging chain with a wake-up time of less than 1 minute. Next to this, a field logging analysis provided information about the percentage of time a system would go in stand-by if we would have a tube in stand-by mode, hence going from eco-mode light to full eco-mode. The time tube eco-mode is active, has been estimated as the time for which the system is on, but not actively used for a procedure. On average, eco-mode would be active 37% (median of 29%) of the time, based on current use. If the automatic shutdown option is used in the field, this percentage will go down, because the system will be less time on in an inactive state. From this we conclude that tube eco-mode could be activated around 7 hours per day. Tube stand-by power saving was measured to be 0.90 kW, which is 46% of the total power consumption of the system. The updated data has been collected in the plot in Figure 6.

Based on the logging analysis, we estimate that 75% of the customers belongs to scenario 1 and now already switch off their system (which was around 25% in an older analysis). This means that the behaviour of the end user has changed in the meantime. The remaining 25% must be divided over scenarios 2 and 3, but for this we do not have data, so we assume an equal split: scenario 1 – 75%; scenario 2 – 12.5%; scenario 3 – 12.5%. The average energy saved per system can now be estimated by multiplying the fractions by the energy saved per year per scenario and summing the outcomes, resulting in an estimated average energy saving of 4.34 MWh per system.

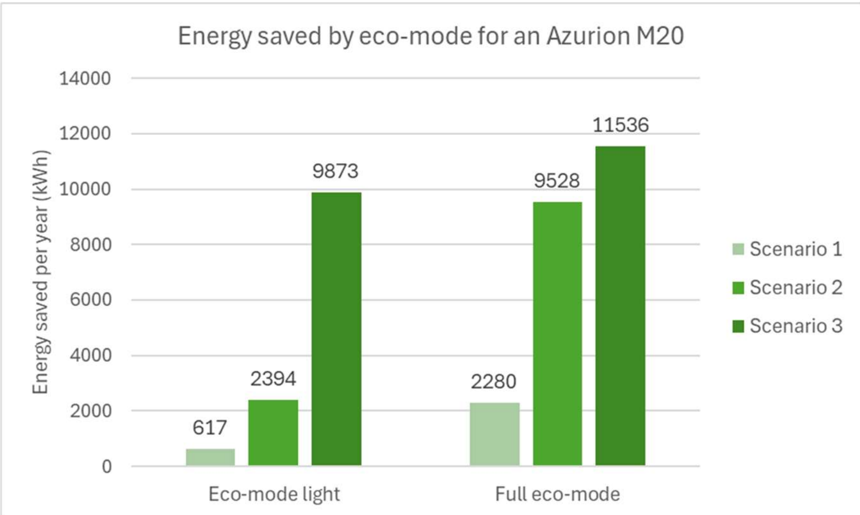


Figure 5. Estimated yearly energy saved by energy saving features for an Azurion M20 monoplane system for the three use scenarios. Hospitals typically have multiple cathlabs in use.

Lightweight, modular geometry

One of the largest contributors of material in the system is the geometry that carries the X-ray tube and detector. In this pilot, we are investigating a lightweight, modular solution that can replace the original design. In Gen 2, a first demonstrator has been created in which a industrial robot, typically used for manufacturing, replace the typical C-arc. We envision several environmental and clinical benefits of this solution. With respect to sustainability, we expect a reduction in material use and transport footprint, options to use the robot longer than the current 10-year guaranteed lifetime that applies to the C-arc, reduce the required floorspace and infrastructure at the hospital (end-user) and the potential to use different end effectors, making the solution more versatile. In Gen 3, a prototype of a modular end-effector has been developed and its benefits on the environmental footprint assessed. One of the main expected benefits is a higher occupation rate of the system, reducing the footprint per patient or procedure.

LCA and LCI processes and tooling

The component database of the Azurion imaging system has been updated with materials and weights. A prototype version of a tool to compare footprints of design alternatives has been created.

Value proposition creation process with sustainability integration

In the early phase of development, the proposition of the product is investigated with the Value Proposition Creation process (VPC) via the three perspectives of Customer, Offer and Business. However, sustainability is not an explicit element of the VPC while choices in the VPC stage can have a big impact on the sustainability of the final product. Sustainability was therefore added as a fourth perspective to test how this could benefit the VPC process and the proposition itself. This was tested as a process on the proposition of the lightweight geometry design. Five key questions have been defined based on this pilot that can bring in sustainability in VPC in a comprehensive way:

1. What are the general sustainability needs and drivers?
   External and internal drivers that are not VPC specific
2. What is the current performance?
   Baseline LCA with hotspots, value mapping, competitor benchmarking
3. What are the opportunities for improvement?
   This VPC has the potential to improve… (Energy, Material, Nature, Total footprint)
4. What is the sustainability ambition of this VPC?
   Conclude and set target: for this VPC, the ambition is to improve/outperform on…
5. How will the sustainability ambition be realized?
   - *Determining the sustainability impact on three levels: the product/NPI, the system, and the total solution*
   - *Determining business model drivers for sustainability and how this can impact the business model*
   - *Learnings feed back into the other three perspectives, appointing requirements and wishes for sustainability to product development*
     - *Customer = key sustainability needs*
     - *Offer = potential sustainability benefits and claims, sustainability as needs/ features*
     - *Business = business drivers for sustainability*

For the lightweight geometry concept, this meant that the proposition was enhanced with the benefits it can bring on material reduction and total environmental footprint. Furthermore, synergy was found between the clinical proposition and the difference it can make to the patient to sustainability, since the innovation has the potential to bring patients home earlier for specific procedures, reducing the environmental footprint of the patient journey.

Sustainability & social targets and their status in Gen 3:

This section describes the status of the Pilot 1.1 KPIs and the main activities and results of the four elements in the pilot. The sustainability KPIs are presented in Table .

Table 1: Sustainability KPIs for Pilot 1.1.

KPI	Baseline	Target	Status at Gen 3
Decrease energy consumption	10.3 MWh* (updated w.r.t previous baseline based on scenario fractions)	30% reduction	Reduced by 4.34 MWh / 42%
Reduction of LCA score of IGTS (10 years lifetime)	Benchmark scenario 1: 163 ton CO2 eq. (24 hrs. per day ready to scan mode) Benchmark scenario 2: 125 ton CO2 eq. (12 hrs./day ready to scan mode, 12 hrs./day and during weekends off, as COCIR methodology proposes)	10% reduction	40% reduction compared to Benchmark 1 22% reduction compared to Benchmark 2
Material reuse in remanufactured systems	0%	25%	Systems remanufacturing has been discontinued and replaced by reuse of installation frames
Systems recovered from the field for repurposing	66%	80%	The systems recovery activity has been discontinued and replaced by the reuse of installation frames
Reuse of installation frames	Not implemented	5x reuse of installation frames	1x reuse of installation frames. Focus shifted to new geometry concept, which brings a larger sustainability benefit.

** Average energy consumption for 1 year: 25% 24 hrs. per day in ready-to-scan mode and 75% 12 hrs. per day in ready-to-scan mode.*

End user engagement:

- Co-creation sessions with 3 customers to discuss the eco-mode solution and sustainability needs in general. Conclusions for eco-mode captured in a broader value proposition analysis.
- Pilot of frame reuse executed together with logistic service provider.
- The geometry concept has been demonstrated and discussed with 32 customers from various clinical domains, incorporating direct feedback from end users throughout its

development. This engagement ensured that clinical workflows, usability, and real-world constraints were addressed early on.

Pilot Achievements & key challenges in Gen 3:

Achievements

- Eco-mode prototypes available for the light version (automatic shutdown and display standby) and full versions (automatically putting the tube in a low-power state). Automatic AI-based triggers implemented to achieve this.
- Sustainability defined as an integral element of the value proposition creation process, with five key questions that need to be addressed in the proposition phase. Piloted on the Gen 3 proposition setting the sustainability ambition and how to realize in one integral VPC.
- Designed and demonstrated a modular end-effector prototype that validates decoupling of imaging functionality from fixed system geometry, enabling standardized components, refurbishment, and scalable integration into future system architectures.
- Prototype tool available for lifecycle assessment available based on live component database with sustainability information

Key challenges

- Using reliable AI-based triggers for eco-mode. In Sustronics the happy flow has been investigated. A future implementation requires a thorough risk assessment on system and user level.
- Identification and management of key technical and integration challenges associated with realizing a modular end-effector within a new imaging geometry.
- Ensuring robust validation and end-user relevance of the prototype while maintaining modularity and lightweight design.
- Aligning the modular end-effector concept with scalability and lifecycle objectives, including sustainability assessment and future system integration.
- LCA, eco-design and design for recyclability as integrated part of the design process. Collecting reliable data and having a good understanding of the design options at the start of the design process is often not feasible.
- Embedding sustainability in the value proposition creation process:
  - Setting a clear ambition for the VPC: when is the sustainability performance good enough?
  - Having a holistic view on impact: important to consider not just the product impact but also the effect it has on patient flow and procedures since this can make a major difference in overall impact. However, it is challenging to get a full view of all the energy and materials used in a complete patient flow.
  - Valuing sustainability: sustainability is increasingly important to hospitals (e.g. in tenders) but is often not the core of the proposition compared to e.g. clinical value or efficiency. The challenge is therefore to find the synergy where these aspects can come together.

Technology and sustainability readiness levels:

Table 2 : Pilot 1.1 Technology and sustainability readiness levels

	Gen 2	Gen 3
TRL	3-5	5-7
SRL	2-3	3-4

2.1.2. Pilot #1.2 Sustainable system integration and product design of personals health products

Pilot Leader: Philips (Philip Monsbourgh and Sharina Ligtelijn)

Pilot Goal/Objective

In Pilot 1.2, Philips Consumer Lifestyle (PCL) focuses on reducing the environmental footprint of Grooming & Beauty (G&B) devices. Previous LCAs have shown that printed circuit board assemblies (PCBAs) are significant contributors to the total impact of these devices. This Pilot therefore explores how alternative technologies can reduce these impacts and provide insights for future electronics innovations and product generations.

Below is an overview describing the aims of each Generation:

> <u>Generation 1 – Learn</u>
> Identification of environmental hotspots and refinement of the LCA methodology.
>
> <u>Generation 2 – Fast Iteration & Test</u>
> Application of insights from Generation 1 to a simple PCBA and assessment of environmental improvement potential of new design features.
>
> <u>Generation 3 – Integration</u>
> Integration of the improved technologies into a more complex PCBA and evaluation of effect on the environmental impact at both PCBA Level and at a Total Product Level.

This deliverable reports specifically on the Generation 3 results, with broader reflections from all three generations included in the final interpretation.

NOTE: Due to confidentiality, details on the technologies and results will not be shown in this deliverable. All detailed results are presented in the non-public sensitive deliverables.

Updated Pilot Description for Gen 3

For Generation 3 (Gen 3), the focus was on implementing all the knowledge and experience derived from Generation 1 (Gen 1), and Generation 2 (Gen 2) into a more complex PCBA, which is then finally integrated back into the original appliance.

The results are presented in the following sections.

Work Carried Out: Gen 1 and Gen 2 Overview

<u>Generation 1: Learn</u>

In Gen 1, the focus was on learning what were the most important key contributors to the environmental impact of PCBAs. To do this, a sharpened LCA methodology was used including new cross-capability collaborations to obtain improved data quality.

From a technical point of view; this phase was leveraged to have a more nuanced understanding of the alternative technologies in scope. Gen 1 was concluded with the selection of two alternative technologies.

<u>Generation 2: Fast Iteration and Test</u>

For Gen 2, the focus was on fast iteration and testing to verify if the proposed solutions indeed significantly reduced environmental impact.

A simple PCBA was chosen for further investigation. Three alternative technologies were selected to test from a technical as well as environmental perspective. From both perspectives, the results were promising. Overall, these positive outcomes meant the new methods and technologies described above are adopted for integration in Generation 3.

Technologies involved and role of Project partners in Gen 3

For the development of the Gen 3 PCBA, the three alternative technologies tested in Gen 2 were all adopted. A key development partner for the alternative technologies was TNO Holst Centre. The LCA was performed internally with input from Fraunhofer.

Technical layout and Characterisation of Gen 3

The selected Baseline PCBA is a relatively simple single-sided PCBA. All three alternative technologies were implemented.

The resulting Gen 3 PCBA was integrated back into its original existing appliance. Since the design of the existing appliance was never intended to accommodate these new innovations, some parts required adaptation to enable secure and robust electrical connection to the other key modules

NOTE: Details on the technologies are sensitive and therefore will not be shown in this deliverable. All results are presented in the non-public sensitive deliverables.

Sustainability and its status in Generation 3

This section describes the LCA results on a PCBA Level as well as on a Product Level.

Afterward a scenario analysis will be presented followed by conclusions of the LCA Section. Finally, the social aspects of the Pilot are addressed.

<u>Sustainability Targets and Results</u>

While the original KPIs were defined at proposal stage, the KPIs used as final targets for Gen 3 were refined during project execution under Task T3.1 and are reported in the approved pilot deliverables (D3.2 and D3.3). A PCBA Level and a Product Level target were defined. The exact targets are confidential and are stated in the non-public deliverables.

PCBA Level

The Gen 3 PCBA achieved the PCBA Level target. This reduction is predominantly driven by one of the alternative technologies. The two other alternative changes have significant reduction on Part Level, but the impact on PCBA Level is negligible.

Product Level

On Product Level, integration of the Gen 3 PCBA resulted in a significant impact reduction. However, it was not sufficient to meet the target.

Scenario Analysis

Two additional approaches to further reduce the impact on a Product Level were evaluated. They show to be promising to further reduce the impact on Product Level.

Conclusion

In conclusion, the new more detailed LCA method delivered a more accurate PCBA impact assessment than the default LCA method, and therefore well suited for cases where sufficient time is available and the need for detailed PCBA Level LCA results exist.

All three alternative technologies show clear potential. However, their effectiveness at PCBA and Product Level depends strongly on their relative contribution to the overall Baseline design.

For this specific PCBA studied, one of the alternative technologies was the dominant driver for improvement. Together the combined contributions resulted meeting the impact reduction targets on a PCBA Level. On a Product Level, the current proposed changes did not meet the target. More work is needed to understand the effect of the other intended circular strategies.

Pilot Achievements & Key Challenges in Gen 3

Achievements

- Improved LCA methodology for more accurate PCBA Level LCAs.
- Obtained understanding of key contributors to the high environmental impact of PCBAs.
- Identified trends between PCBA type and hotspots. This knowledge is to be used for strategic decisions on approaching Philips wide topic of Sustainable PCBAs.
- Tested the three new alternative technologies.
- Verified via LCA the electronics innovations had lower environmental impact.
- Tested new integration techniques for new PCBA technologies.
- Explored the impact of the new technologies on recyclability efficiency.
- Initiated a Sustainable PCBA community with a goal to address the environmental impact of PCBAs. For Sustronics specifically the focus was to further spread the Sustronics knowledge across Philips, suggest focus areas and advocate for change. The community kicked off at the start of 2025. With Sustronics as key knowledge source, it delivered significant increase in awareness on the topic of Sustainable PCBAs in the wider organisation, triggered the gathering of readily available knowledge to be captured centrally as a resource, identified knowledge gaps and triggered several new internal activities across multiple Philips Business Units (BUs).

Key Challenges

- Despite the improved LCA methodology, it remains a challenge to obtain a high level of accuracy of LCA results due to uncertainty in the input data. Especially with the new technologies not existing yet at an industrial scale.
- Industrialization of new sustainable PCBA technologies should be compatible with high production volumes.
- Further work is required to better understand the cost-performance balance for industrial deployment.
- It remains to be explored how success in creating more sustainable PCBAs can best be communicated towards consumers as components remain invisible and largely unknown.
- Regulatory and safety compliance will need to be validated at higher maturity levels.
- If new PCBA technologies were to be adopted, product architectures will need to be optimised to accommodate the new electronic solutions effectively.
- Current WEEE recyclers in Western Europe are not set up for certain alternative PCBA technologies. Certain changes in design risk resulting in lower recyclability of the PCBA.

Technology and sustainability readiness levels (TRL/SRL)

Table 3:Pilot 1.2 Technology and sustainability readiness levels (TRL/SRL)

	Gen 2	**Gen 3**
TRL	Simple PCBA = 4	Groomer Appliance PCBA = 6
SRL	Simple PCBA = 4	Groomer Appliance PCBA = 5

2.1.3. Pilot#1.3 Sustainable luminaire

Pilot Leader: Signify (SIG) (Peter Bancken, Simone Poort)
Pilot Goal/Objective

A luminaire is a complete lighting unit and depending on the application area where the luminaire is used, the specifications of the product can differ. In Figure 6 two examples are shown. The goal of the pilot is to design a fully sustainable luminaire, with as low as possible LCA, based on new technologies, materials, and end of life strategies:

- Based on a sustainable LED lighting technology to enable slim lighting luminaires to reduce materials use.
- More sustainable housing than current references.
- Designed according to the principles of eco-design and having a modular architecture for easy repair, upgrade, or end-of-life dismantling.
- Dismantling and separation to component level should upgrade the waste streams in which the components and materials can be reused for new luminaires.

This pilot focusses on the main components of a luminaire, viz. the light module, optics, and housing.

Figure 6: Examples of luminaires and their application areas

Updated Pilot Description for Gen 3:

No changes to the pilot description of D3.2/Gen 1 and D3.3/Gen 2.

Work Carried Out: Gen 1 and Gen 2 Overview:
In Gen 1, the focus was on separate luminaire components. Characterization concentrated on the different materials and main components, viz. printability, absorption, reflection, transmission, light technical properties of the light source, etc.
For Gen 2, the focus was on realizing a small-size working demonstrator. This implied that different design options and producibility were explored for the housing, the light module, and the optics. Furthermore, the light technical properties of the individual components and the small-size demonstrator were characterized.

Technologies involved and role of project partners in Gen3:

The housing of the luminaire is 3D-printed. The materials used are renewable, more sustainable materials that are supplied by project partners UPM (with in-kind partner KCL) and ARNP.

As technology for the light module, printed electronics is used. For the process as well as the materials, this pilot cooperates with different partners, viz. VTT, SCR and TNO.

For the optics, renewable, more sustainable materials are used. In cooperation with VTT, different options were explored.

LCA modelling is done together with FHG.

Finally, assessment of the design circularity and recycling performance are done with MIR.

Technical layout and characterisation of Gen 3:

Based on the available materials and manufacturing methods, it was decided to focus on a line luminaire. In Figure 7 , a schematic drawing of the architecture is given.

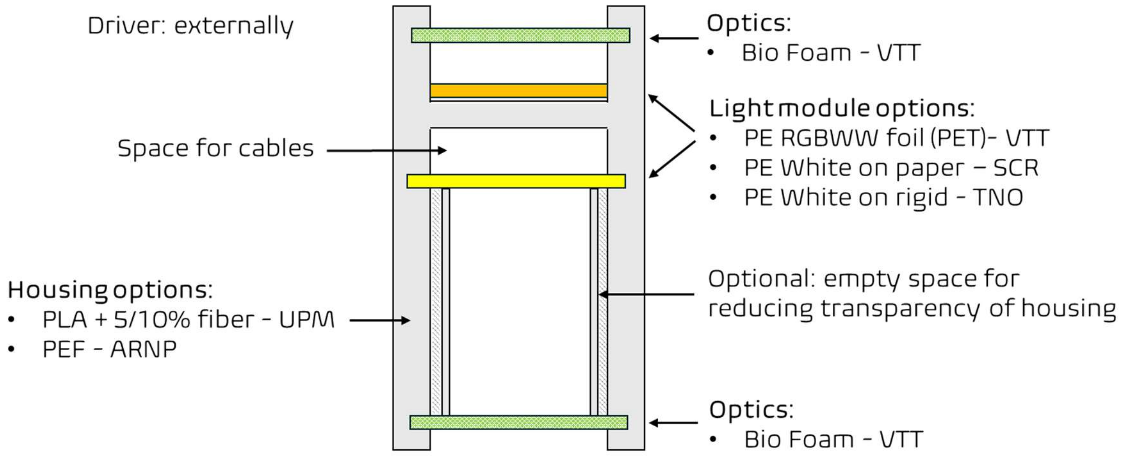


Figure 7. Schematic drawing of the luminaire architecture

For Gen 3, the focus is on realizing a full-size working demonstrator. This combines all the learnings regarding the different design options and producibility that were explored in Gen 1 and 2 for the housing, the light module, and the optics. Furthermore, the light-technical, electrical, and mechanical challenges of making a full-size demonstrator must be solved.

The sustainability targets for this pilot are:

- Dismantling and separation to the component level
- Reduce material use
- Lowest possible LCA

For reaching the first target, dismantling and separation to component level, the circular design principles, like modularity, single material components and reversible connections, are taken into account. For example, for incorporating the light modules and optics into the housing, no screws or glue are used. The design is discussed with MIR and its suitability for optimal dismantling and recycling options was validated.

With respect to the second and third targets, reduce material use and lowest possible LCA, good results are achieved for Gen 3. For all the luminaire components, more sustainable, renewable materials are used, which has a positive impact on the LCA. In the design, especially of the housing, the optimum is investigated between minimal material use and optimal performance. Further, additive manufacturing techniques are used for the housing (3D printing) and the light module (printed electronics) which results in lower material use during manufacturing. This also results in a lower LCA.

LCA modelling is being done together with FHG. The main goals of this study are:

- Comparing different versions of the product using different manufacturing techniques and materials

- Getting a sense on what the environmental hot spots of the different versions are
- Getting insights on what the relevant environmental aspects of the product are

In the modelling, the different options regarding housing, light module, and optics are studied and analysis is done for different impact categories, like climate change, mineral resource use, fossil resource depletion, and water use. The modelling was done for phases A1-A3 (cradle to gate).

Figure 13 below shows the climate change comparison. The Sustronics model shows almost a 50% drop in the production emissions. The biomaterial-based housing, alongside the material reduction due to the semi-hollow design allowed by 3D printing, brings about the biggest reduction in comparison with the heavier aluminium housing. Furthermore, the printed electronics-based LED strips also show an impact roughly half of that of the conventional PCB LED strip. Lastly, the new diffuser also has a lower impact than the reference, although its low contribution makes the difference less relevant.

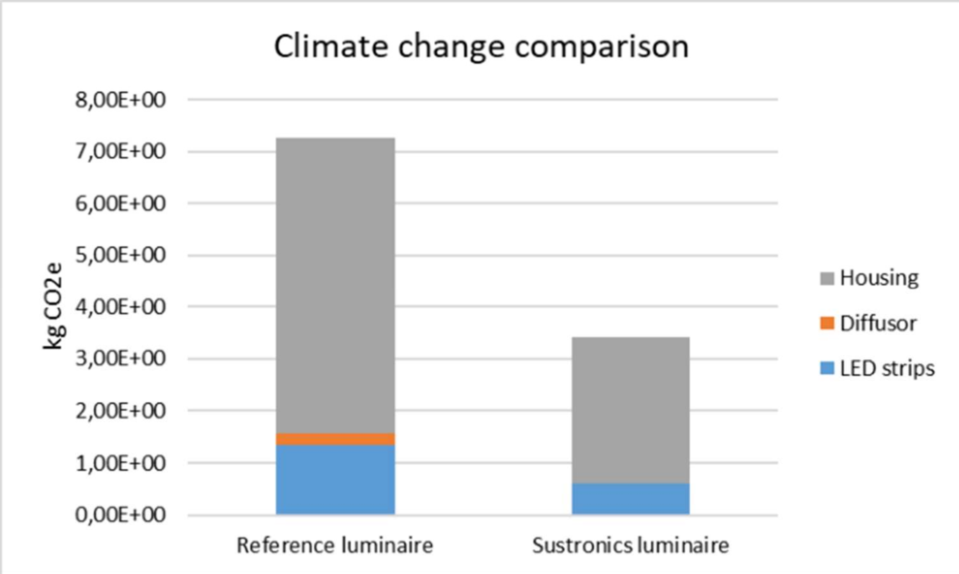


Figure 8. Results of LCA modelling: comparison of the reference and sustainable luminaire production impact, for the indicator climate change

Sustainability & social targets and their status in Gen 3:

End user engagement:

The project is presented at many locations, both internally and externally:

- Presented at the LOPEC conference in Munich (Feb 2025)
- Presented and discussed with several external lead customers during visits or online meetings
- Showed during the Innovation Day with leading European customers
- Showed during the Research Innovation Market
- Internal meetings and discussions with the OEM business and with several businesses of the DDS division

In general, the internal businesses and lead customers are very enthusiastic about the many possibilities offered by the new technologies, but they need time to translate those opportunities into the right value product propositions. Various new options for several lead customers have been discussed, which has led to follow-up meetings. At those meetings, the possibilities and limitations were discussed in detail, and a number of product studies are currently being conducted.

Pilot Achievements & key challenges in Gen 3:

Achievements

In Figure 9, the Gen 3 demonstrator is shown. The main achievements will be discussed below per luminaire component.

Figure 9. Gen 3 demonstrator of pilot 1.3.

For the housing bio-based materials are used, viz. PLA (PolyLactic Acid) from UPM (KCL) and PEF (PolyEthylene Furaonate) from ARNP. The housing is made by 3D printing. As can be seen in Figure 9, the housing is insufficiently blocking the light. Therefore, tests on material properties and design optimisation were done in order to reduce this transparency issue. The material properties were changed by adding masterbatch (MB). As shown in Figure 10, increasing the percentage of masterbatch reduces the light transparency. However, there are limitations to the percentage of masterbatch that can be added: too high percentages reduce the quality and thus printability of the filament. The effect of design optimisation was investigated by varying the percentage of infill (see Figure 11). Although the transparency is reduced when using higher percentages of infill, the issue is not completely solved. Furthermore, as higher percentages of infill result in more material use, this is not a favourable solution from a sustainability point of view. Therefore, the options of an integrated light source and reflector were further investigated. Although an improvement was made, the issue of transparency is not completely solved.

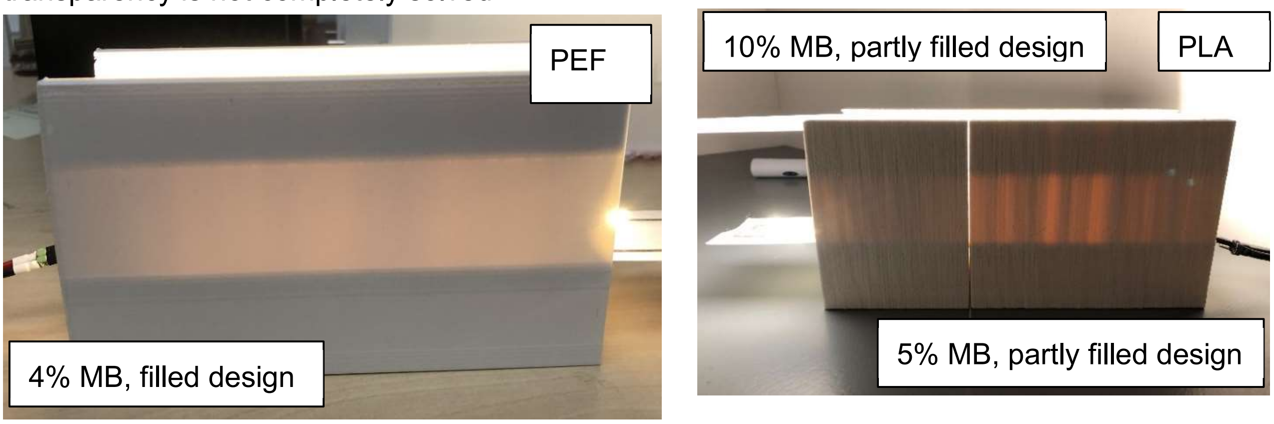


Figure 10. To reduce the light transparency of the housing, material properties (% masterbatch (MB)) and design changes (% infill) were investigated.

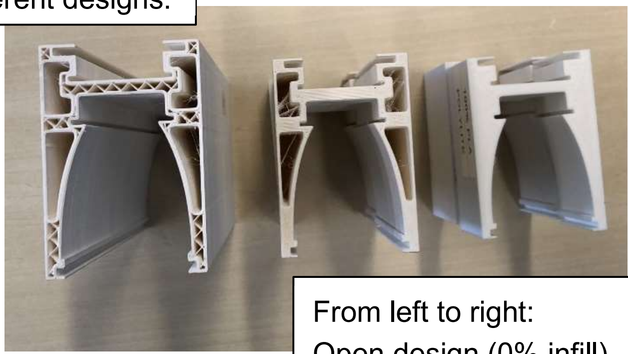
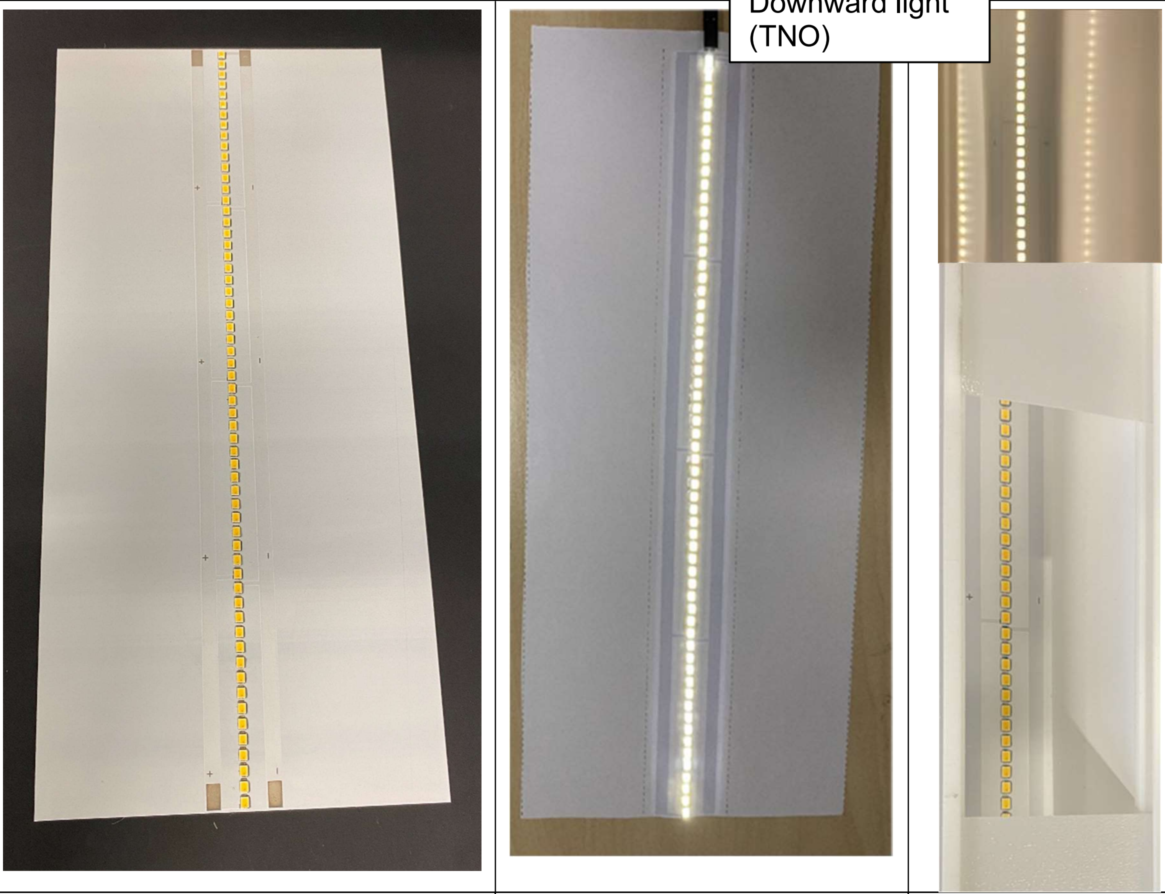


Figure 11. Design variations investigated: different percentages of infill

For the light module several tests and evaluations were performed. For the paper light source (SCR), several options made and tested (see Figure 11). For the rigid light source (TNO), an inventory of possible candidates for the substrate was done. The most promising rigid substrates were tested and evaluated (see Figure 12). Finally, the flex light source (VTT) was finalised (see Figure 13). Furthermore, suitable connectors were selected for realising Gen 3.



Off state	On state	In luminaire

Figure 12. Different light modules designed, tested, and evaluated: downward light design, rigid.

Upward light (VTT)

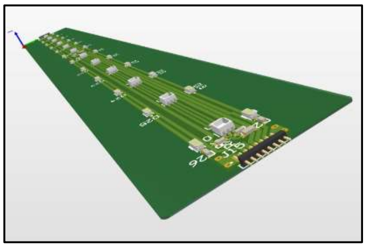
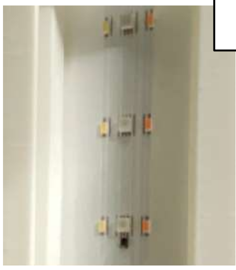
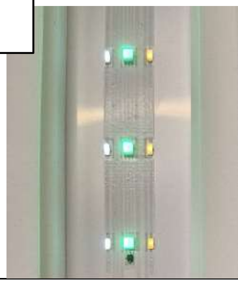
		
Design	In luminaire	On state

Figure 13. Different light modules designed, tested, and evaluated: upward light design, flexible.

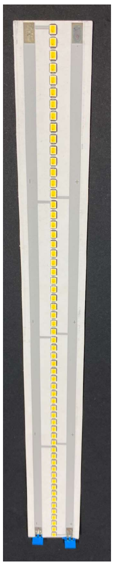
Upward & downward light (SCR) 	
Downward lighting	Upward lighting

Figure 14. Different light modules designed, tested, and evaluated: downward and upward light design, paper based.

For the optics, bio-based materials were used instead of fossil-based plastic diffusor (Figure 15). Cellulose based materials with TiO2 coating were evaluated for transmission and scattering properties (Figure 16 and Figure 17). The transmission properties were not as good as aimed for, but the scattering properties met the specifications set for Gen 3.

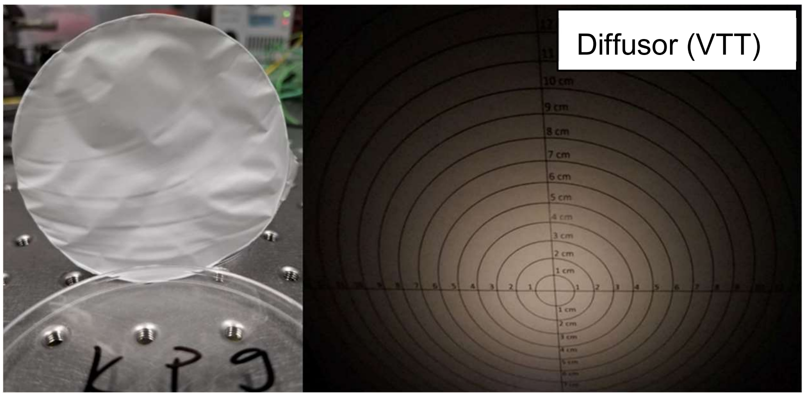


Figure 15. Bio-based material as a diffusor.

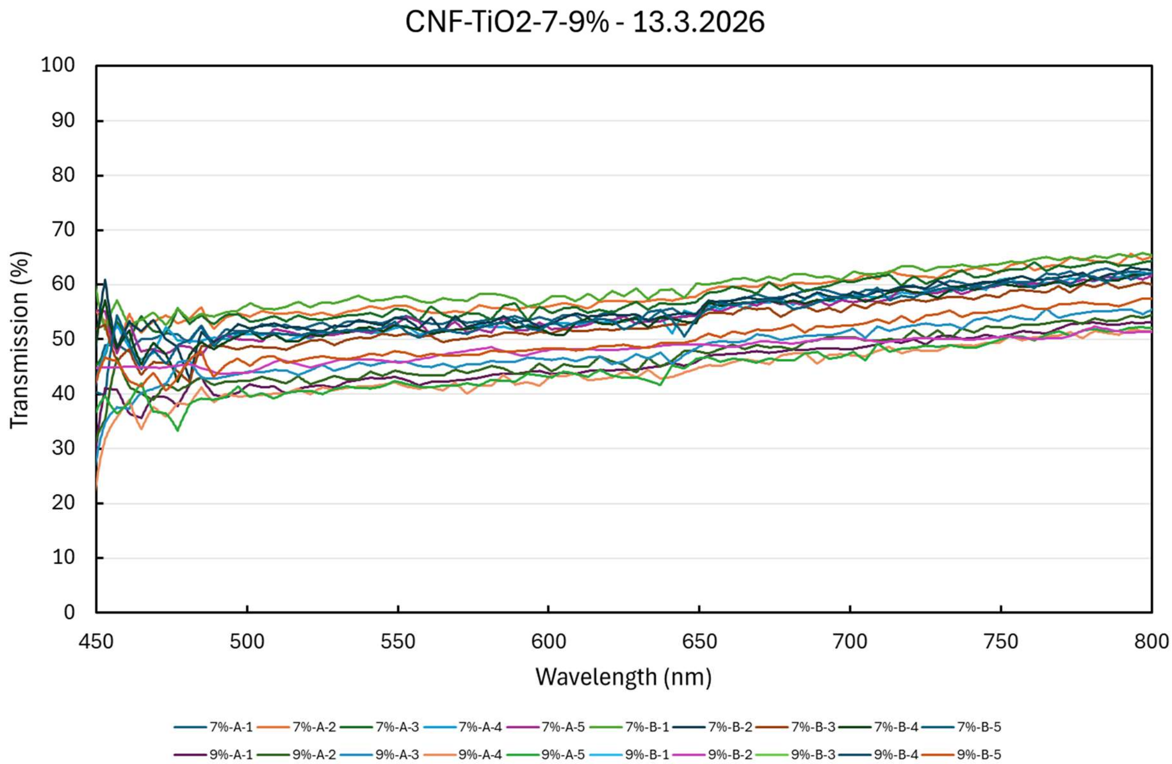


Figure 16. Transmission of the bio-based diffusor.

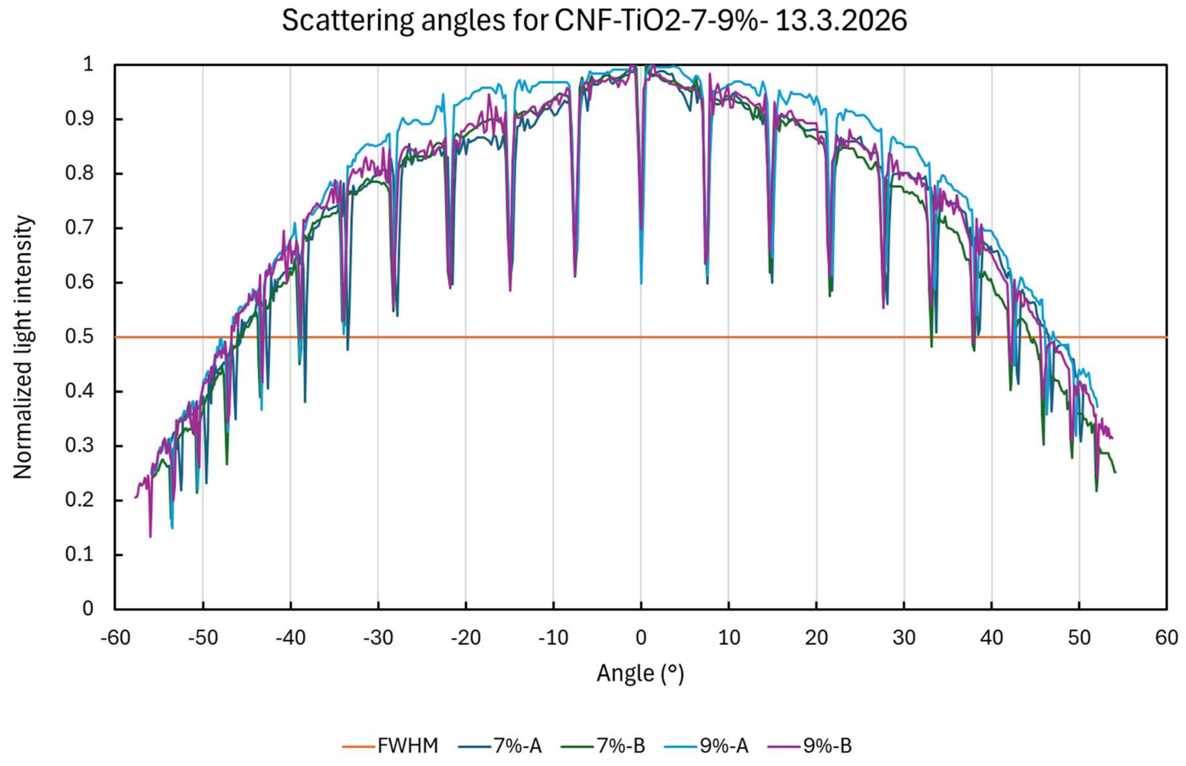


Figure 17. Scattering of the bio-based diffuser.

Key challenges

To summarise, for housing, the key challenge is to reduce the transparency of the housing while maintaining suitable material properties and limiting the amount of material used. For the light modules, the main challenges are the robustness in the application and connecting the different modules. Finally, for the optics, it is challenging to find a good balance between transmission and scattering properties of the diffusive materials and to realise rigid and robust samples.

Technology and sustainability readiness levels:

Table 4: Pilot 1.3 Technology and sustainability readiness levels

	Gen 2	**Gen 3 objective**
TRL	3	4
SRL	3	4

2.2. Use Case #2 Sustainable manufacturing for electronics

Use Case 2 Leader: SCR (Mikko Paakkolanvaara)

Use Case 2: Sustainable manufacturing consists of three pilots:

- Pilot#2.1 Embedded electronics for EEG monitoring (PLUX)
- Pilot#2.2 Wearable health monitoring (SCR)
- Pilot#2.3 Sustainable dashboard for automotive (FAU)

respectively, described in more detail in sections 2.2.1, 2.2.2 and 2.2.3

The objective of UC 2 is to develop different approaches for decreasing the environmental footprint of selected electronic devices with a focus on sustainable manufacturing processes with novel materials, such as bio-based, renewable, and abundant ones. The pilots represent two end-use categories:

- Wearables monitoring (Pilots#2.1-2.2) and
- Automotive (Pilot#2.3).

The purpose is to transform existing products into environmentally friendly alternatives while maintaining the device functionality and other requirements, such as lifetime, skin compatibility, and end-of-life management.

2.2.1. Pilot#2.1 Embedded electronics for EEG monitoring

Pilot Leader: PLUX (Rita Cristóvão)
Pilot Goal/Objective

Pilot 2.1 focuses on developing a sustainable EEG monitoring solution by integrating embedded electronics, novel materials, and circular design principles. The objective is to significantly reduce the environmental footprint of EEG systems while maintaining clinical-grade signal acquisition performance.

The pilot is led by PLUX Biosignals, with contributions from Screentec (printed electrodes), PIEP (embedded EEG sensor based on LDS technology), and VTT (Life Cycle Assessment and Digital Product Passport integration). The system architecture is based on a two-channel forehead EEG configuration combining disposable printed electrodes and a reusable sensor connected to a biosignal acquisition unit.

Updated Pilot Description for Gen 3:

In Generation 3, the pilot achieves a **functional system architecture**, combining:

1. **Paper-based printed EEG electrode (Screentec)** – sample 126W is pilot-ready and validated against gold-standard hydrogel electrodes;
2. **Reusable embedded EEG sensor based on Laser Direct Structuring (PIEP)** – sample 3 of the third sensor test is the first functional prototype with validated signal quality;
3. **Integration with biosignalsplux acquisition system (PLUX)** – reference platform for validation and benchmarking;
4. Initial integration of Digital Product Passport (DPP) through **QR-based identification** in the sensor housing.

The Gen 3 development emphasizes:

- **Sustainability**: replacement of fossil-based materials with paper-based and printed electronics, and reduction of system-level environmental footprint through LCA-driven design;
- **Performance**: validation of signal quality (SNR, THD) and power consumption, ensuring comparability with clinical-grade EEG systems;
- **Usability**: wearable, lightweight, and user-friendly configuration suitable for daily-life and home-based monitoring scenarios.

From a sustainability perspective, **LCA results confirm significant improvements in electrode design**, while identifying the sensor and packaging as key areas for further optimization. In Gen3, VTT provided a demo about the DPP app developed by Upcode (UPC) to score electronics products based on their LCA and DPP. The app demo showed that we can define a score to classify a product's sustainability, and the results are very promising for classifying other products, not only electronic ones.

From a technical perspective, **functional validation has been achieved at component level**, with:

- Electrodes reaching **pilot readiness**.
- Sensor achieving **proof-of-concept functionality (Sample 3)**.

Full **system-level validation (sensor + electrodes)** is ongoing and represents the final step toward a complete demonstrator.

Overall, Generation 3 demonstrates the **feasibility of a sustainable EEG system.**

Regarding TRL / SRL assessment (Generation 3):

- Printed EEG electrode: **TRL 6–7 / SRL 6** (validated in relevant environment, near pilot-ready)
- Embedded EEG sensor (LDS): TRL 3–4 / SRL 3 (functional prototype demonstrated at the component level, final prototype and industrialization not yet validated)
- Integrated system: TRL 5 / SRL 4–5 (system integration ongoing)

EEG sensor with LDS

Generation 3 was mostly marked by the development of the EEG sensor with LDS (Laser Direct Structuring) technology. PIEP developed several PoC that were tested in Gen2 and Gen3, but only one sample (sample 3), delivered in Gen3 for testing, was validated as a functional prototype in terms of signal quality compared to the gold standard (PLUX EEG sensors). These milestones and tasks are not in the original proposal but were agreed upon after the project started.

The first samples delivered in Gen2 were not functional, but in Gen3, 3 additional samples were tested in March 2026, and the results are:

- **Sample 1:** discarded due to a critical soldering defect
- **Sample 2:** partially functional but failed distortion requirements
- **Sample 3:**
    - Meets key performance metrics (THD < 1%, SNR > 20 dB)
    - Produces a **measurable and reliable output signal**
    - Performance comparable to PLUX reference sensor in controlled tests

Sample 3 represents a significant improvement over previous iterations; however, it´s still a prototype with low TRL and needs some refinements, such as changing the pinout order of the UC-E6 connectors. PIEP is implementing the necessary improvements and has designed the 3D printed form factor for the final prototype, which will be delivered to PLUX for testing by the end of April. The final test will be a combined system with both the EEG LDS sensor final prototype and 126W electrodes.

The EEG-LDS sensor faced several assembly-level challenges in Gen1 and Gen2. Due to temperature limitations during soldering, there were visible issues with this step of the LDS process. However, using low-temperature soldering and process optimization, it was possible to obtain a functional prototype produced by LDS (sample 3).

Figure 18: Sample 3 of EEG LDS PCB prototype / PLUX EEG sensors to connect with the PCB / test setup

PIEP developed the design for the EEG-LDS sensor prototype and will implement the LDS technology in the 3D-printed part and assemble the components for the final prototype, as shown in Figure 18 and Figure19 below. After the validation in planar form, the integration into 3D shape takes place, being the cover printed by additive manufacturing. The final prototype has the QR code for DPP in the casing as shown below.

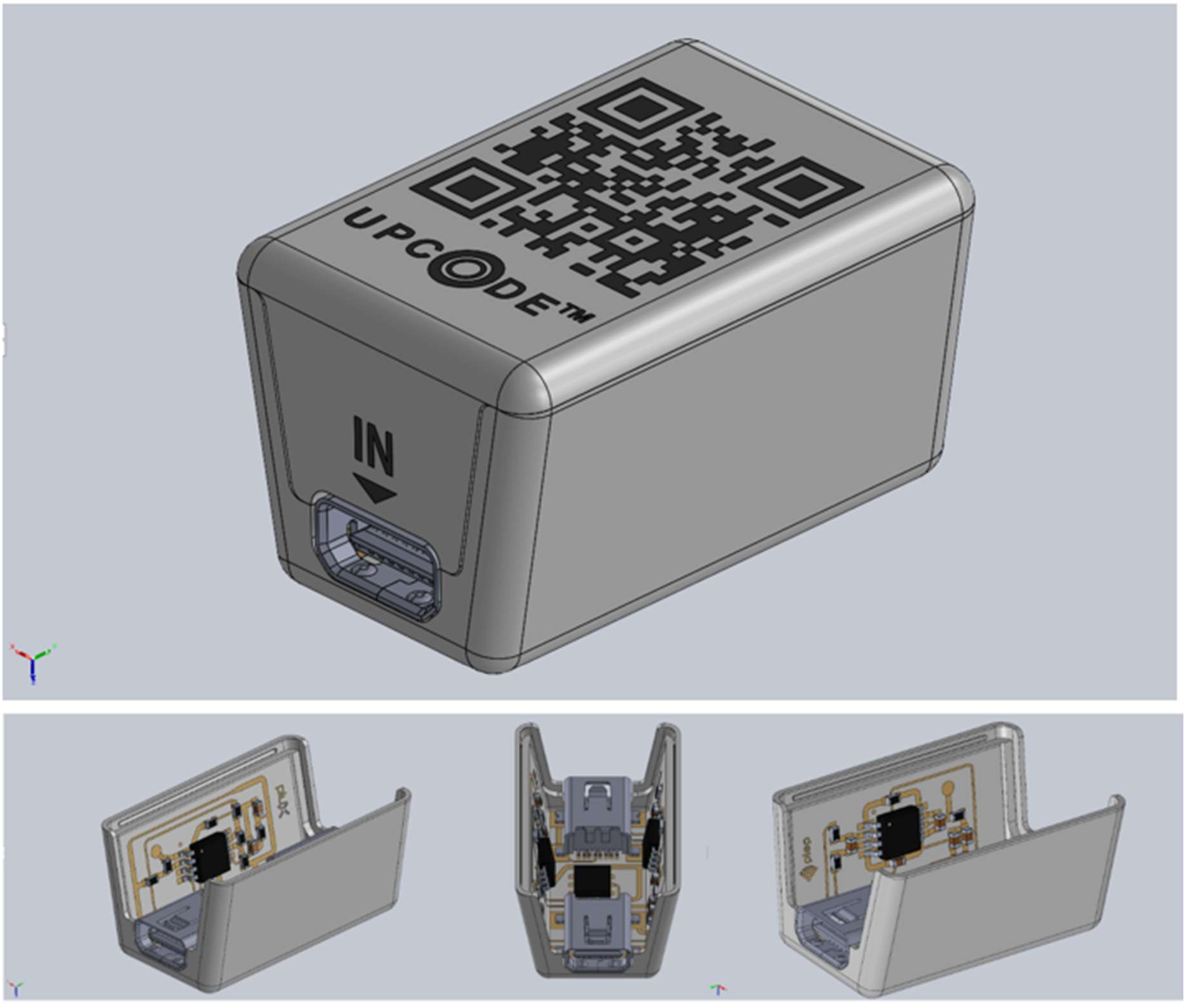


Figure 19: Design of the EEG sensor produced by LDS for Gen3 of Pilot 2.1.

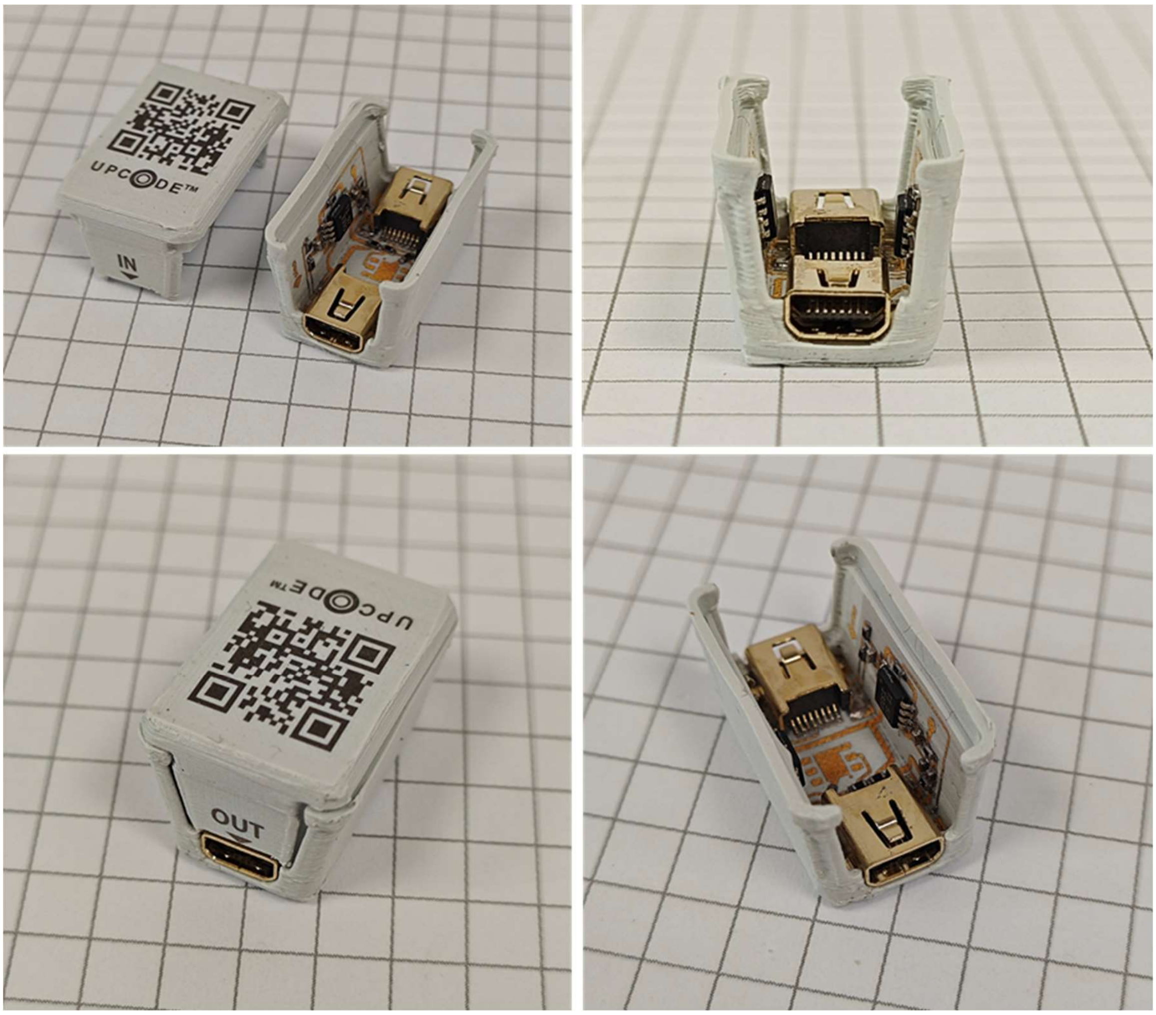


Figure 20: Final EEG sensor produced by LDS for Pilot 2.1.

Sustainability & social targets and their status in Gen 3:
Table 7 presents the sustainability targets for Pilot 2.1 and their status for Gen 3.

Table 5: Sustainability targets of Pilot 2.1

Sustainability target	Gen 3
Share of bio-based materials up to 50%	Paper used as an alternative substrate for electrodes, together with a paper liner, accounts for more than 50% of the materials used in the electrode. 50% post-consumer recycled (PCR) polycarbonate in the sensor.
Lower environmental footprint	< 30% compared to the reference/baseline for the electrode. Reduction compared to baseline is possible for the sensor with optimized manufacturing
Reusability	Sensor part designed and tested for reusability. Replacement of subtractive manufacturing with additive manufacturing ≥ 50%

The life cycle assessment of the electrode and sensor was updated to Gen 3, including the entire electrode and the new sensor design, along with their lifetime emissions. Results show a 50% reduction in the total environmental impacts of Gen 3 electrode compared to baseline (Figure 21). Comparing the LDS-MID sensor with the baseline PCB shows that, with the current manufacturing process, the new sensor has higher total environmental impacts but reusing metallization baths 100 times or more results in even higher or lower impacts, depending on the casing manufacturing method. This is promising for the sensor's future development.

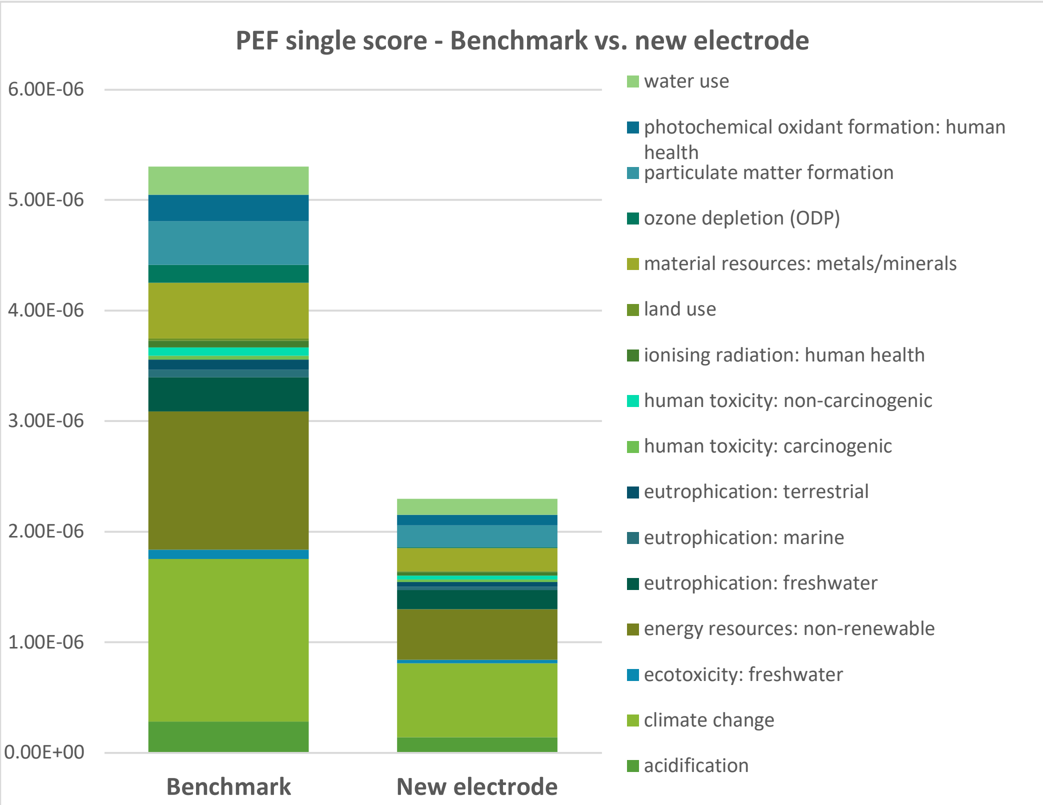


Figure 21: PEF single score comparison between the benchmark electrode and the new Gen 3 electrode.

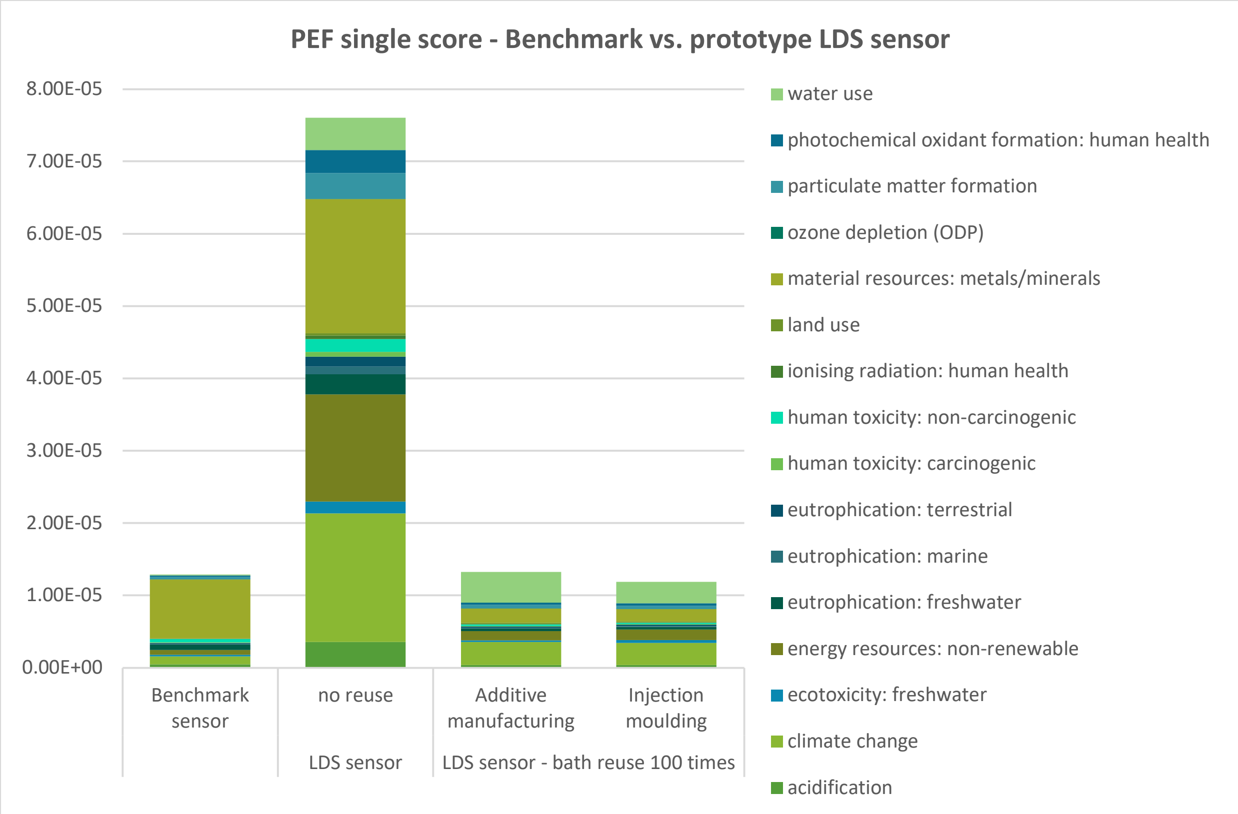


Figure 22: PEF single score comparison between the benchmark versus the LDS-MID sensor prototype of pilot 2.1. Metallization bath reuse scenario is included.

During use, a small Li-ion battery that can last up to 5000 hours is used. One measurement cycle is set to 10 h and uses two single-use electrodes and one sensor. The sensor can last up to 500 operational cycles, which was set as the studied timeframe. Contribution analysis results are depicted in Figure 23. By far, the biggest impact comes from the repeated manufacturing of electrodes.

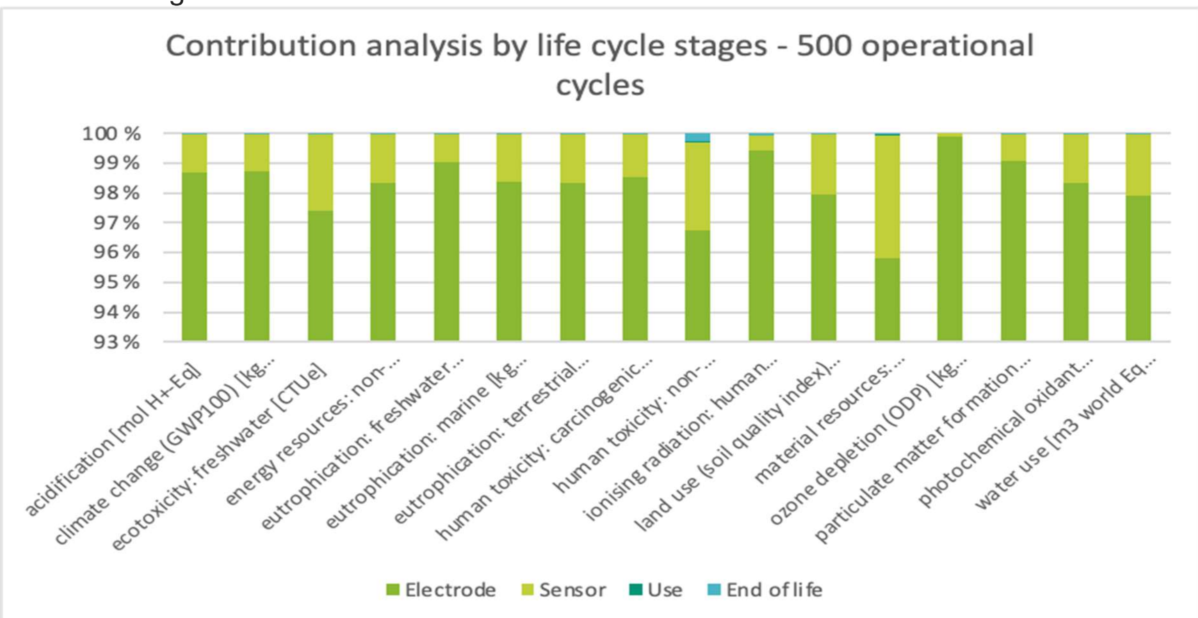


Figure 23: Contribution analysis during 500 operational cycles for two electrodes using paper substrate and copper ink and an LDS-MID sensor. End-of-life treatment is medical waste treatment using steam sterilisation.

DPP app report for Pilot 2.1

- **Purpose and scope**

This part documents the Digital Product Passport (DPP) app demonstrated in Generation 3 of Pilot 2.1. The report describes the purpose of the DPP app, the information model, consumer and manufacturer features, the product-scoring formula, validation approach, screenshots and current limitations. The DPP app is used as a digital layer for the sustainable EEG monitoring system, linking physical pilot components to structured lifecycle, sustainability and ownership information.

- **Application in Pilot 2.1**

In Pilot 2.1, the DPP app is applied to the sustainable EEG system, including the Screentec paper-based electrode and the PIEP LDS-based EEG sensor. Smart tags, such as QR codes, are used as physical access points to the digital passport. For the Gen 3 demonstrator, the final sensor casing is planned to include a QR code that provides direct access to the DPP from the physical sensor. The DPP is therefore relevant for both the disposable electrode and the reusable sensor module.

- **Information model**

The DPP app is designed as a modular product passport that can contain product-level and item-level information. This distinction is important because the Pilot 2.1 system combines reusable and disposable components.

1. **SKU-level information**: product data such as materials used, certifications, service information, support documentation, spare parts information, company climate policy, recycling instructions and product labelling information.
2. **Item-level information**: the lifecycle history of an individual product or component, including manufacturing, customer ownership, second-hand ownership, refurbishment, transfer of ownership and recycling events.
3. **Unique identifiers**: each product unit can receive a unique identifier that links the physical product to its digital passport and enables unit-level lifecycle tracking.

- **Consumer-facing features**

- Register a personal account to track ownership and consumption of electronics.
- Scan product packaging in the store to access product information before purchase.
- View company climate policy, support information, documentation and spare parts information.
- View carbon emissions and the sustainability score of the product.
- Scan the unique code inside the packaging and redeem digital ownership of the product, supported by a PIN-code process where applicable.
- Transfer the product digitally to another person when the product changes hands.
- Find nearby recycling points that accept the product, based on the product component and material list.

- **Manufacturer-facing features**

- Maintain public and private product documents in one structured digital environment.
- Generate unique identifiers for unit-level tracking across manufacturing, ownership, refurbishment and recycling phases.
- Generate PIN codes for customer redemption of digital ownership.
- Maintain product lifecycle records, including manufacturing, customer ownership, second-hand ownership, refurbishment and recycling events.
- Generate PDFs for product labelling and product information communication.

- Provide product, service, repair, recycling and compliance-related information through a single passport interface.

- **Product-scoring formula**

The current sustainability score shown in the DPP app is based on product carbon intensity. The scoring method compares the carbon intensity of the product or component under assessment with an electronics-sector reference value. The current implementation is therefore an environmental performance indicator based on carbon intensity, not yet a complete circularity score.

Relative difference (%) = [(product carbon intensity - reference carbon intensity) / reference carbon intensity] x 100

where the reference carbon intensity is 24.645 kg CO_2e/kg.

Interpretation of the result:

A negative relative difference means the assessed product performs better than the electronics-sector reference value.
A value close to zero means the assessed product is close to the reference value.
A positive relative difference means the assessed product performs worse than the reference value.
The current score can be used to classify products by carbon intensity and to support comparison between product variants. Future versions should expand the methodology to include additional circularity indicators, such as reuse, repair, refurbishment, recycling potential, material recovery and end-of-life value retention.

- **Validation approach in Pilot 2.1**

The DPP validation in Pilot 2.1 focuses on confirming that the app can operate in a realistic product use case. The validation includes insertion of product data into the DPP backend, addition of an item-level smart tag, linking of the smart tag to the relevant product data and testing of the main DPP functions.

- Consumer ownership claim and redemption.
- Product information lookup.
- Service, documentation and recycling information lookup.
- Transfer of ownership.
- Display of carbon intensity and sustainability score for the pilot component.

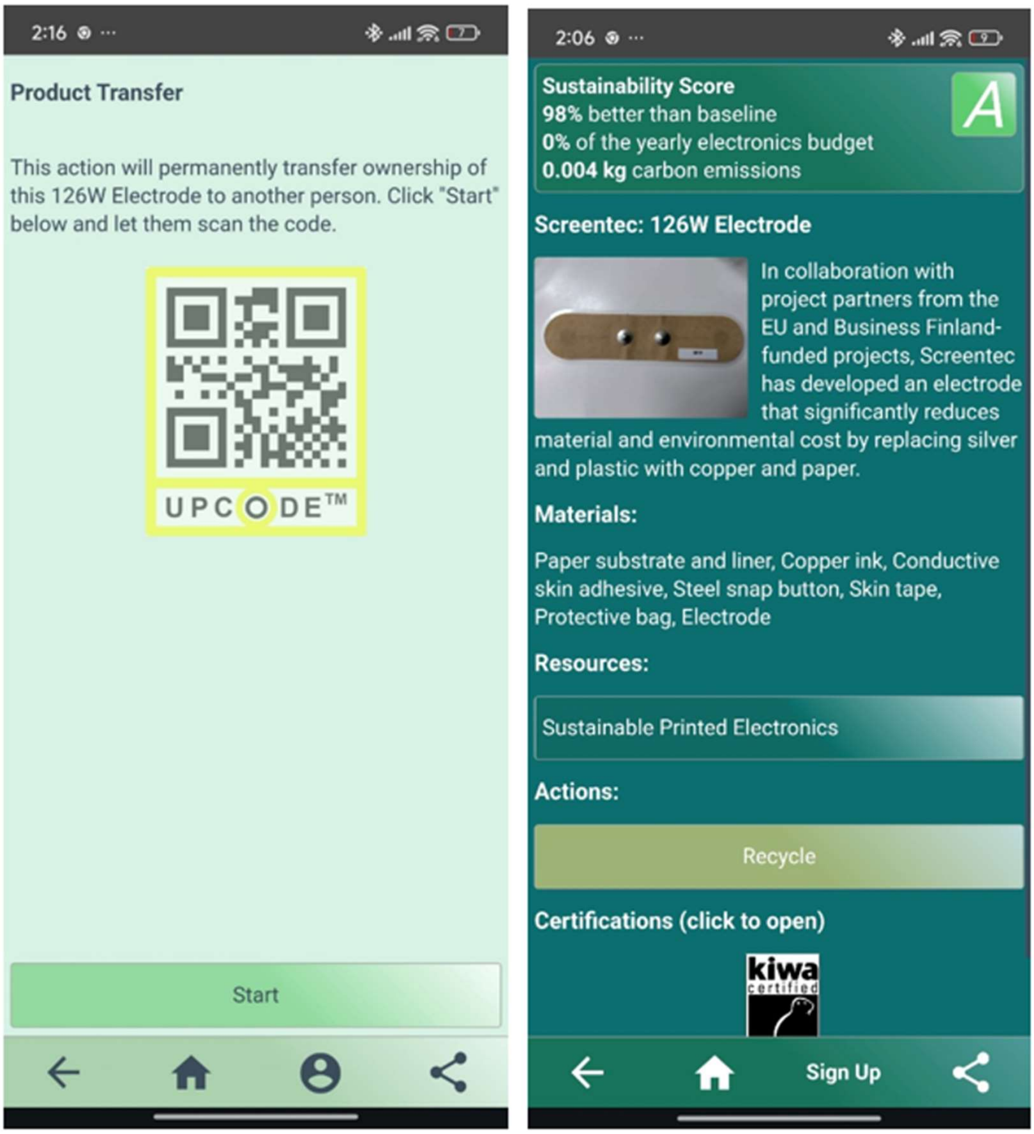


Figure 24: DPP app screenshots and functional legend. Left: QR-code based ownership transfer and product access screen, illustrating how a smart tag can connect the physical product or packaging to the digital product passport. Right: sustainability-scoring view

- **Value added for Pilot 2.1**

- Sustainability communication: makes environmental information visible to users and supports transparent communication of the sustainability benefits of the paper-based electrode and reusable sensor architecture.
- Circularity support: provides structured information for service, recycling and ownership transfer, supporting circular economy practices and future reverse logistics.
- Design decision support: links DPP information with LCA-based environmental data, enabling comparison between product variants and supporting future improvements in materials, manufacturing and end-of-life strategies.
- Regulatory preparedness: creates a structured framework for managing product information in a format aligned with expected European digital product transparency requirements.

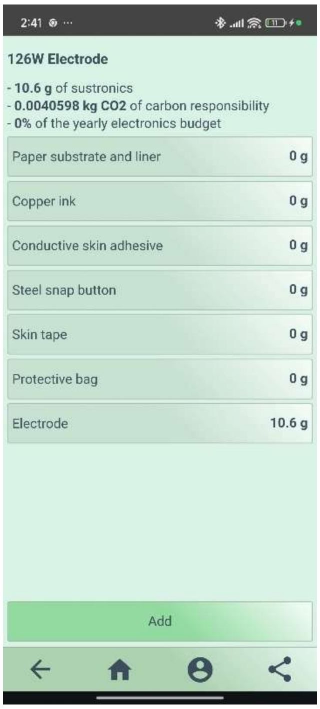


Figure 25: DPP app screenshots and functional legend

Current limitations and future development

The current DPP implementation should be considered a functional prototype for Pilot 2.1. It demonstrates that sustainability data, product identification and lifecycle information can be integrated into a single digital interface. Further development is required to expand the scoring methodology beyond carbon intensity, include additional environmental and circularity indicators, validate dynamic lifecycle updates, and ensure scalability across different product categories and future sustainable medical device systems.

Conclusion

The DPP app developed by UPC/Upcode is an enabling tool for the Gen 3 Pilot 2.1 demonstrator. It complements the technical and sustainability work performed on the Screentec electrodes and PIEP LDS sensor by providing a digital layer for traceability, environmental communication, ownership management and lifecycle support. The results are promising not only for EEG components but also for broader application to other electronic products.

End user engagement:

Objective:

End-user engagement in Pilot 2.1 aimed to validate the developed EEG system from a **user-centric perspective**, focusing on usability, comfort, and applicability in realistic use conditions, while ensuring alignment with the pilot's healthcare use case (wearable EEG monitoring).

Approach:

End-user validation was conducted through **controlled experimental testing with human subjects**, simulating realistic EEG acquisition scenarios. The engagement focused on:

1. **Application context**
    a. Two-channel forehead EEG configuration
    b. Short-duration monitoring sessions representative of real use
2. **Comparison methodology**
    a. Benchmarking against **clinical gold-standard hydrogel electrodes**
    b. Use of biosignalsplux acquisition system for consistency
3. **Evaluation dimensions**
    a. Signal quality (user-perceived reliability)
    b. Ease of use (application/removal)
    c. Comfort and skin compatibility

Validation Activities:

The following activities were performed:

1. **EEG acquisition tests with users**
    a. Measurement of brain activity under controlled conditions (e.g., eyes open/closed, blinking)
    b. Comparison of signals obtained with sustainable electrodes vs gold standard
2. **Usability assessment**
    a. Evaluation of electrode placement on the forehead
    b. Assessment of adhesion, stability, and removal
3. **User perception (qualitative)**
    a. Feedback on comfort and wearability
    b. Perception of lightweight and flexible design

Key Results

1. **Usability and comfort**
    a. Paper-based electrodes (126W) demonstrated:
        i. Easy application and removal
        ii. Good skin compatibility
        iii. No residue after removal
2. **Signal reliability (user perspective)**
    a. EEG signals obtained were:
        i. Stable and consistent
        ii. Comparable to gold-standard electrodes
    b. No significant degradation observed in practical use conditions
3. **User acceptance indicators**
    a. Lightweight and flexible design supports wearable use
    b. Materials perceived as more user-friendly compared to traditional electrodes

Alignment with DoA Objectives

- Objective to ensure **user-friendly, wearable EEG solution**: **achieved**
- Objective to maintain **clinical usability and performance**: **achieved at component level**
- Objective to enable **real-world deployment readiness**: **partially achieved** (pending full system validation)

End-user engagement activities confirm that the developed sustainable electrode solution is **usable, comfortable, and functionally equivalent to current clinical solutions in**

controlled conditions. While validation is currently limited in scale and scope, the results provide **sufficient evidence of user acceptance and usability**, supporting the feasibility of the proposed system for wearable EEG applications.

End-user validation has been appropriately performed for a TRL 5–6 system, demonstrating usability and acceptance, with clear plans for expansion at higher maturity levels.

Further work is required to:
- Validate the **fully integrated system**
- Conduct **larger-scale and longer-term user studies**
- Quantify user experience through structured metrics

Pilot Achievements & Key Challenges in Gen 3:

Achievements
- **Mature paper-based electrode (126W)** with clinical-level performance
- **First functional LDS-based EEG sensor** (PIEP – Sample 3)
- Validated system concept:
  - o Successful demonstration of **modular EEG architecture** (electrodes + sensor + acquisition)
  - o **Component-level validation completed**
- **Sustainability assessment and tools (VTT)**
  - o **LCA completed for Gen 3 baseline**, identifying key environmental hotspots
  - o **DPP app prototype available**, enabling environmental footprint scoring of electronic components
  - o Provides decision support for sustainable design improvements

Key challenges
- **System integration with LDS sensor to be tested**: sensor (Sample 3) and electrode (126W) not yet fully validated together as a unified system
- **Sensor manufacturability issues**: LDS sensor still requires improvements in soldering consistency, connector reliability, and overall robustness
- **Electrode industrial optimization pending** packaging impact, scalability, and durability
- **Final sustainability validation**: LCA consolidation and full DPP integration at the system level

Table 6: Pilot 2.1 – KPI Assessment in Gen 3

KPI	DoA Target (Quantified)	Gen 3 Result	Status	Evidence / Notes
EEG Signal Quality – SNR	≥ 20 dB (clinical-grade threshold)	**31.9 dB (Sample 3)**	**Achieved**	Exceeds minimum requirement for EEG acquisition
Signal Distortion – THD	≤ 1%	**0.49% (Sample 3)**	**Achieved**	Within high-quality signal range
Power Consumption (sensor)	≤ 100 µA (wearable target)	**~65 µA**	**Achieved**	Suitable for low-power wearable applications

Electrode Signal Deviation vs Gold Standard	≤ 5% deviation in key EEG bands	**< 3% deviation (126W)**	**Achieved**	Validated vs hydrogel electrodes
Environmental Impact – Electrode	≥ 20–30% reduction vs PET baseline (multi-category)	**Reduction across all categories (LCA)**	**Achieved**	Quantified in LCA (relative improvement confirmed)
Environmental Impact – Sensor vs PCB	≥ 20% reduction vs PCB baseline	**Higher impact at prototype stage**	**Not achieved yet**	Metallization ≈80% of impact
Sensor Reusability	≥ 100 use cycles (design assumption)	**Reusable (multi-cycle validated conceptually)**	**Partially achieved**	Not fully experimentally quantified
System Integration	Fully integrated demonstrator validated	**Component-level validated only**	**Partially achieved**	Integration ongoing
Manufacturing Yield (sensor)	≥ 80% functional yield	**1/3 functional prototypes (≈33%)**	**Not achieved**	Sample 3 only functional
TRL Level (system)	TRL 6–7	**~TRL 5**	**Partially achieved**	Component TRL higher
DPP Implementation	Functional digital traceability demonstrated	**QR-based DPP integration in prototype**	**Achieved**	Implemented in final casing
Carbon Intensity (electronics benchmark)	≤ sector average (~26.5 kg CO_2/kg electronics)	**Used as benchmark for scoring (DPP)**	**Partially achieved**	Methodology defined

Technology and sustainability readiness levels:

Table 7: Pilot 2.1 Technology and sustainability readiness levels

Electrode 126W

	Gen 2	Gen 3 status
TRL	TRL5	TRL6
SRL	SRL 5	SRL6

EEG sensor sample 3

	Gen 2	Gen 3 status
TRL	TRL1	TRL3
SRL	SRL2	SRL3

2.2.2. Pilot#2.2 Wearable health monitoring

Pilot Leader: SCR (Mikko Paakkolanvaara)
Pilot Goal/Objective:

The target of this pilot is to demonstrate the developed technologies for more sustainable wearable systems for health monitoring. To make the health monitoring electrodes more sustainable, there is need to change materials in the typical product stack and compare the functionality and usability of these developed electrodes. The main focus of this pilot included the following:

1. Single-use or multi-use medical electrodes for ECG (electrocardiography) and bio-impedance monitoring by using more sustainable materials.
2. Energy-efficient bio-impedance signal acquisition and processing for respiratory parameter measurement.
3. Energy and material-efficient fabrication process of interconnect fabric for body sensor networks.

Processing of the electrodes made in this pilot was made using industrial-scale facilities for printed electronics manufacturing.

Updated Pilot Description for Gen 3:

No changes to the pilot description of D3.2/Gen 1.

Work Carried Out: Gen 1 and Gen 2 Overview :

In Gen 1 electrodes, the focus was to test the printability of different, more sustainable materials that could be used for later-generation prototypes. A total of 12 different substrates were used as the base of the printing, and nine different conductive pastes were printed on these substrates, in addition a reference print with PET and silver paste was made. These print samples were characterized, tested electromechanically, and used to make ECG electrodes. Functionality of the different ECG electrodes was tested to select the materials to be taken to Gen 2.

For Gen 1 bio-impedance based vital parameter monitoring, a stationary bioimpedance acquisition setup (Zurich Instruments MFIA + personal computer (PC), gold-plated polyimide reference electrodes), characterised by signal to noise ratio (SNR) ≈ 30 and 1 s settling time, together with a Python peak-detection algorithm for breathing-rate/dynamic-range extraction. A baseline smart-garment prototype was built using the state-of-the-art Modern Clothing Manufacturing Technology (MCMT), where wiring and electronics are embedded as a separate, semi-manual second step.

For Gen 2, the focus for the electrodes was to make functional ECG and bio-impedance electrodes and continue electro-mechanical testing of the prints made on more sustainable materials. For Gen 2 a total of six different substrates were used, and five different conductive pastes were printed on them, including one new material not tested during Gen 1. The made prints were used for characterization, electromechanical testing and as a base for manufacturing ECG and bio-impedance electrodes. Prints and made electrodes were tested to select the materials, material stacks and designs for the Gen 3.

Regarding the bio-impedance measurement, Gen 2 moved from a stationary instrument to a compact wearable bioimpedance front-end and validated more sustainable electrode variants received from SCR against the reference gold/polyimide electrodes. EDI confirmed that a subset of the Gen 2 sustainable electrodes provides signal quality sufficient for respiratory-parameter extraction. In parallel, EDI published the first version of the guidelines for standardized interconnect fabric (KER 35.1) and implemented the software and lab-tested the methods for automatic mapping, communication, calibration, and reprogramming of wearable sensor nodes (KER 35.2). Technologies involved and role of project partners in Gen 3:

For Gen 3 samples, three more sustainable substrates were selected as the base of the screen-printing of conductive structures. In addition, fossil-based plastic PET was also used as a reference. An industrial-scale screen-printing facility, together with cutting, lamination, snap button riveting, and other processes were used to manufacture the samples. For MOV's ECG electrode three different conductive pastes were used, one copper and two carbon pastes, while for EDI's bio-impedance electrodes, one copper and one carbon pastes used. TER and UPM provided more sustainable substrate materials for the Gen 3 samples.

During Gen 3 SCR printed selected material combinations, prepared samples for VTT and TAU for characterization and electro-mechanical testing as well as finalized the assembly of the ECG electrodes for MOV and bio-impedance electrodes for EDI. In addition, UPM provided skin adhesive and TER material to be tested as replacement materials for MOV electrodes. 27 different variants were provided for EDI while MOV received 11 different variants.

TAU made final electro-mechanical tests for their sample parts. VTT made characterization tests for the printed sample and finalized the LCA for made sample electrodes.

EDI is responsible for the wearable bioimpedance sensor node (hardware + embedded signal-processing software) and for integrating it with the sustainable electrodes produced by project partners. EDI assigned variety of tests for their bio-impedance electrodes to find out their functionality and usability for wanted purpose while MOV did the same tests for their ECG electrodes. Additionally, EDI provided the standardised interconnect fabric and the sensor-network software stack (mapping, robust communication, calibration, safe reprogramming) that connects the bioimpedance node and potentially additional partner wearables that have adapted the interconnect framework to a single gateway.

Technical layout and characterisation of Gen 3:

Electro-mechanical testing:

Electro-mechanical testing was made on a test bench that was prepared for the samples made in the Sustronics project. Linear movement test bench included electrical contacts for the test patterns to measure the change of the resistance in the sample print during tests. The test method was parallel plate cyclic bending with one plate moving and the other stationary. The distance between plates was varied and bending radiuses of 5 mm, 7 mm and 9 mm were tested. Testing was possible to be made with compressive and tensile testing by changing which way the sample was attached to the test bench. Total four material combinations were tested with conductive carbon prints and four material combinations with copper prints. Failure criteria for the resistance increase were set to 1,7 times the initial resistance. Maximum cycle count was set to 10.000 bending cycles.

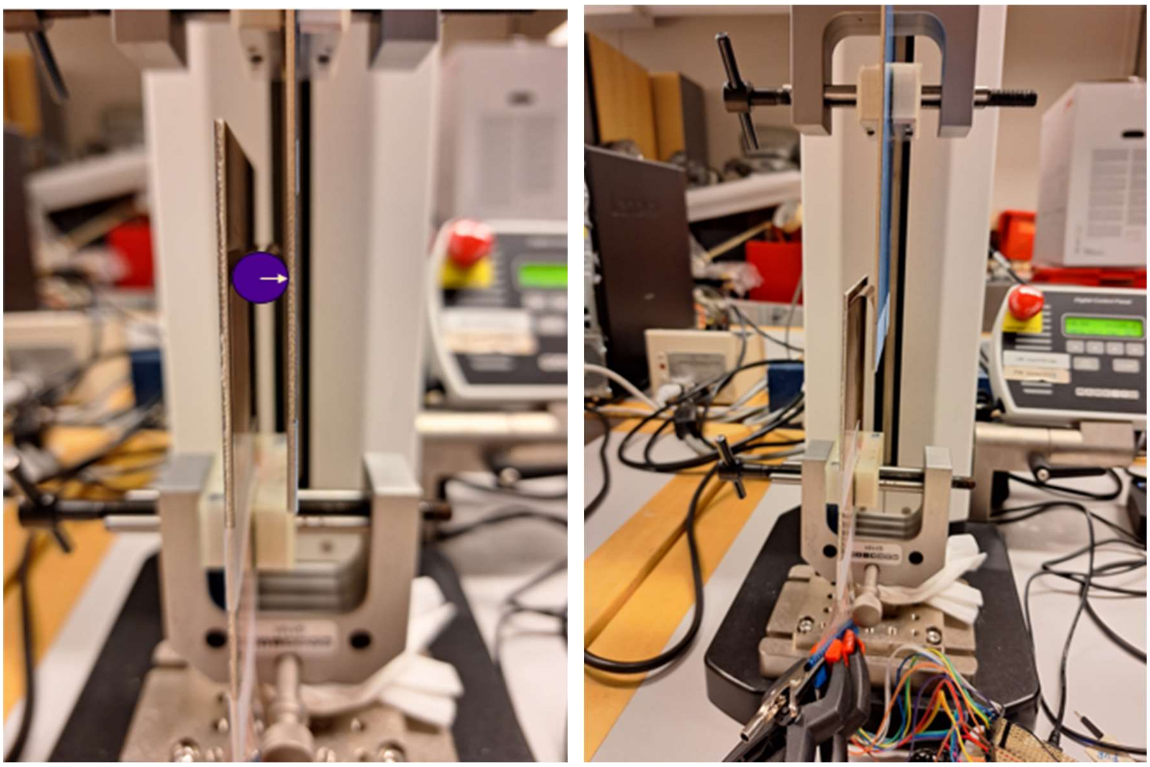


Figure 26: Test bench setup for samples

Tests with carbon prints showed that carbon prints didn't show signs of degradation after 10.000 bend cycles. There was no significant variation between different substrate materials – only two individual tracks failed. There was also no significant variation between compressive and tensile bending – ~0.99 x relative resistance saturation with compressive and ~1.01 x with tensile bending. On below figure it can be seen how bending cycle count affects the resistance of the sample.

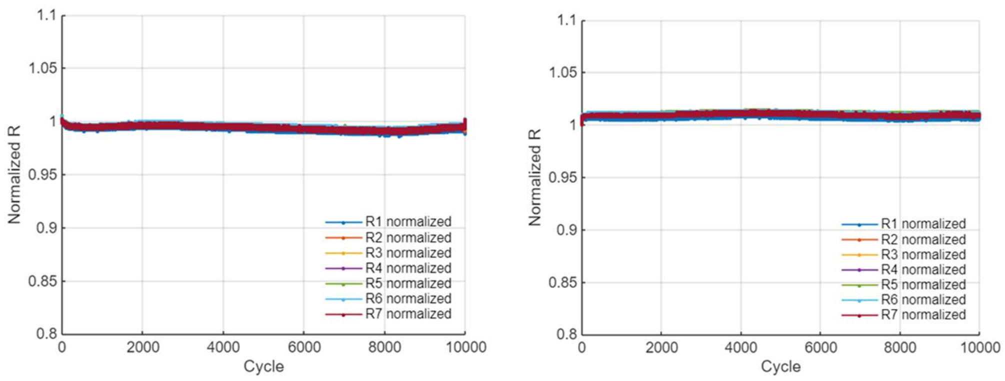


Figure 27: Left: 5mm compressive and Right: 5mm tensile bending for carbon prints on paper

Tests with copper prints showed that the cyclic bending reliability depends on the design parameters. With tensile bending the failure happens earlier than with compressive bending. Cyclic bending reliability increases when the bending radius is increased. Thinner substrates endure more bending cycles than thicker ones.

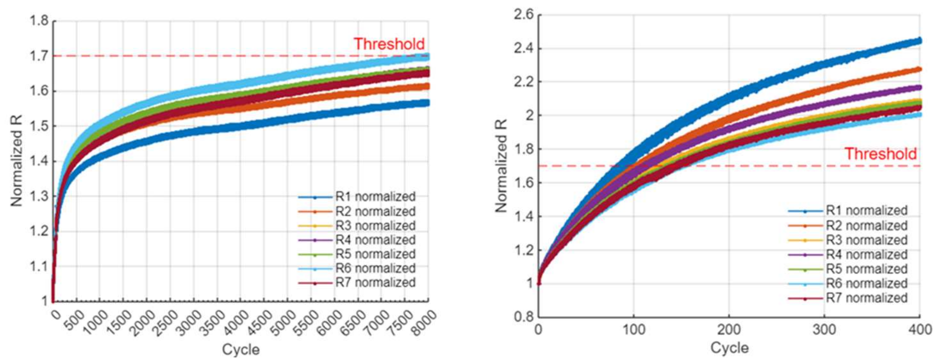


Figure 28: Left: 5mm compressive and Right: 5mm tensile bending for copper prints on paper

MOV ECG electrodes:

Gen 3 prototypes for MOV followed the same design as which was tested during Gen 2. Material usage was reduced were possible, taking into account manufacturability, products usability, and sustainability. In addition to test which of the more sustainable substrates and conductive pastes work best for the ECG measurement also a foam replacement material from TER and skin adhesive from UPM were also tested. First test samples for Gen 3 were made on fossil-based PET to check the suitability of foam replacement material from TER – it was found not suitable for the use and therefore not tested on the second and final test sample round for Gen 3. Selection of the Gen 3 MOV electrodes can be seen in Figure 29.

Figure 29: Gen 3 MOV electrode prototypes for Pilot 2.2

Gen 3 electrode prototypes, 11 different material stack combinations, were taken through a real-life test protocol, consisting of functional and performance tests. Both mechanical performance (adhesion, durability), as well as electrical performance (signal quality) were evaluated. Testing was done by individuals wearing the Gen 3 patch prototypes during a normal working day, while doing normal chores expected in the intended use case (at-home measurement; measurements in healthcare facilities were considered to be environmentally less demanding and fall under the at-home scheme). ECG signal was registered with medically certified (MDR Class IIa) Movesense MD sensors and related ECG Recorder data collection application running on the test person's mobile phone. The data recordings were stored as EDF files (European Data Format), which were then analyzed and evaluated for each samples' measurement performance.

Examples of measurement data obtained in the Gen 3 electrode prototype tests are shown in figure 30 below.

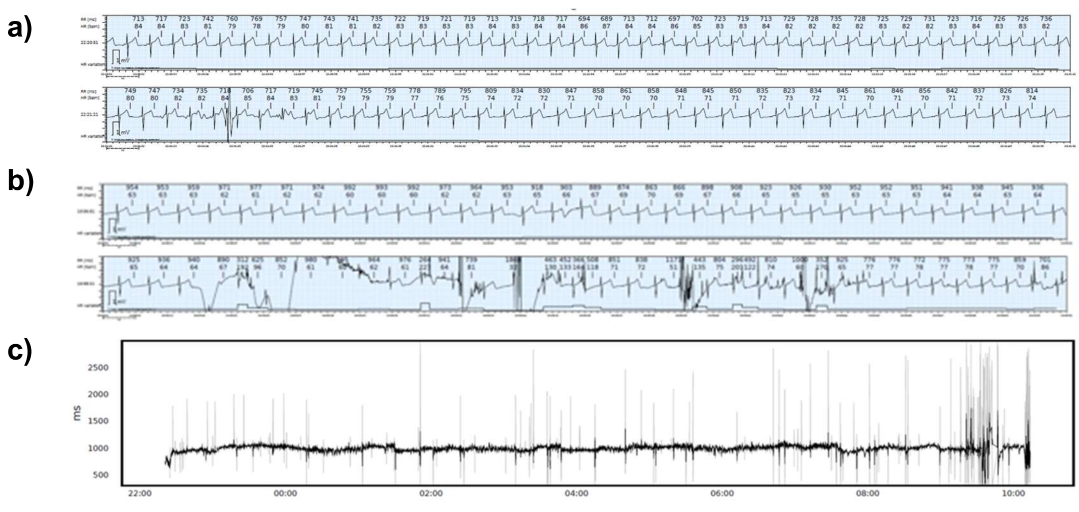


Figure 30: Gen 3 MOV electrode prototype 431-8MS signals: a) electrocardiogram in the beginning of the test, b) electrocardiogram after 11hrs 53min of continuous use and c) R-R intervals throughout the test. Test consisted of showering in the end, which shows inthe end, which shows in the date as increased noise due to skin interface glue softening.

Table 10 below summarizes the test results of the Gen 3 electrode prototype tests.

Table 8: Summary of the Gen 3 electrode prototype test results.

Patch Sample Model #	Test duration	Signal Irregularity percentage	Observations	Candidates for further study
411-8MS	11h 55min	6.7%	Adhesive skin contact weakened due to moisture.	
411-8US	14h 30min	3.4%	Signal OK whole duration.	X
412-8MS	20h 33min	43.4%	Substrate torn apart after moistening.	
421-8MS	2h 37min	80.1%	No useful signal. Test interrupted.	
422-8MS	1h 16min	83%	No useful signal. Test interrupted.	
431-8MS	11h 53min	2.7%	OK signal until moistened.	X
431-8MC	6h 12min	13.7%	OK signal until moistened. Glue did not hold when wet, hence test interrupted.	
431-8US	12h 56min	1.6%	OK signal until moistened; substrate disintegrated after moistening.	
432-8MS	14h 36min	1.8%	Signal OK; Paper substrate disintegrated when became wet.	
432-8MC	8h 8min	2.9%	Substrate disintegrated after moistening.	
433-8MS	25h 31min	25.9%	Skin contact glue adhesion gave away. Substrate handled moisture well.	X

Most of the paper-based ECG patch electrode samples performed initially well, performance differences becoming apparent when the electrodes were moistened, either by sweating or from external exposure, such as showering. Some electrode glues tested did not maintain adequate skin adhesion after exposed to water. Some soft paper based base materials disintegrated mechanically due to moisture ingression (as was somewhat expected - but still these innovative material stack elements were selected for evaluation), while harder paper based ecological substrates performed mechanically rather well in the tests. Skin adhesive type, placement and water resistance were identified to be critical factor in maintaining good electrical contact throughout the usage cycle.

Figure 31: Gen 3 MOV electrode sample on user after exercise

EDI Bio-impedance electrodes:

For Gen 3 EDI prototype electrodes, three different (A, B and C) designs were used to test the effect of different conductive patterns and connectors on the functionality and usability of the electrodes. Design B was the basic design while design A was copy of design B with the exception that the conductive patterns were five times wider than in the design B. With wider conductive patterns, the goal was to get lower resistance between contact electrodes and connector. Design C had similar conductor widths as the Design B, but the connector was a tail type connector instead of snap button connectors. By using tail type connector, it is possible to remove further materials from the product stack and make the electrode even more sustainable. Drawback with this design is that it generates higher resistance between the contact electrodes and connector due the longer and partly also narrower conductive lines used. A total of 32 different variants were made with different designs, substrates, and conductive paste. Selection of the Gen 3 EDI electrodes, including the differences between designs, can be seen in Figure 36.

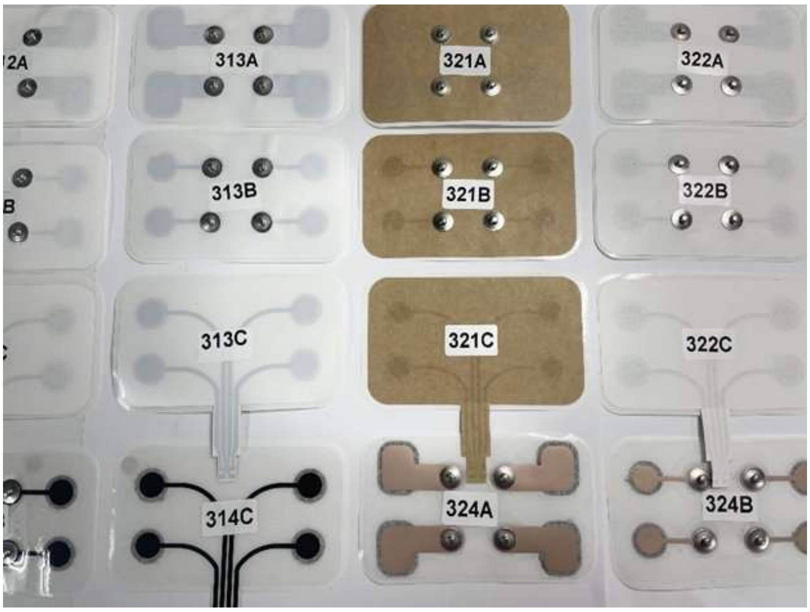


Figure 32: Gen 3 EDI electrode samples for Pilot 2.2

To evaluate the suitability of the electrode designs for bioimpedance measurements, 27 electrode types were experimentally tested using agar-gelatine models and human participants under both resting and physical activity conditions, specifically during squatting. The experimental setup used for measurements on human participants is shown in Figure 33.

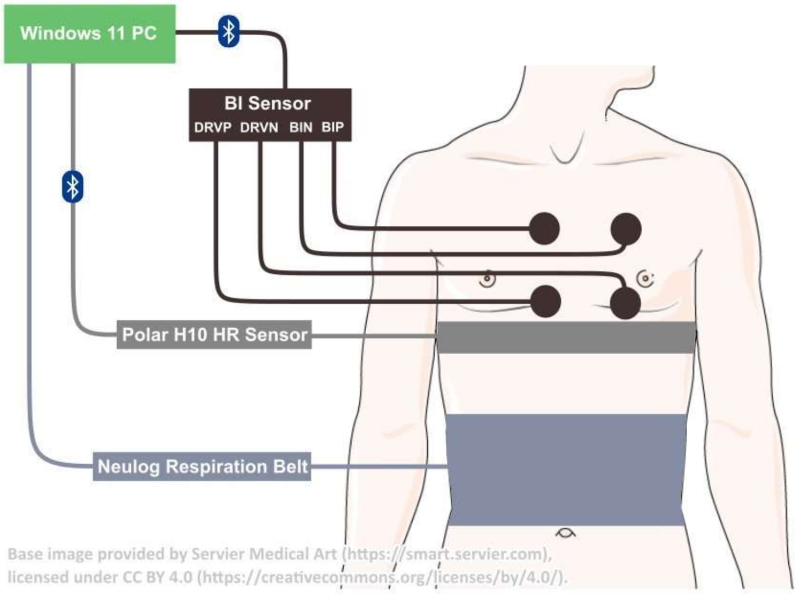


Figure 33: Generation 3 measurement setup for EDI electrode testing.

The setup consisted of EDI's wearable bioimpedance sensor, based on the MAX30001 bioimpedance analog front-end and operating in a tetrapolar measurement configuration. A Polar H10 heart rate sensor was used as the reference for heart rate measurements, while a NeuLog respiration belt was used as the reference for breathing rate measurements. For the gelatin tests, the electrodes were placed on agar gelatin, and only the impedance was measured using the bioimpedance sensor with the MAX30001 analog front-end.

Electrode performance in tests with human participants was characterised using Pearson correlation coefficients and the residual interquartile range (IQR). Figure 34 presents the results for the 14 best-performing electrodes for breathing monitoring, sorted by the Pearson correlation coefficient between the bioimpedance signal and the NeuLog respiration belt reference signal.

Based on these results, the A-type electrode variants generally showed the best overall performance, with high Pearson correlation coefficients for both breathing and heart rate signals. Only one example of electrode 312B, showed a matching correlation values to A-variants. Two C-type variants (312C and 313C) showed excellent agreement with the breathing reference signal and low residual IQR values. However, their agreement with the heart rate reference signal was comparingly weak, with Pearson correlation coefficients below 0.5.

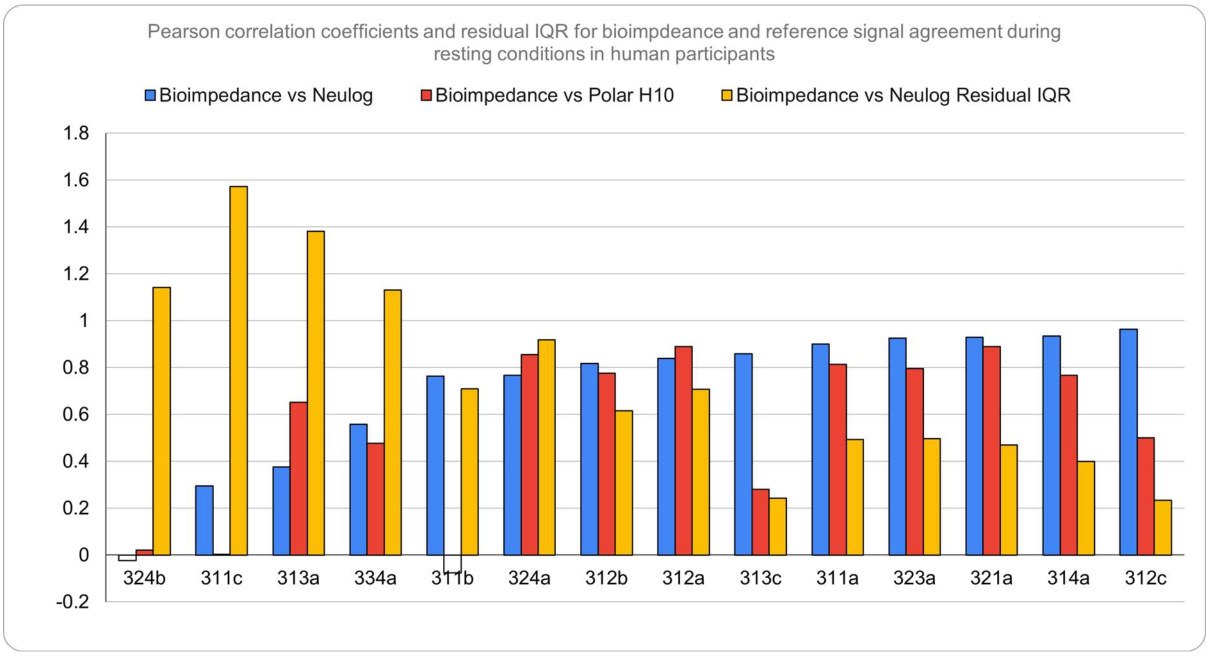


Figure 34: Pearson correlation coefficients and residual interquartile range (IQR) for agreement between bioimpedance and reference signals during resting conditions in human participants.

The agreement between bioimpedance-derived and reference heart rate signals during squat activity is shown in Figure 38. Under these dynamic conditions, considerably fewer electrodes demonstrated acceptable performance. The best-performing electrodes were A-type variants; however, only three electrodes achieved Pearson correlation coefficients greater than 0.4, indicating moderate correlation. Among these, electrode 323A achieved a coefficient above 0.6, indicating a moderately strong correlation.

In addition to the tests with human participants, gelatin tests and resistance measurements were performed to evaluate the electrodes under static conditions. Bioimpedance signal drift and noise were assessed during these tests. Figure 35 presents the values for the best-performing electrodes. In these tests, A-type variants again showed the best overall performance, although some B-type variants produced comparable results.

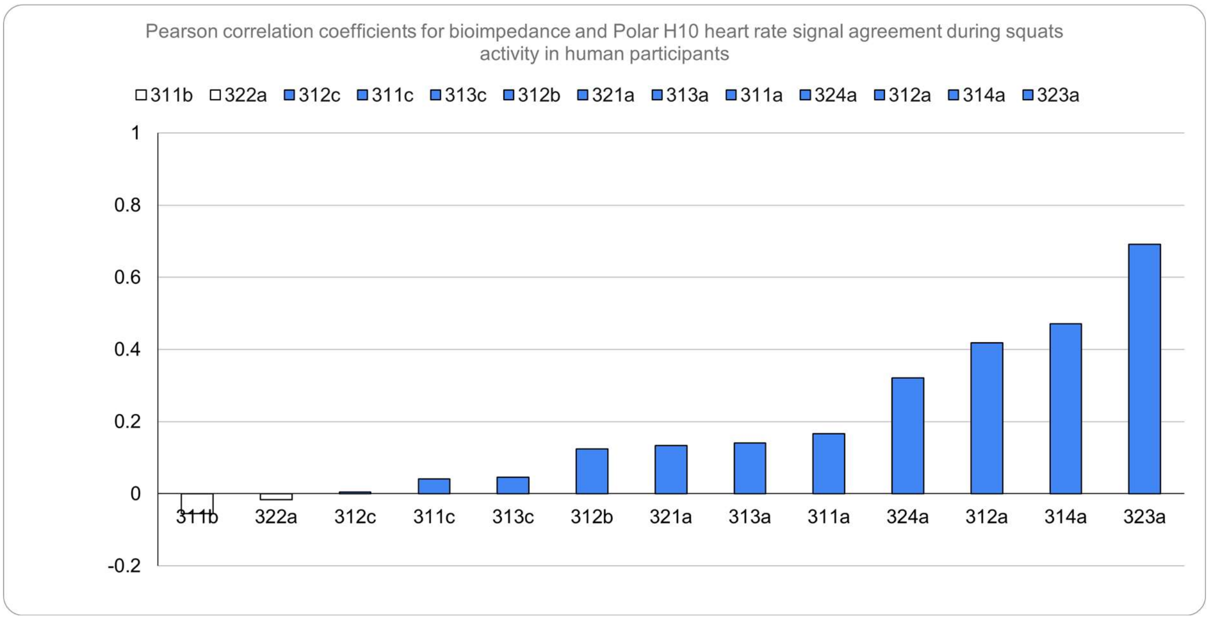


Figure 35: Pearson correlation coefficients for agreement between bioimpedance and continuous wavelet-processed ECG signals during squat activity in human participants.

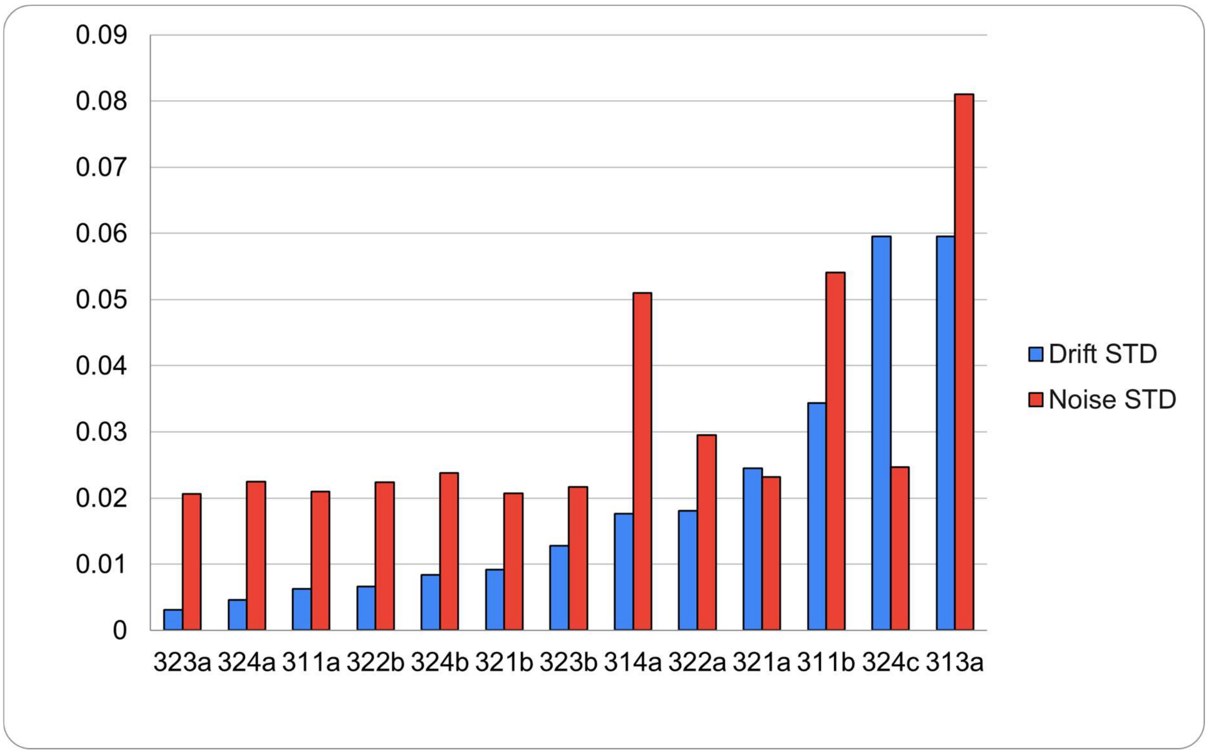


Figure 36: Bioimpedance signal drift and noise standard deviation (STD) for 13 best performing electrodes.

Resistance measurements proved useful as a first-pass screening method. Electrodes with resistance values above 10 kΩ were generally unusable, whereas electrodes with resistance values below 1 kΩ typically performed well. However, low resistance alone did not guarantee successful performance. For example, electrode 322A showed excellent conductivity, with a resistance of 0.011 kΩ, but failed due to mechanical tearing. Similarly, electrode 313A exhibited acceptable resistance but experienced intermittent loss of connection. C-type electrodes sometimes showed good conductivity on individual leads but still failed to produce reliable signals. The best-performing electrodes, such as 311A and 323A, combined low resistance with good mechanical usability.

EDI wearable sensor system

The Gen 3 pilot demonstrator integrates three EDI results into one system (KER 35.3): (i) a garment manufactured using the updated MCMT process with wired interconnect embedded before cutting/sewing (KER 35.1), (ii) the sensor-network software library running on the nodes and gateway (KER 35.2), and (iii) the energy-efficient wearable bioimpedance sensor using Gen 3 sustainable electrodes down-selected from Gen 2 (KER 31.1).
The stationary MFIA+PC setup used for Gen 1 is replaced by an embedded acquisition front-end and an optimised, embedded C implementation of the respiratory-parameter algorithm, targeting < 5 W total power consumption while preserving the Gen 1 baseline signal quality (SNR ≈ 30, 1 s settling). The actual measurements demonstrate much lower footprint: the bio-impedance sensor consumes 1.78 mW measured via Nordic Power Profiler Kit II at 64 Hz sampling rate) while running simultaneous respiratory and heart rate monitoring with signal quality scoring, and the wireless gateway prototype consumes 120.58 mW. Finally, via the

developed software library, sensor nodes integrated into the fabric can be discovered, mapped to their physical locations, calibrated, and re-flashed post-assembly and post-deployment. This eliminates the "sealed-firmware" limitation of the Gen 1 suit.

Sustainability & social targets and their status in Gen 3:

The target for sustainability is to make the single-use electrodes more sustainable by changing used materials to more sustainable alternatives. Another approach is to study the possibility of making multi-use electrodes instead of single-use electrodes and to verify how many use cases such electrodes should be used so that they would be more sustainable than reference or sustainable single-use electrodes.

Most of the LCA results for Pilot#2.2 are reported in D4.6 (Life cycle assessment and handprint study results for select case studies). This report presents only the results for EDI electrodes, which were not included in D4.6 as well as the final comparison between 3rd gen MOV single use electrode and the benchmark.

Three design alternatives were considered for EDI: one without any snap buttons but a longer tail (tail) and two without a tail but with four snap buttons each (narrow and wide). Comparing these alternatives to each other shows that the differences are significant in some impact categories and minimal in others. Especially in freshwater eutrophication and carcinogenic human toxicity, the snap button alternatives have almost twice the impact compared to the tail design (Figure 37). This is due to the additional stainless steel snap buttons.

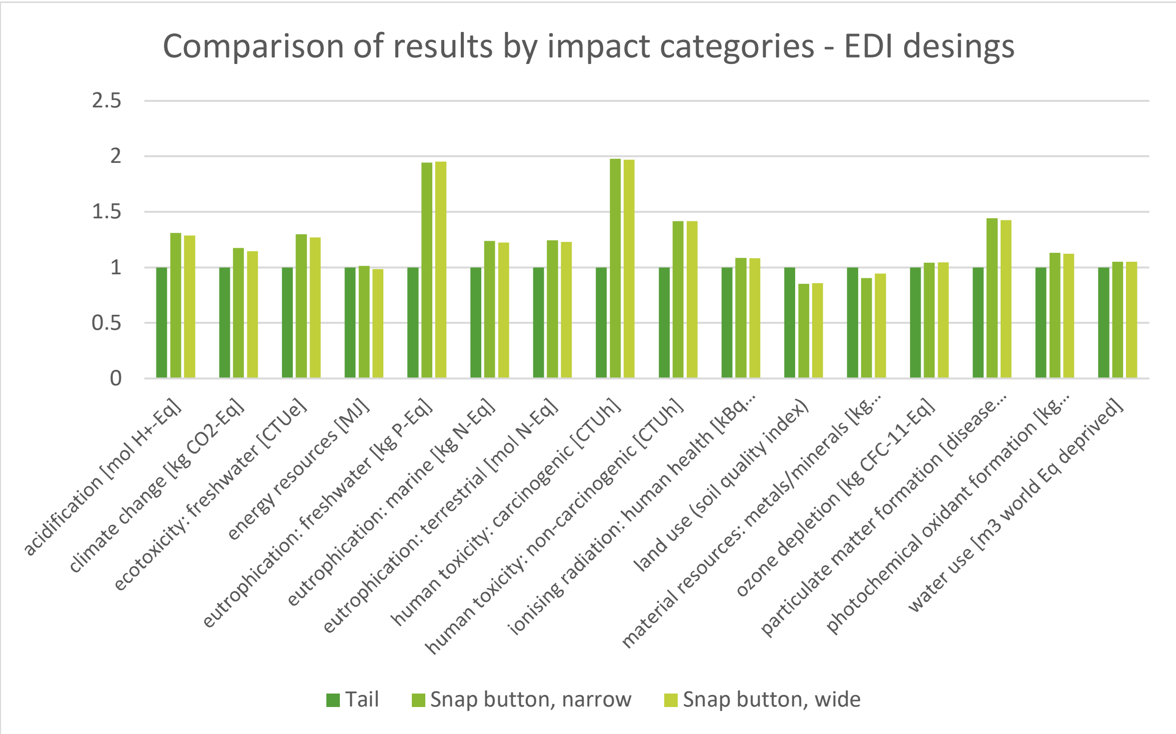


Figure 37: Comparison of manufacturing environmental impacts for EDI design alternatives. PCR PET substrate and copper ink.

Digging deeper into a single EDI electrode, the contribution analysis of environmental impacts for the tail design is shown below in Figure 38. Alternatively, the snap button narrow is shown in Figure 39. The wider snap button design has very similar impacts, therefore it is not shown separately.

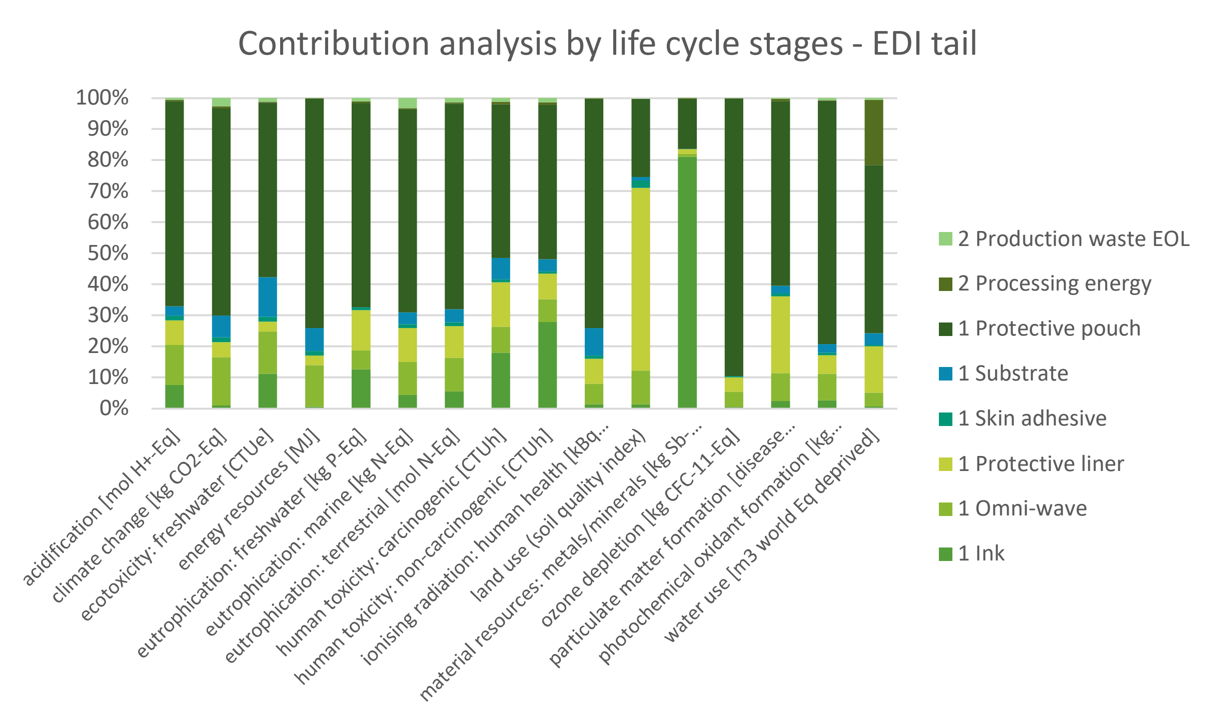


Figure 38: Contribution analysis of EDI tail electrode environmental impacts from materials and manufacturing. PCR PET substrate and copper ink.

The protective pouch made from plastic is responsible for majority of impacts in almost all categories except land use and material resources (metals and minerals). Protective liner has the biggest impact in land use and the conductive ink in material resources (metals and minerals). The protective pouch impacts are linked to plastic manufacturing while the protective liner impacts originate from forestry as the liner is paper based. Ink impacts arise from the small amount of silver (5%) used in the copper ink.

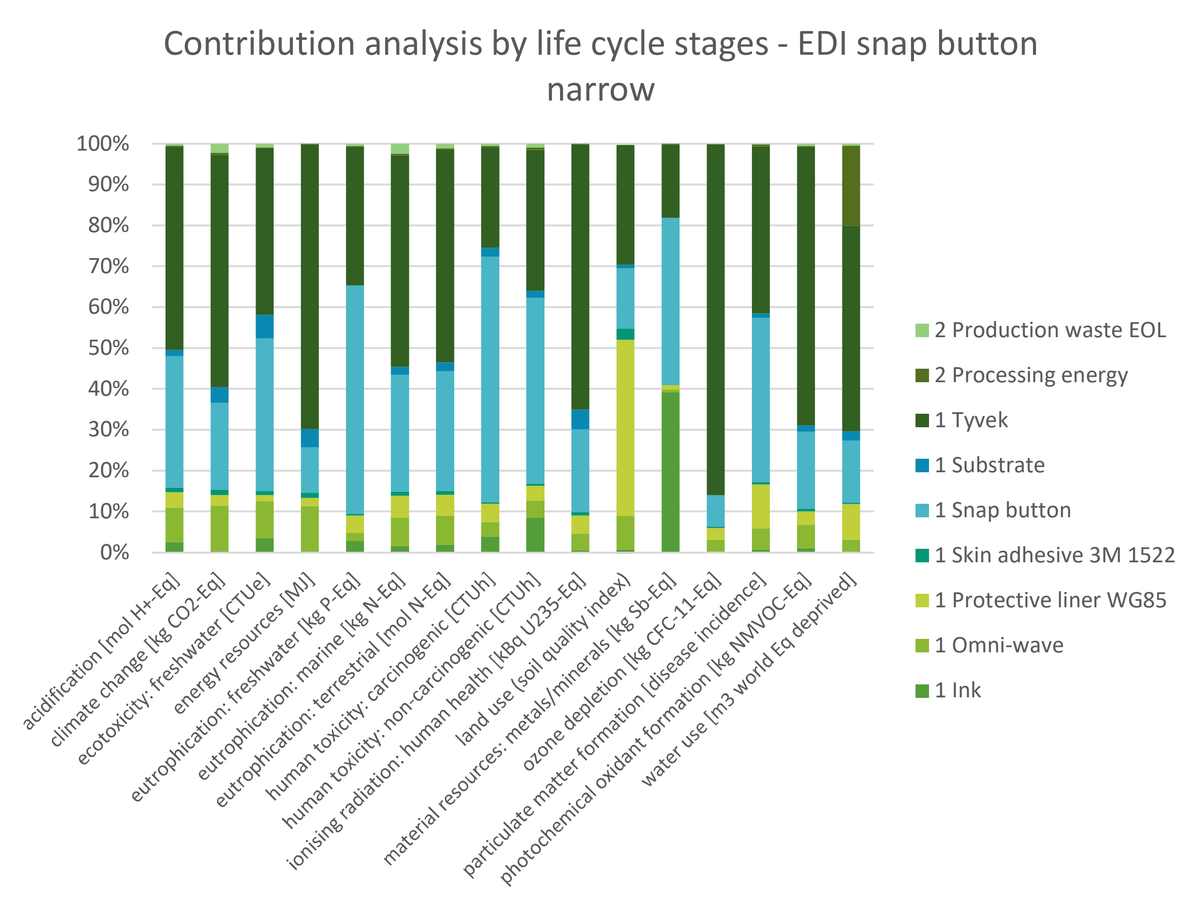


Figure 39: Contribution analysis of EDI snap button narrow electrode environmental impacts from materials and manufacturing. PCR PET substrate and copper ink.

Similar to the tail design, the protective pouch, protective liner and conductive ink show significant impacts. The pouch in many categories. Additionally, the snap button causes a good portion of impacts in most categories. Especially in acidification, freshwater ecotoxicity and eutrophication, human toxicity and particulate matter formation but also in many others. These impacts originate from the stainless-steel manufacturing process.

In the comparison between the benchmark electrode and MOV 3rd generation single-use electrode, the benchmark electrode is comprised of the standard materials used in an EEG electrode on the market including but not limited to fossil TPU substrate, silver conductive ink, a PET/Al protective pouch and a PET/silicone protective liner. The MOV 3rd gen electrode uses a coated white paper substrate, copper ink, PET protective pouch and paper-based protective liner. The skin adhesive is also changed from a non-woven to an alternative without the fabric layer. As shown in Figure 40, the new 3rd gen electrode design has approximately 20% lower PEF single score compared to benchmark.

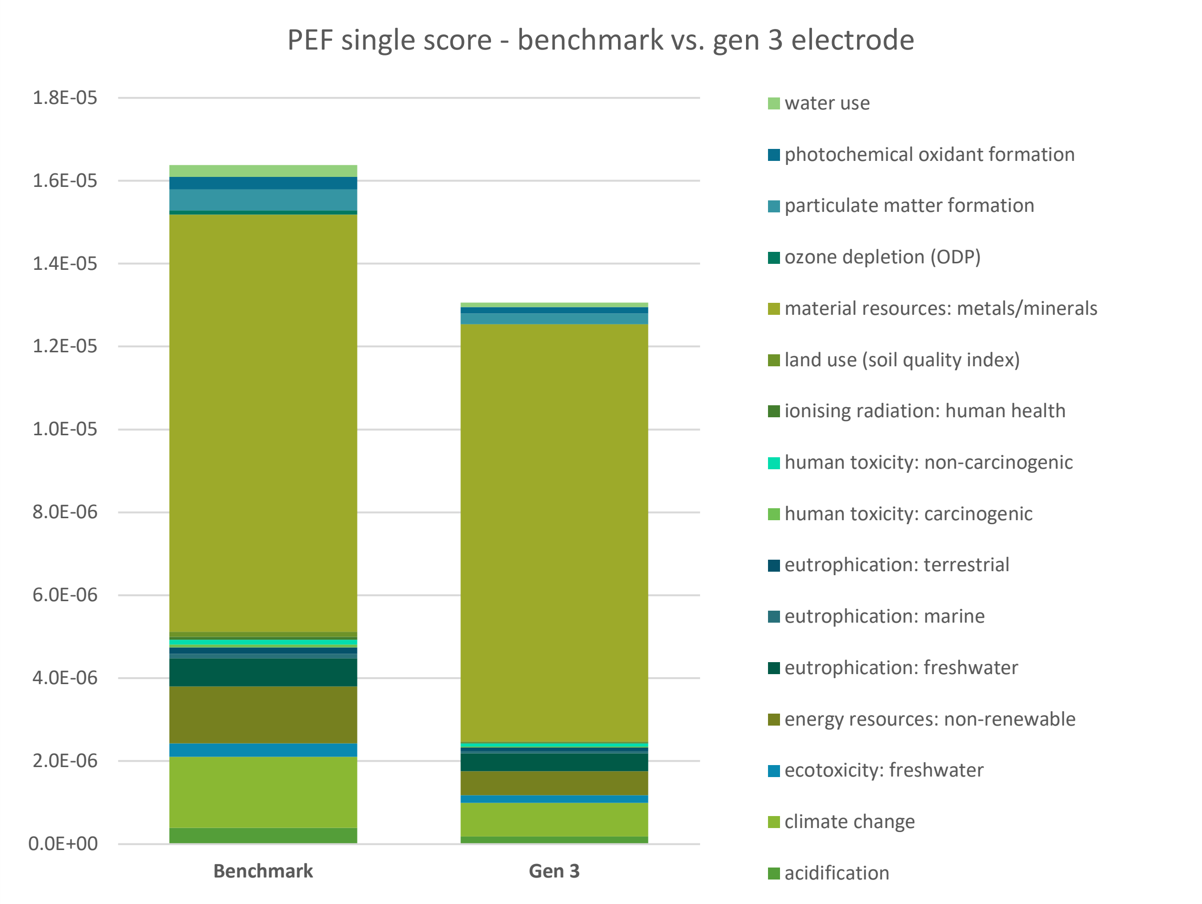


Figure 40: PEF single score comparison between benchmark and MOV gen 3 single use electrodes.

End user engagement:

Both electrodes, EDI bio-impedance and MOV ECG electrodes, were presented in several events (trade fairs, conferences, seminars), telcos and face-to-face meetings to potential customers and product owners. The more sustainable material stack together with proven functionality raised interest among many and first prototype electrodes have already been made by SCR to handful of customers. So far there is no information if any of the product owners who have tried the developed more sustainable material stack for their electrodes want to go further with it or not.

VTT also made a customer survey for medical electrode product owners regarding the more sustainable medical electrodes and their thoughts for the topic.

Achievements

- Functional ECG and bio-impedance electrodes made with more sustainable materials and carbon-based prints were proven to tolerate easily huge amount of mechanical stress.
- Up to 24-hour wear time could be achieved with the developed material stack – this time is typically enough for many medical electrode use cases.
- Manufacturing costs for the more sustainable medical electrodes is ~-20% less than reference electrodes, main savings come from the cheaper conductive material and from changing the PET/Al pouch to plastic-paper pouches.

Key challenges

- LCA data gathering was time consuming and difficult from some material suppliers.

Technology and sustainability readiness levels:

Table 9: Pilot 2.2 Technology and sustainability readiness levels.

MOV ECG electrode

	Gen 2	Gen 3 status
TRL	TRL7	TRL8
SRL	SRL7	SRL8

EDI ECG electrode

	Gen 2	Gen 3 status
TRL	TRL7	TRL8
SRL	SRL7	SRL8

Wearable sensor-network with interconnect fabric guidelines

	Gen 2	Gen 3 status
TRL	TRL3	TRL4
SRL	SRL2	SRL8

2.2.3. Pilot#2.3 Sustainable dashboard for automotive

Pilot Leader: FAU (Axelle Poteaux)
Pilot Goal/Objective :

The Pilot 2.3 is an innovative automotive dashboard offering a more comfortable and pleasant user experience for drivers, while answering the need for a green and circular approach.

This dashboard is based on the combination of printed electronics and injection moulding and it is made of several parts: a decorative film, that has an aesthetic role and creates visuals that appear on the device; a technical film that contains the electronic functions, and finally an injected plastic material in between.

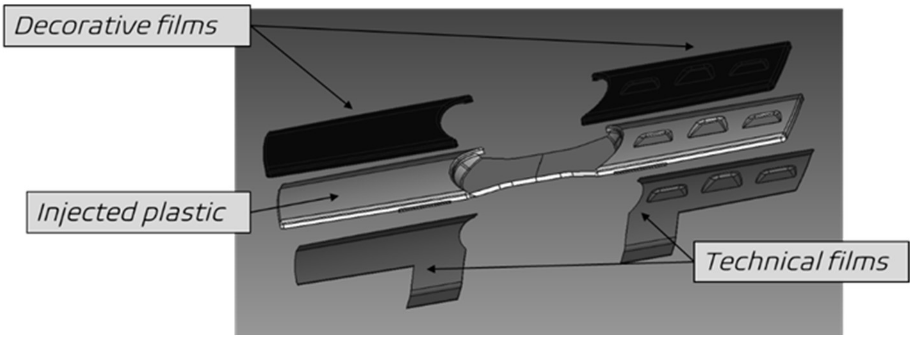


Figure 41: Building blocks of the Pilot 2.3 dashboard

Printed electronic devices, like the decorative and technical films, are an alternative to conventional FR4 and etched Cu-based printed circuit boards. They are fabricated using additive techniques (screen printing) which use less energy, material and chemicals, and are therefore more sustainable. Thermoforming is used to give the film 3D shapes and injection moulding is used to assemble the building blocks to create a robust final device. Bio-based materials are introduced in the device to replace fossil-based standard materials. Components disassembly and materials recovery are evaluated as part of the project.

The dashboard has two specific areas as pictured in Figure 42:

- Left side is a dynamic lighting composed of various LEDs driven by a microcontroller and a circuitry combining several SMDs (Single Mounted Device).
- Right side is an active command panel, with one capacitive back lighted slider on the top and 3 capacitive backlighted buttons below. The circuit contains RGB LEDs together with a microcontroller, resistors and capacitors.

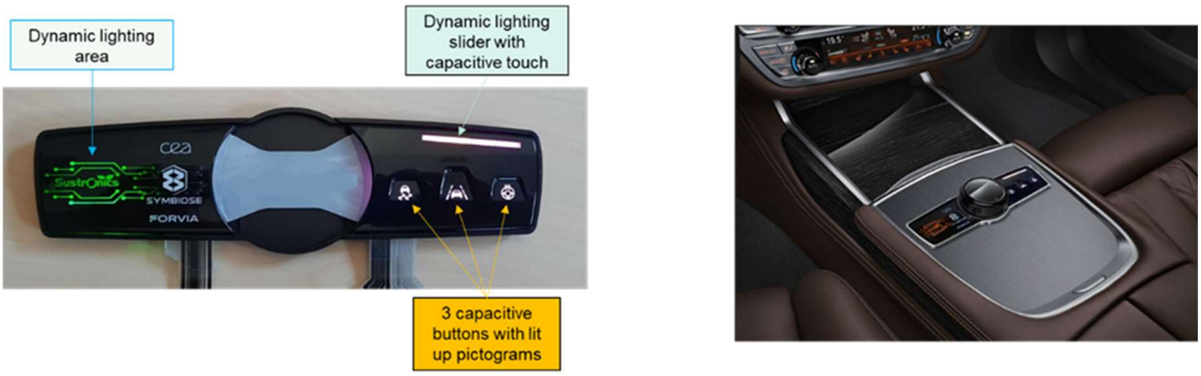


Figure 42: Dashboard presentation for Pilot 2.3

Updated Pilot Description for Gen 3:

No changes to the pilot description of D3.2/Gen 1.

Work Carried Out: Gen 1 and Gen 2 Overview

In Sustronics, three generations of the device have been developed:

Gen1 was created with commercial materials (standard polycarbonate - PC) and sustainable processes (additive manufacturing by screen printing). This generation permitted to validate the design/layout of the device as well as the fabrication steps. Moreover, the Gen1 devices serve as a baseline for devices created with materials from the project.

Gen2 have been created using the layout validated on Gen1 devices but employing sustainable Sustronics materials and fabrication processes optimized for these materials.

Gen3 incorporates guidelines for the end of life (recycling and dismantling) for injection mold devices.

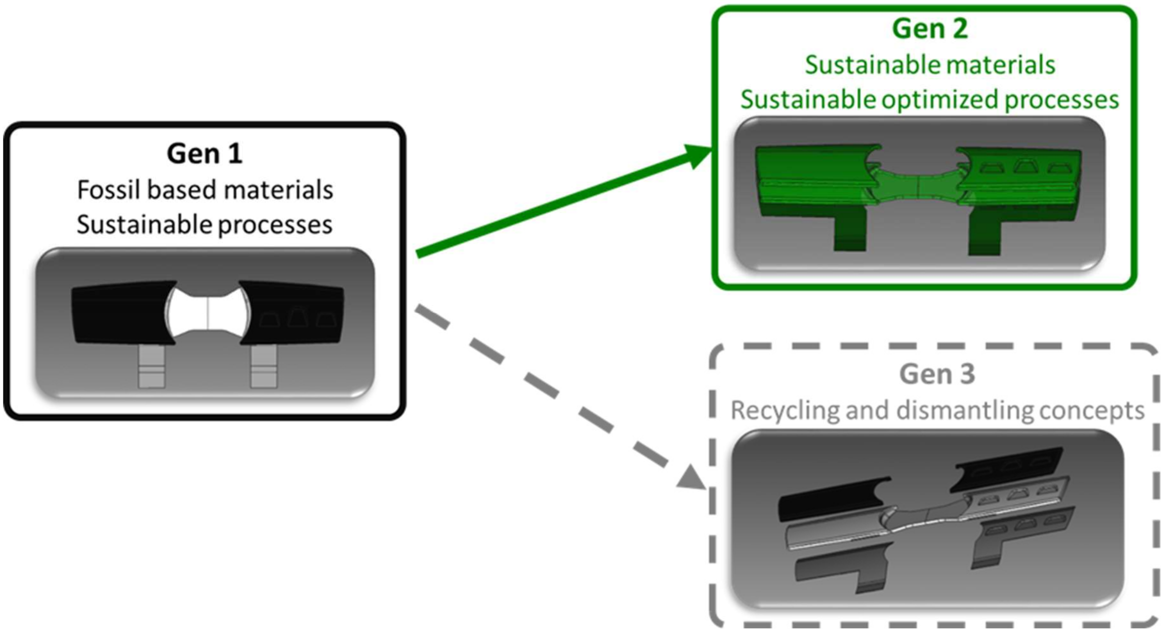


Figure 43: Generations description for Pilot 2.3

Technologies involved and role of project partners in Gen 3:

The Pilot 2.3 combines sustainable materials and processes, and recycling concepts.

FAU provided specifications and requirements for the dashboard, as well as specifications of materials regarding their optical, mechanical and thermal properties (WP1). In terms of materials, the device requires both extruded films and raw material in form of pellets for the injection phase. VTT developed extrusion method for various materials (WP1) and provided films for testing. ARNP provided PEF in form of films and pellets as well for injection tests. Compatibility with processing steps (screen-printing and thermoforming) was tested by CEA (WP1) and optimized when possible. SYM was responsible of design and fabrication of Gen1 and Gen2 devices. Design and validation of capacitive part were carried out in WP2. Process parameters for ink curing and thermoforming of material used for Gen2 were provided by CEA. After fabrication, CEA and SYM carried out functional evaluation of the devices (LEDs functioning and capacitive sensor) before sending them to FAU, in charge of product qualifications regarding the automotive field, including environmental and mechanical tests. VTT was in charge of the LCA of the Pilot (WP4). RISE provided conductive and non-conductive adhesives and methods for forming interconnects. MIR carried out sorting and shredding experiments on Pilot 2.3 samples. Technical layout and characterisation of Gen 3:

Injection moulding process step

Process optimization for the injection moulding step was specifically addressed within the project, as SYM was responsible for device fabrication, including adapting this final step to bio-based materials. Initial trials using standard process parameters led to material degradation, requiring targeted adjustments.

For bio-PC, the main adaptation involved reducing the processing temperature during the heating phase. PEF, however, showed higher sensitivity, necessitating further optimization of injection speed and holding pressure in addition to temperature control. Despite extensive parameter tuning, achieving parts with a fully homogeneous appearance remained challenging, with internal humidity-related defects consistently observed. Moreover, PEF exhibited increased brittleness compared to both conventional materials and bio-based PC, further complicating processing.

Nevertheless, several devices were fabricated using PEF and the correct functioning of the printed circuit that lights up the pictograms embedded in the device was validated.

Similarly, functional demonstrators made of bio-PC were successfully manufactured and delivered to FAU for subsequent testing.

Characterization results on sensor

Sensor characterisation activities were carried out to assess the maturity of each material. SYM developed dedicated FR4 PCB hardware and software platforms incorporating capacitive touch buttons and LED driving functions in this purpose. Initial validation was successfully performed on standard PC substrate materials.

Following injection with bio-PC, no degradation in overall functionality was observed, confirming good process compatibility.

In contrast, injection with PEF resulted in limited functional yield, with only a few parts operating correctly. This behaviour is attributed to the non-standard injection moulding conditions required for PEF, indicating that further improvements in material stability during processing are necessary.

Characterization results at system level

FAU carried out a system-level test campaign to assess the functional and environmental robustness of dashboard modules integrating lighting and touch-sensitive films, comparing samples manufactured with standard fossil-based materials and bio-based polycarbonate (bio-PC).

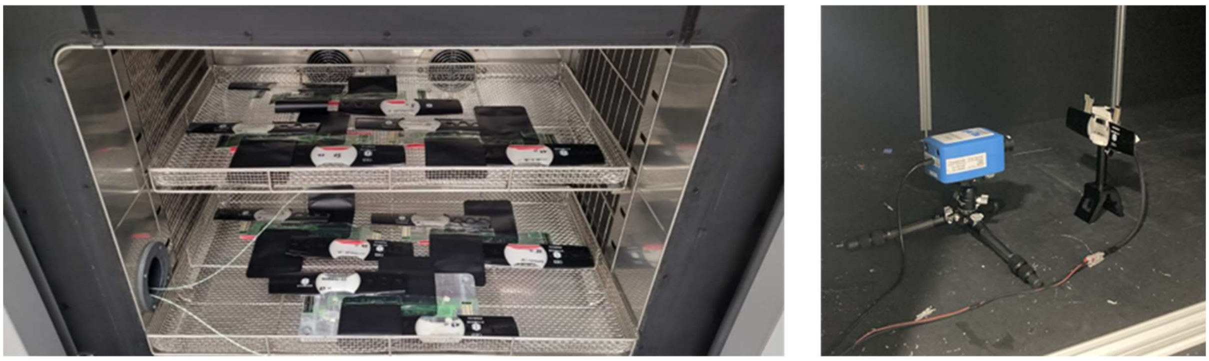


Figure 44: Pictures of Dashboard validation at system level

The tests were conducted using an identical validation protocol for both material families, relying on a standard PCB configured to simulate various lighting and touch interaction scenarios, as well as a comprehensive set of mechanical and environmental tests representative of real automotive use conditions.

Environmental testing includes initial mechanical tests (adhesion, flammability, scratch resistance) as well as a series of climatic and chemical exposure tests simulating real-life operating conditions (thermal shock, high-temperature ageing, gas corrosion, humidity, and solar radiation). These tests are structured into three test pathways according to the applied conditions: LEG1 (thermal shock, high temperature ageing, gas corrosion), LEG2 (damp heat, temperature–humidity cycles), and LEG3 (solar radiation exposure). Optical (luminance, homogeneity, color, transmission) are performed before and after each testing phase. Final mechanical measurements are done after the last test phase.

The results obtained on the standard fossil-based material samples provide a solid performance benchmark for comparative analysis. They demonstrate good colorimetric stability and overall satisfactory mechanical cohesion after exposure to severe climatic and chemical stresses, despite lumen output being the most sensitive optical parameter, particularly under UV exposure. The LEG1 and LEG2 test pathways highlighted a progressive but controlled degradation of optical performance combined with mostly compliant adhesion behaviour, while the LEG3 pathway confirmed the critical impact of solar radiation ageing on luminance.

These reference results enable an objective assessment of the ability of bio-PC-based solutions to reach equivalent or comparable performance levels. Observed variations in adhesion underline optimization levers related to material–process interfaces, independently of the fossil-based or bio-based nature of the substrate.

Overall, this first system-level test campaign confirms the feasibility of dashboard systems integrating sustainable alternative materials, while providing key insights to guide the optimization of bio-PC solutions within an eco-design approach compatible with automotive requirements and the sustainability objectives of the Sustronics project.

Sustainability & social targets and their status in Gen 3:

The results for Pilot 2.3 LCA studies are reported in D4.6 (Life cycle assessment and handprint study results for select case studies).

The LCA study performed by VTT in Gen 1 determined that the most impacting element in our Dashboard is the PC (Polycarbonate), which is present in both decorative and technical films and is the bonding material between them, shaping the final device. PC represent more than 95% of the complete weight of the device (Figure 45).

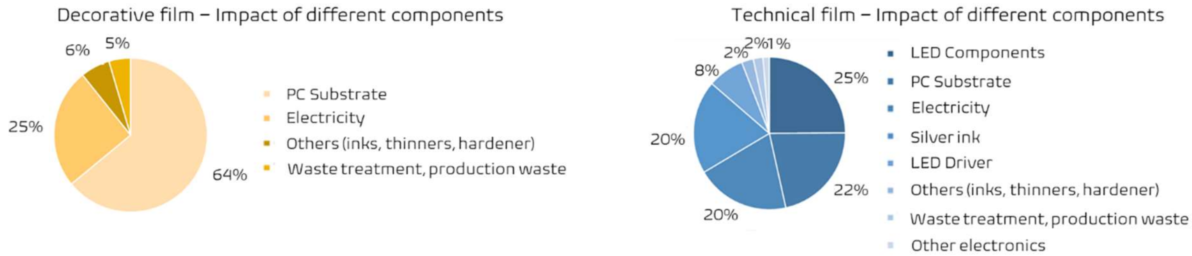


Figure 45: LCA - Impact of different components in decorative and technical films.

Therefore, actions were taken in Gen 2 to replace the standard PC by more sustainable materials.

Two potential materials for the pellets and films were considered, bio-based polycarbonate (bio-PC) and polyethylene furanoate (PEF).

LCI for bio-PC was taken from a public report by Sabic which was used to scale the ecoinvent fossil-PC production process based on Sabics reported carbon footprint deduction - as for PEF, an Avantium study by Nova Institute was used.

Figure 46 below shows the contribution analysis results for a dashboard made using bio-PC and Figure 47 similarly for a dashboard using PEF.

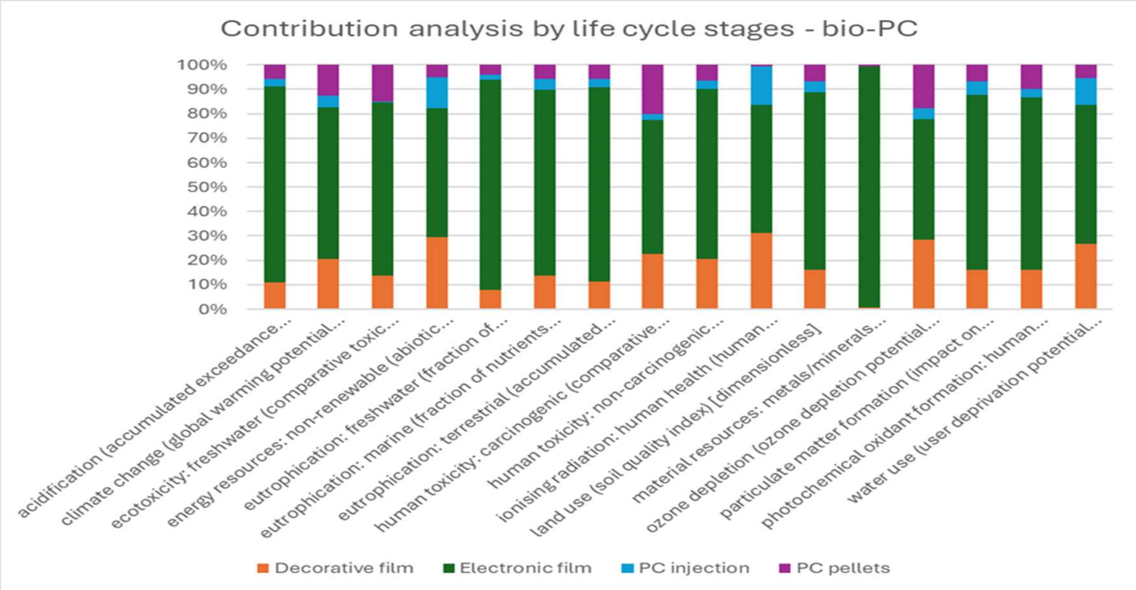


Figure 46: Contribution analysis of automobile dashboard manufacturing emissions using bio-PC

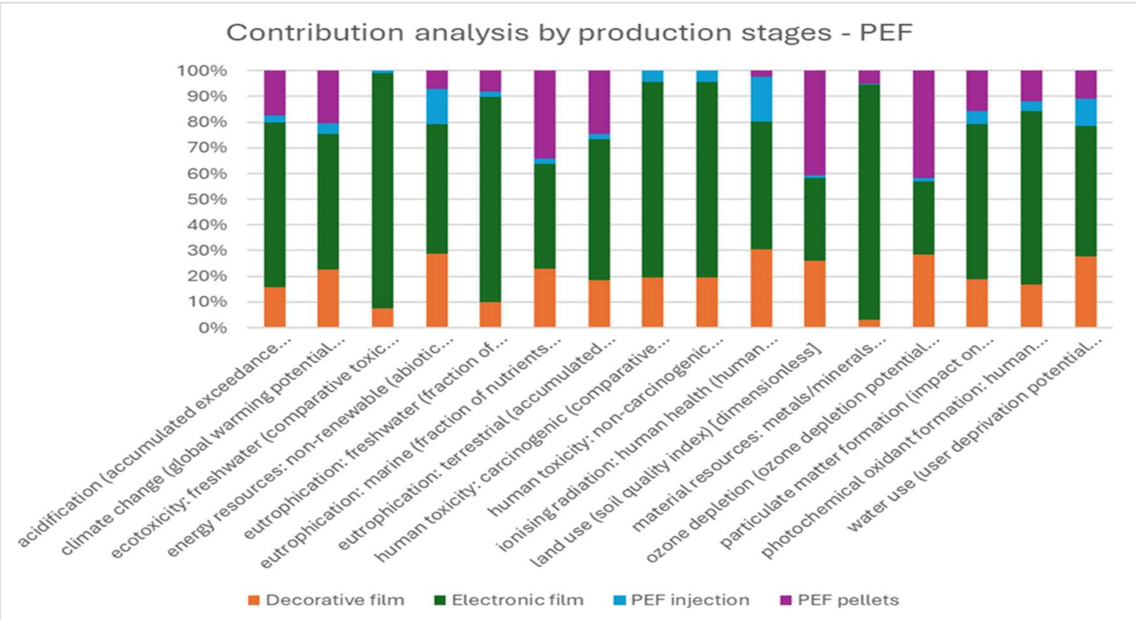


Figure 47: Contribution analysis of automobile dashboard manufacturing emissions using PEF

Both materials show similar overall environmental impacts, mainly driven by the technical film das it contains components like LEDs and capacitors. PEF appears to have higher impacts in some areas (e.g. land use and marine pollution), while bio-PC seems lower, but this comparison remains uncertain due to limited and incomplete data. Overall, more robust data is needed, as bio-based materials can sometimes involve trade-offs in areas such as water use and ecosystem impacts.

Comparison to reference

To see the impacts of switching from fossil PC to bio-PC or PEF, a comparison was made. Figure 48 shows the Gen 1 dashboard made with fossil PC set to 1 and the Gen 2 bio-PC and PEF alternatives are presented as relative to it. The comparison only includes manufacturing of the dashboard.

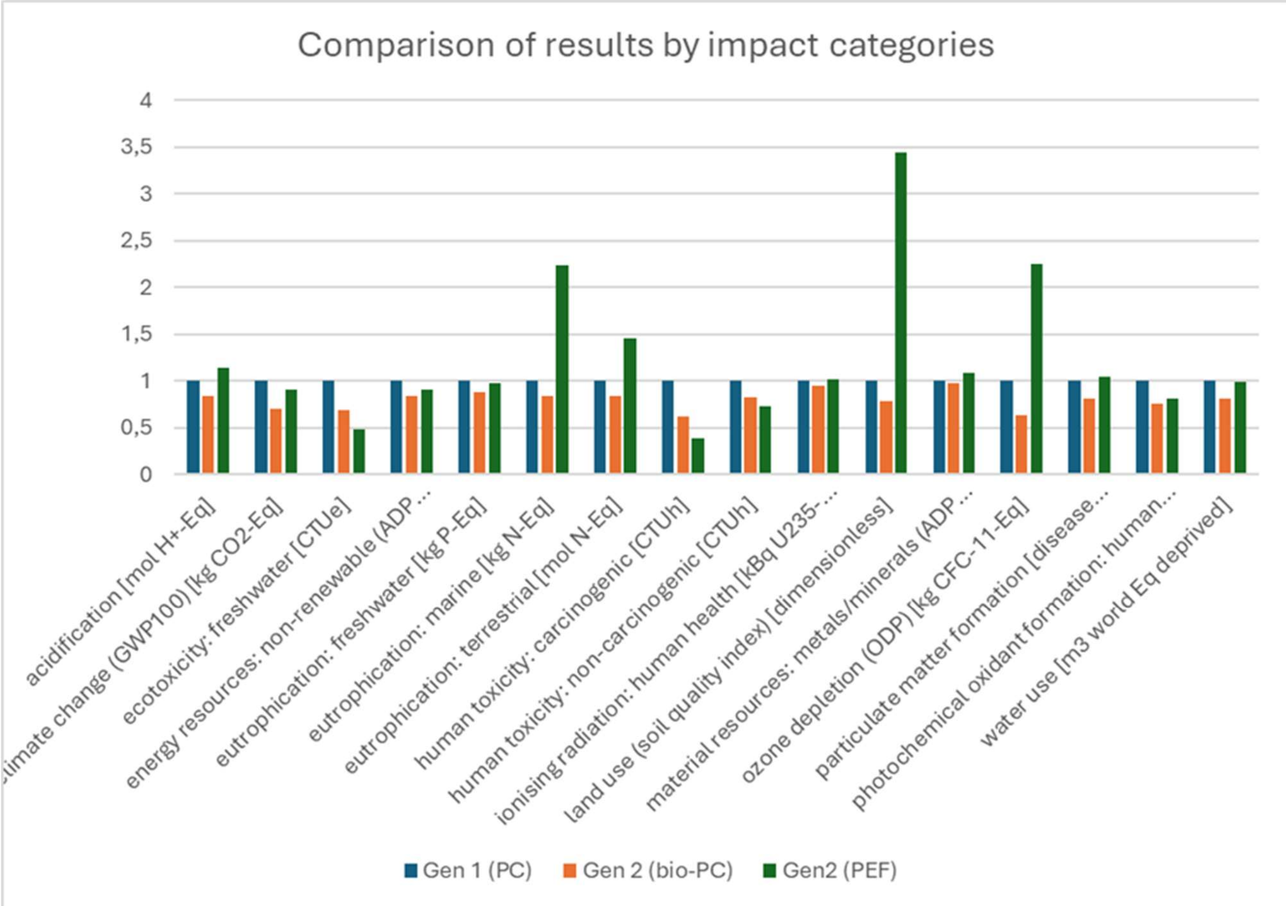


Figure 48: Contribution analysis of automobile dashboard manufacturing emissions using PEF

PEF shows higher impacts in areas such as land use and water pollution, while bio-PC appears to perform better in these categories. As both materials are derived from plant-based sources, they generally require more land and may increase water-related impacts.

While PEF shows improvements compared to fossil-based PC in certain aspects, bio-based PC consistently demonstrates lower impacts than fossil-based PC. However, this comparison remains uncertain due to incomplete data for PEF and partially estimated data for bio-PC.

In Gen 3, the focus was on end-of-life options and recyclability. No changes in product design were made.

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.

Figure 49 and Figure 50 show the comparison of climate change impacts between generation 1 and generation 2 and including the possible end-of-life options and credits from material and energy substitution.

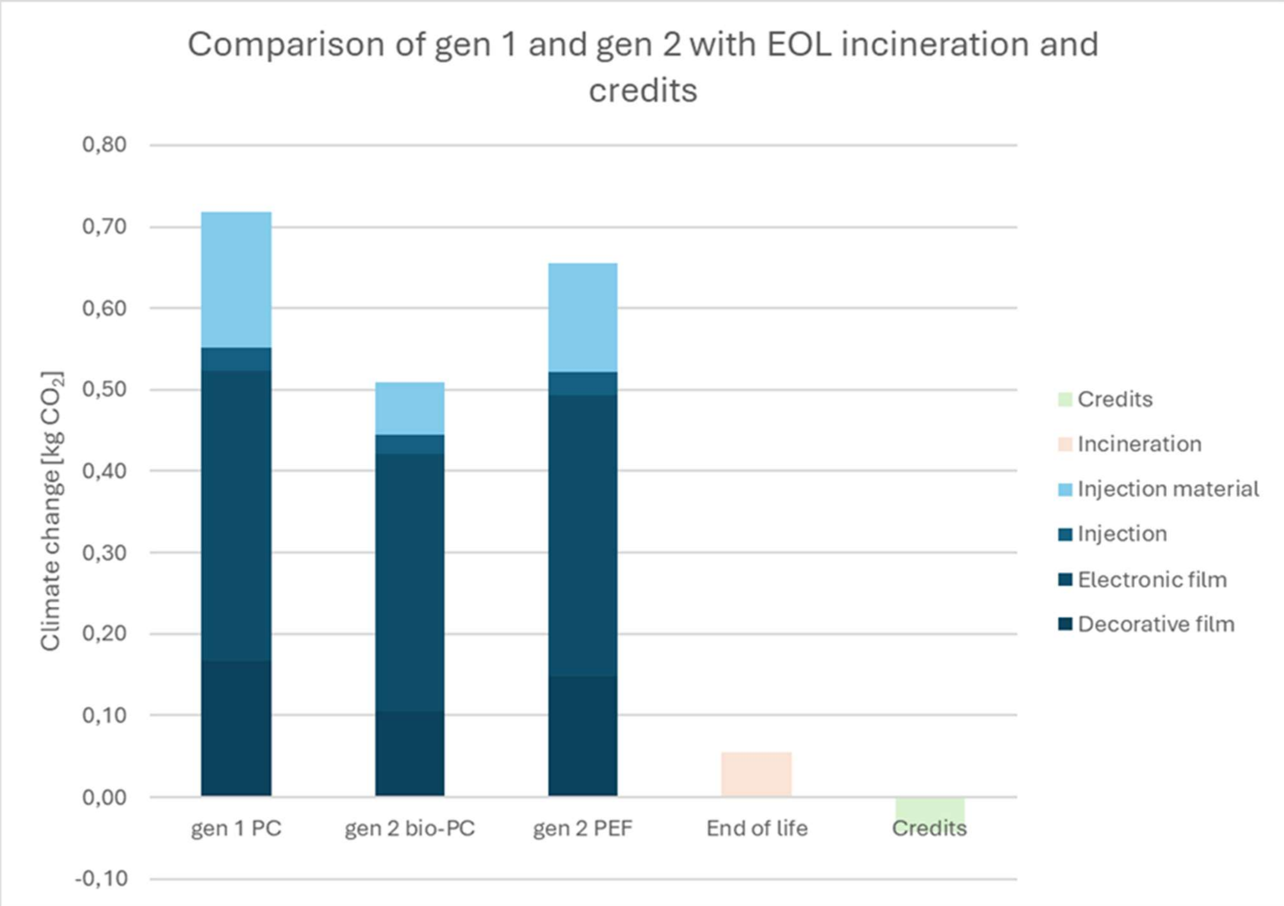


Figure 49: Comparison between climate impacts of generation 1 and 2 dashboards with end-of-life incineration and potential credits from substitution included

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.

In this study, emissions from incineration are assumed to be the same for all materials. However, in reality, bio-based materials could have an advantage, as their carbon emissions are considered neutral, meaning their overall climate impact may be even lower than Gen 1.

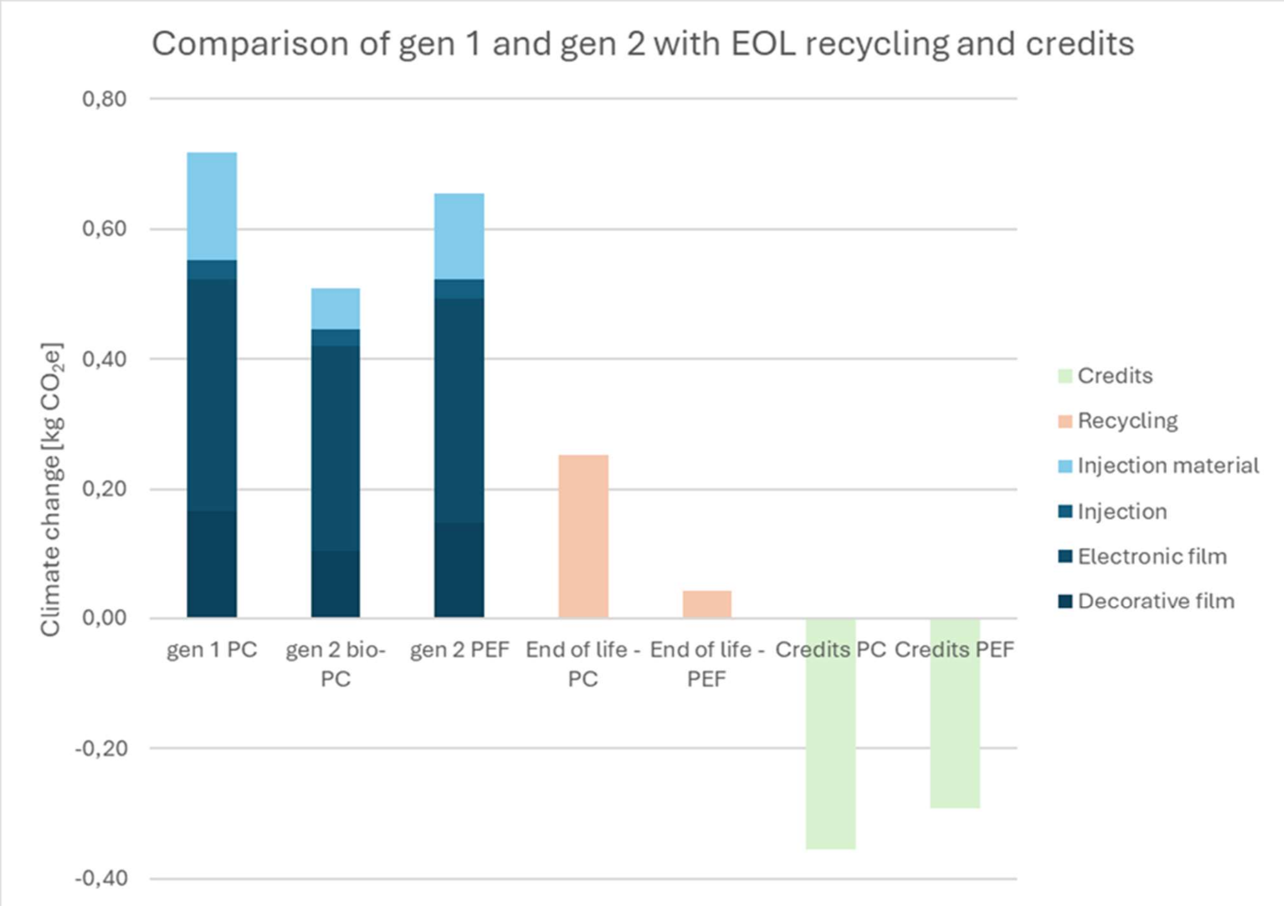


Figure 50: Comparison between climate impacts of generation 1 and 2 dashboards with end-of-life recycling and potential credits from substitution included

Recycling the dashboard can have varying climate impacts for bio-PC and PEF, but these are often offset by the benefits of recovering materials that replace new (primary) plastics.

However, the two materials are treated differently: PEF is recycled mechanically (crushed and reused), while bio-PC is assumed to be chemically recycled, which uses more resources but can produce higher-quality material. Because these processes are different and some assumptions are uncertain, the results are not fully comparable.

Overall, the study demonstrates that while bio-PC and PEF have the potential to reduce certain environmental burdens, a holistic evaluation of their life cycle impacts is constrained by current data availability, necessitating caution in drawing definitive conclusions and underscoring the need for more comprehensive and representative data for future assessments.

Recyclability

Recyclability aspects were investigated in WP4 through dedicated tests performed by MIR on both standalone printed foils and fully integrated injected parts. The evaluation focused on key recycling steps, including sorting and shredding.

Sorting proved to be effective, with reliable detection of the samples using metal detection systems, regardless of their orientation on the belt.

During shredding, it was observed that the silver (Ag) from the printed electronics remained embedded within the plastic matrix and is not separated at this stage.

These initial tests were conducted on samples based on standard materials; however, the same methodology is applicable to systems integrating bio-based/sustainable materials.

Further discussions are ongoing to assess the potential recovery of silver from shredded devices through external recycling partners.

As a guideline for future developments, recycling considerations should be integrated at the design stage by adopting a design-for-recycling approach.

In particular, systems should be conceived to enable the removal of electronic components prior to end-of-life vehicle processing.

As injection encapsulates electronic functions and complicates material separation, alternative integration strategies should be explored, such as the use of reversible or debondable assembly solutions to facilitate dismantling.

In addition, prioritizing mono-material architectures wherever feasible will support improved recyclability by limiting material complexity and ensuring better compatibility with existing recycling streams.

End user engagement:

The IME solution was presented by Forvia to OEMs during internal demo shows, innovation days, and tech days, and further showcased by CEA at major industry events such as LOPEC and TechBlick. These activities enabled direct engagement with key stakeholders and end users, providing valuable feedback on both functionality and integration. The interactions confirmed strong OEM interest and highlighted the added value of IME in simplifying human–machine interaction, thereby supporting safer and more intuitive use for drivers.

In parallel, these exchanges clearly emphasized the growing demand from OEMs and Tier 1 suppliers for the integration of more sustainable, bio-based materials. However, this transition is subject to stringent industrial constraints: alternative materials are expected to deliver equivalent performance without compromise, while maintaining cost neutrality or achieving cost reductions. Any increase in component cost is only considered acceptable if accompanied by clear added value, underlining the challenge of balancing sustainability objectives with performance and economic requirements.

Pilot Achievements & key challenges in Gen 3:

Table 10: Pilot 2.3 Achievements & key challenges in Gen 3:

Technical Specifications	
KPI's	Results
Electrical resistivity of printed tracks after injection <10-6 Ω▪cm (technical)	Track properties on standard material and SUSTRONICS alternatives are similar, as process parameters were chosen to guarantee this
Capacitance standard deviation and luminance homogeneity deviation < 10% (technical)	OK - Capacitance: Equivalent capacitance between standard PC and bio-PC parts for two main reasons: (i) all HMI components were manufactured using the same injection tool, ensuring identical sensor distances, and (ii) both materials are electrically non-conductive thermoplastics, resulting in

	equivalent capacitive sensor operation without additional calibration needs. Functional validation using identical hardware and software confirmed fully operational and comparable sensor behaviour for all evaluated devices. OK - Luminance: in average, in comparison with Standard PC, the luminance of bio-based prototypes is reduced by ~ 9%
Sustainable Specifications	
KPI's	Results
Share of bio-based materials up to 50% (environmental)	OK: replacement of 100% of virgin material in films and pellets by bio-based materials
Control panel weight reduction compared to conventional electronics up to 50% (environmental)	OK: Conventional electronics (with PCB): 114g SUSTRONICS prototype (+ control card): 49g → - 57%
Reduction of energy consumption for manufacturing control panels up to 50% (environmental)	Difficult to estimate as no FR4 reference. However, life cycle analysis studies show that additive manufacturing (screen printing) of electronic devices involves less process steps than standard subtractive methods, and both material and energy consumption is reduced as well
Include dismantling and recycling strategies at the device's end of life	Limit the number of plastic materials used in the device to facilitate dismantling: devices will be created using a single material (only bio-PC) Discussion related to the recycling: samples were sent to MIREC for evaluation of recyclability and now discussions are on-going with an external partner for the recovery of the Ag inks

Achievements

- Successful design and fabrication of devices made of commercial fossil-based materials and bio-based materials by using additive manufacturing techniques
- LCA-driven design improvements (mono-material) and material substitutions with more sustainable alternatives
- Optimised processing conditions for bio-based materials for all the device fabrication steps: printing, thermoforming and injection
- Successful validation of bio-PC for both films and injection process

Key challenges

- Reliable and precise LCA data gathering both for commercial and sustainable materials was difficult
- Achieve uniform film thickness and thermoformability
- Ensure compatibility of bio-based materials with demanding processing conditions (high temperature thermoforming and injection), automotive thermal and mechanical constraints

- Balance sustainability goals with performance and manufacturability
- For Gen 3, integration of recycling and dismantling strategies

Technology and sustainability readiness levels:

Table 11: Pilot 2.3Technology and sustainability readiness levels

	Gen 2	Gen 3 status
TRL	4	5
SRL	4	5

2.3. Use Case #3 Environmentally compatible single use electronics

Electronics meant for one-time use are a challenging topic, since this can be foreseen to create new sources for e-waste. However, in many diagnostic applications, single-use devices are essential for improving user experience, monitoring capabilities, and response time, as well as maintaining hygiene and safety. Thereby, this use case will integrate pilots compatible with end-of-life management strategies, such as composting, biodegradability and recycling. The four pilots represent innovative new products for diagnostic purposes also from technical perspective. In this sector specifically, new sustainable technologies will offer sustainability benefits, such as no need for separate dedicated readout device when using already available infrastructure of smartphones. This has all the capabilities to replace bulky, expensive, and energy consuming laboratory equipment with digital solutions.

Sustronics integrates four pilots for single-use electronics theme each characterised by miniaturisation, environmental compliance, integration, and multi-functionality.

- Pilot#3.1a In Vitro Diagnostics (IFAT)
- Pilot#3.1b Smart Skin Patch (SIGMA)
- Pilot#3.2 Smart hygiene (ESS)
- Pilot#3.3 Smart wound dressing (IFAG)

2.3.1. Pilot#3.1a In Vitro Diagnostics

Pilot Leader: IFAT (Elisabeth Hengge)
Pilot Goal/Objective :

We are developing a novel solution for at-home metabolic testing that aims to provide environmental superiority over current methods and offer an extended view of the metabolism for at-risk patients (e.g. pregnant women, elderly and patients with metabolic disorders) (Figure 55). Our focus is on using c-peptide and creatinine to develop an easy-to-use disposable point-of-care (PoC) device that connects to a smartphone app for patient biomarker monitoring. Ratio of c-peptide and creatinine levels in urine (UCPCR) provides valuable information on patient's metabolism, e.g. early detection of pre-diabetes. Up to now, only lab-based analysis of urine sample can determine the UCPCR-level. The envisioned final product is a sustainable smart urine cup based on paper that is user friendly and disposable. Within the project, a diagnostic prototype platform is developed based on flexible (paper substrate) and sustainable materials.

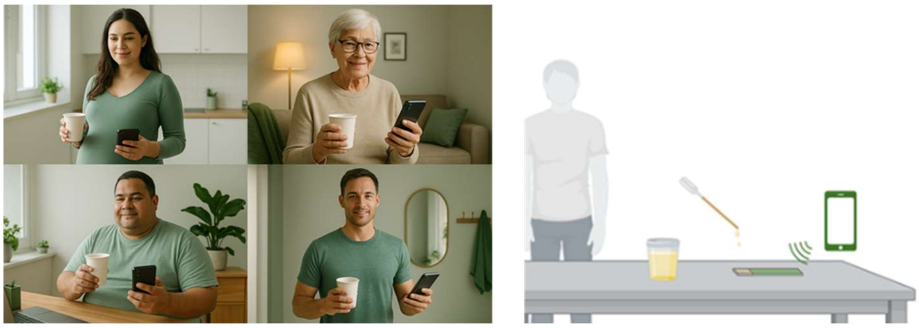


Figure 51: Pilot#3.1a and its context. A PoC device for @home testing of biomarker in urine. A smartphone is used as read out unit, enabled via NFC (Near Field Communication) communication.

Updated Pilot Description for Gen 3:

Due to the constraints of the biochemical assay (e.g. dilution of urine is necessary), integration of the sensor platform in a paper urine cup has proven to not be feasible within the project. Hence, the design of the prototype focused on a sensor cartridge (see Figure 55). In the future, this cartridge can be transformed into a dip stick reducing the bill of materials and increasing user accessibility. Further, if the assay requirements allow it, full integration in a paper cup can be targeted.

For at-home use, a smartphone, the Sustronics sensor platform, a cup to collect the urine as well as a pipette and the “enzyme substrate” in a separate compartment will be needed. The user workflow consists of the following steps (see Figure 56):

- Supercapacitor, which acts a power supply for the sensor, is charged via smartphone
- Urine sample is collected in a cup
- Dilution step is performed with an “exact volume transfer pipette” (1:50)
- Application of urine sample on the LFA (Lateral Flow Assay) sample pad
    - Waiting for 370 s
- Smartphone is placed on sensor which starts the measurement procedure
    - Application of potential -0.4 V for 30 s, current measurement at the end for 100ms
- Application of enzyme substrate (TMB (Tetramethylbenzidine)) – potential off
- Smartphone is placed on sensor which starts the measurement procedure again
    - Application of potential -0.4 V for 200 s. Current measurement: each WE is measured 3 times, each measurement 100 ms (6 WEs), total 3 s
- C-peptide concentration will be calculated in app (expected range: 40-150 ng/mL (normal))

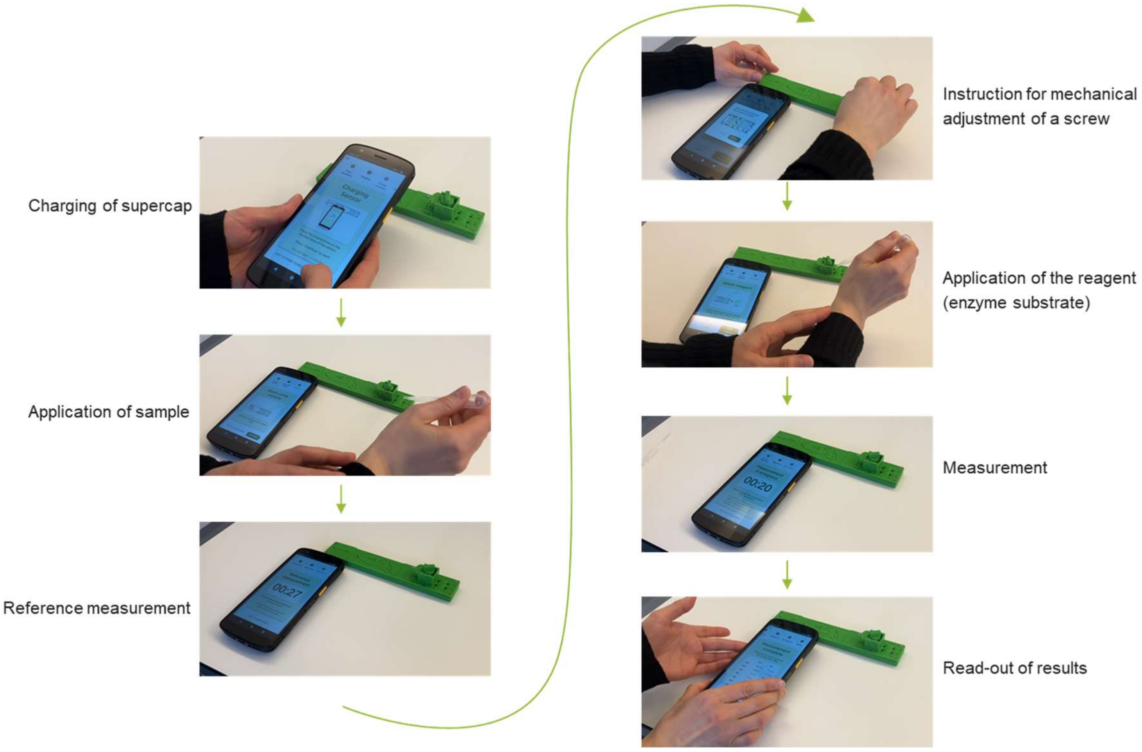


Figure 52: Overview of the user workflow and prototype handling for the P3.1a Gen 3 prototype.

Work Carried Out: Gen 1 and Gen 2 Overview:
Gen 1 was designed as a partial-functional concept prototype to gain basic understanding of the requirements and constraints of such a diagnostic platform. Gen 2 was then completely redesigned and split into two branches, a “sustainable” and a “functional” prototype. This allowed simultaneous work on integration and testing of sustainable materials/components (sustainable prototype) as well as ongoing development of the electrochemical assays (functional prototype). For Gen 3, these prototype versions are combined as far as technological feasible and motivated by the LCA results to obtain a functional and sustainable sensor platform. An updated version of the Gen 2 functional prototype was also used for lab and clinical testing (batch size 65 functional samples) using buffer and real urine samples. Carbon-based electrodes instead of Au, the sustainable supercapacitor and the analytical paper by TER instead of nitrocellulose were integrated. These components were chosen because of their superior technical performance but also increased sustainability.
Figure 57 illustrates the evolution of the development phases of Pilot#3.1a and the materials and components considered. Based on the LCA on both Gen 2 prototypes and their functionality, prioritisation of components for the final demonstrator (Gen 3) was done. Furthermore, the functional prototype of Gen 2 will be used in upcoming clinical tests.

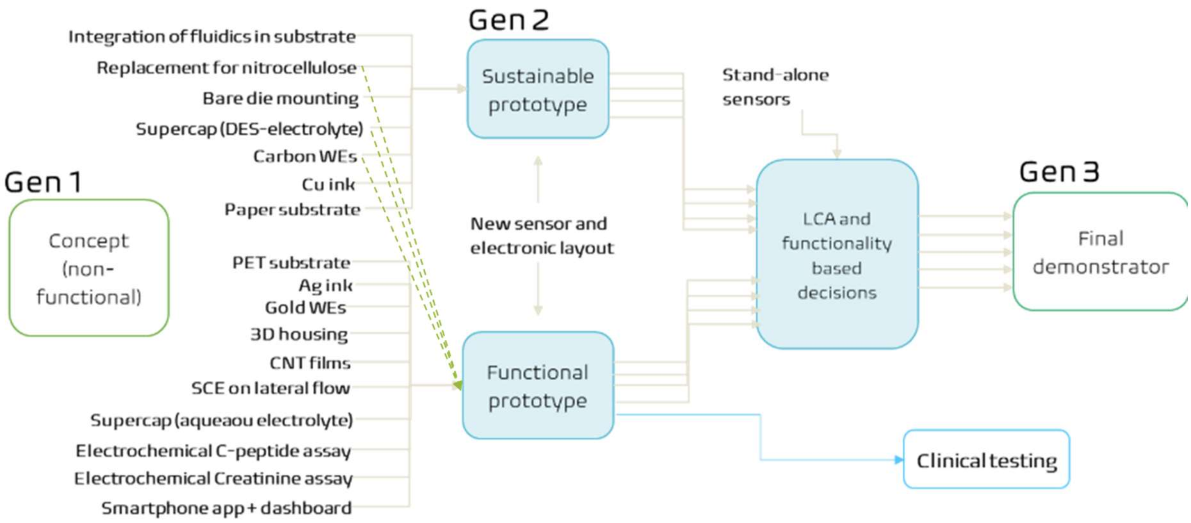


Figure 53: Gen 1/ Gen 2/ Gen 3 development phases of Pilot #3.1a. The dashed green arrows indicate sustainable alternatives already incorporated in the functional prototype for clinical tests due to their superior technical performance.

Technologies involved and role of project partners in Gen 3:

- Microchip and firmware development (IFAT)
- Electrochemical sensor development (CBM, MEDUG, URV)
- Electrode functionalisation and sensor development (CAN, CSEM)
- Sensor and electronic layout design (CSEM, IFAT)
- Electronic circuit printing: antenna, electrodes, interconnects (SCR, VTT)
- Paper substrate development for printing and lateral flow (TER)
- Paper fluidics, component assembly, and hardware integration (VTT)
- Smartphone NFC app development (STS)
- Clinical validation (MEDUG, CBM, URV)
- Power management architecture (CSEM)
- Super capacitors (TAU)
- LCA (FHG)
- Passive devices, microelectrodes and sensor on sustainable substrates (CSIC)

Technical layout and characterisation of Gen 3:

Updated electrical layout for bare-die chip integration (CSEM, IFAT): Gen 3 focused on an updated electrical layout to support bare-die chip integration, including a revised fanout and minor design adaptations based on Gen 2 test results (Figure 58). The elongated strip format was retained to match the two-step biochemical assay workflow and required sample preparation. The NFC antenna concept from Gen 2 was maintained, as prior performance was considered sufficient and no redesign was necessary

Updated supercapacitors: TAU focused on the development of a sustainable printed supercapacitor and advanced it to a Gen 3 design while keeping the same physical dimensions and two-cell layout as Gen 2 to support straightforward integration. The Gen 3 device used graphite current collectors, bio-based activated carbon electrodes, a paper separator, and a deep eutectic solvent (DES) electrolyte, with material updates including a biodegradable substrate (see purple rectangle in Figure 58). Key outcomes included improved average capacitance (118 mF to 133 mF, +13%) and reduced leakage current (22 μA to 17 μA, −23%), indicating better energy storage performance and lower self-discharge. In addition, TAU developed a heat-treatment step for the DES to remove moisture impurities, which helped reduce faradaic leakage current in the final Gen 3 device.

Printing on paper substrate and assembly (SCR, TER, VTT): Gen 3 targeted copper printing on a paper substrate, addressing handling issues observed in preliminary Gen 2 such as wrinkling and bending. Multiple printing strategies were evaluated, and double-sided printing provided the best overall electrical and electrochemical performance. Printing the bare-die fanout required higher resolution than initially available, so third-party mask materials were introduced (see orange rectangle in Figure 58). Prints using Cu-based inks showed trace cracking after curing in the fine structures of the fanout, while coil resistance of the antenna was in an acceptable range. Using Ag-based inks on paper substrate resulted in fully functional samples (small batch).

Full layout housing and 3D printing (CSEM, URV, IFAT): Gen 3 continued the development of a 3D-printed housing to ensure reproducible alignment and contact between the LFD membrane and the electrode array. Several housing iterations were designed and tested across Gen 2 and Gen 3, including full-layout (see Figure 58) and sensor-only variants. While progress was made, achieving consistently reliable functionality remained a key engineering challenge.

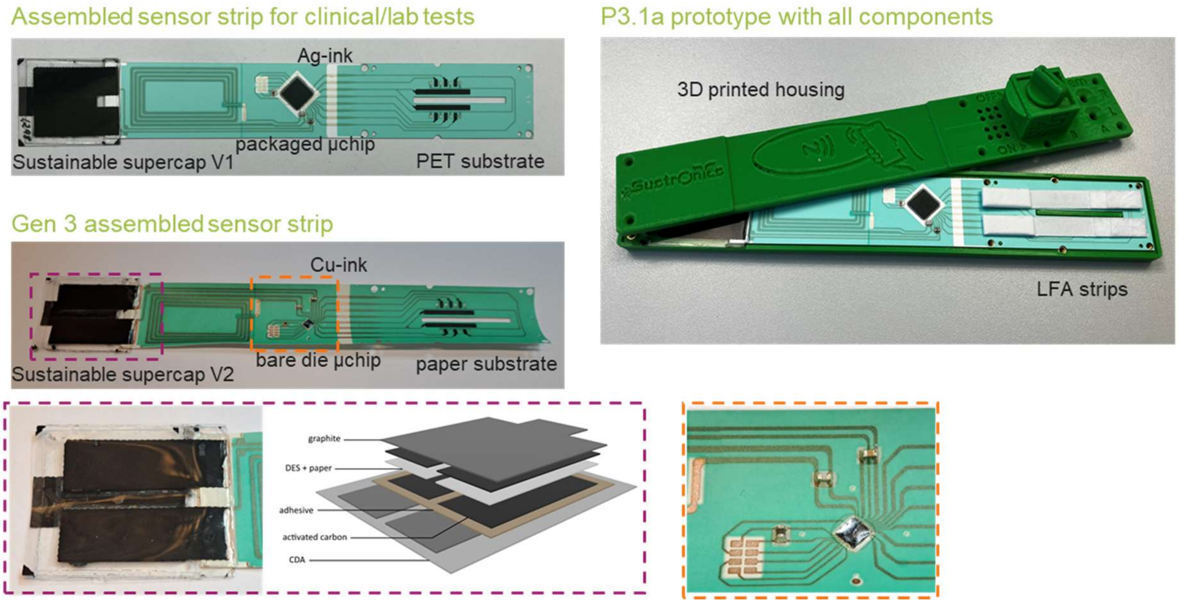


Figure 54: Gen 3 prototypes of Pilot#3.1a including the sensor strip used for the clinical tests.

Mobile app and chip firmware (STS, IFAT): The mobile application and chip firmware were validated within the clinical testing framework, with emphasis on usability and workflow in a laboratory setting. The app was refined through several update cycles based on user feedback from MEDUG testing. The chip firmware was considered stable and did not require changes. Selected screenshots of the app and the dashboard are shown in Figure 55.

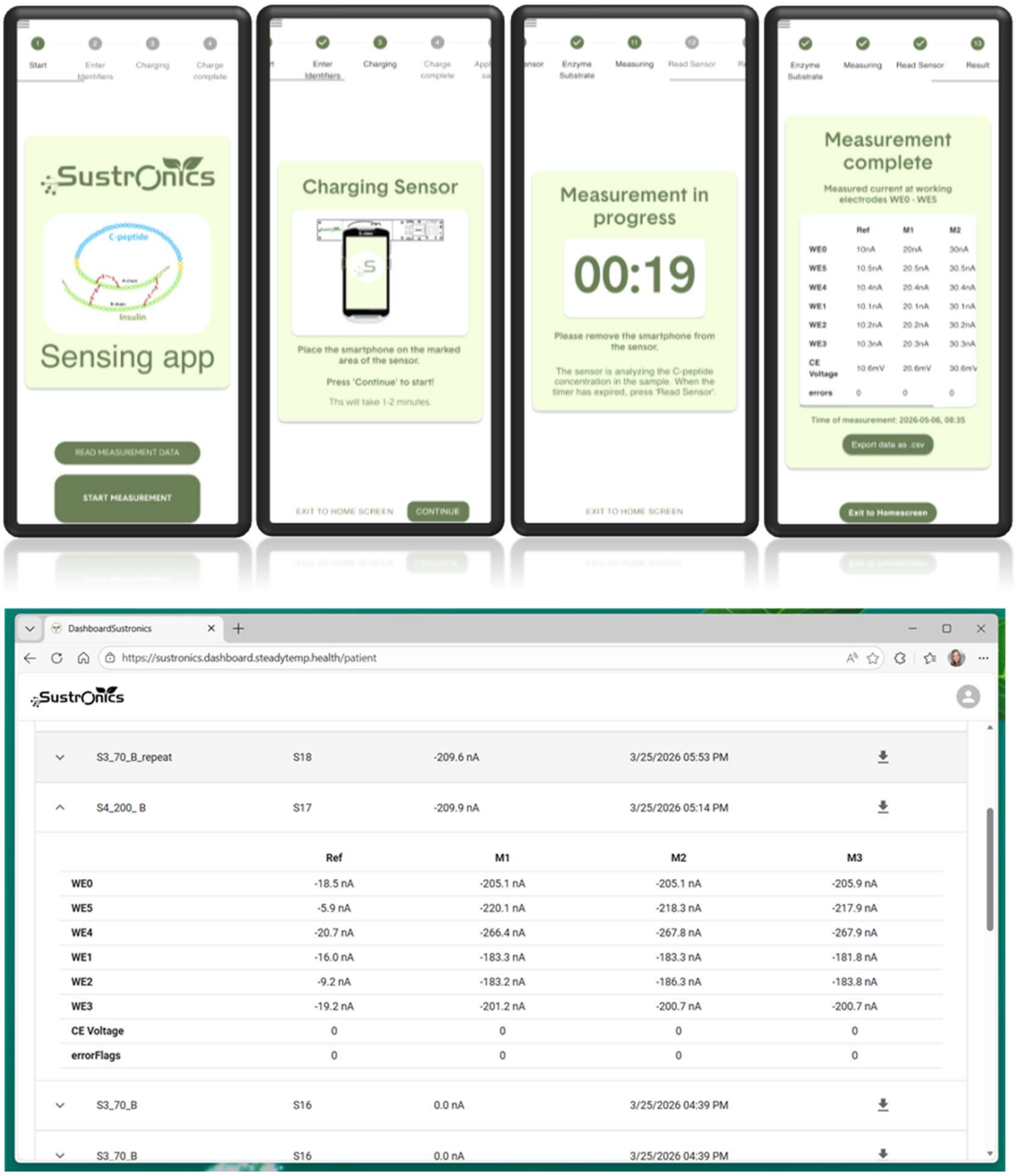


Figure 55: Selected screenshot of the mobile app and dashboard for P3.1a.

Electrochemical assays for c-peptide and creatinine and clinical testing:

URV, MEDUG and CBMED focused on validating and characterizing the electrochemical lateral flow assay (EC-LFA) for C-peptide using the SUSTRONICS cartridge and prototype readout, with emphasis on demonstrating discrimination between clinically relevant concentration levels and understanding measurement variability across the sensor layout. The biochemical assay was implemented as a sandwich-based format with amperometric readout, and performance was assessed both in running buffer and in pooled urine matrices representative of Type 1 diabetes samples. Across the reported experiments, the prototype consistently showed measurable current changes upon target presence and enabled separation between low and elevated C-peptide conditions, while also highlighting electrode-to-electrode differences that inform further design and calibration strategies.

1) Assay characterization in running buffer (prototype + app readout):

Demonstrated amperometric discrimination between 10 and 70 ng/mL C-peptide spiked in running buffer (1× PBS, pH 7.4, 1% BSA) using the fully integrated prototype with mobile app readout. Measurements showed a consistent difference between the left and right working electrodes (WE2 vs WE5), with WE2 yielding a higher response by ~1.39× (without baseline correction) and ~2.3× (after baseline correction), indicating a positional/electrode-dependent response that should be accounted for in interpretation and future calibration.

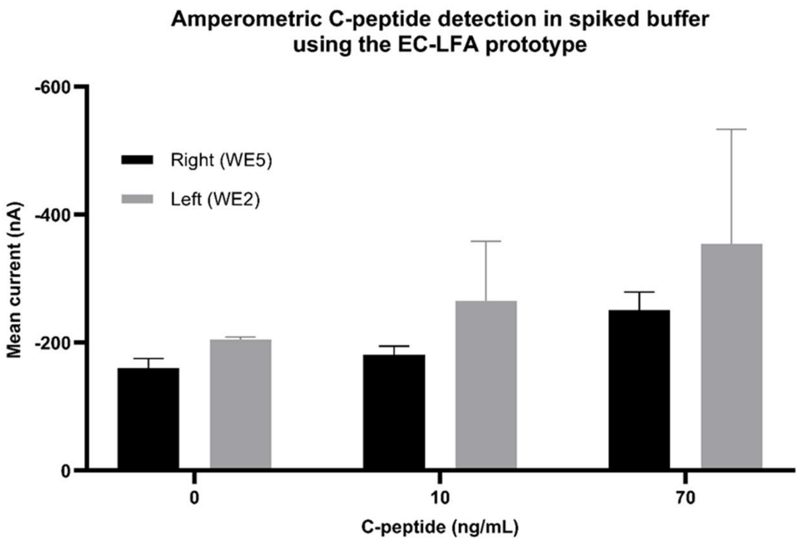


Figure 56: Bar chart showing amperometric detection of C-peptide using a sandwich-based assay with spiked concentrations (0, 10, and 70 ng/mL) in running buffer (1× PBS, pH 7.4, 1% BSA). Measurements were obtained using the electrochemical lateral flow assay (EC-LFA) prototype with integrated mobile app readout. Error bars represent duplicate measurements. Current signals are presented without baseline correction.

2) Calibration and working range:
A calibration curve was generated for spiked C-peptide in running buffer over 2.5–160 ng/mL, resulting in a reported dynamic working range of ~4.75–100 ng/mL under the tested conditions and using sensor-only prints (lab-based readout equipment). The evaluation used a current-increase metric after substrate addition (Δi defined from the change between initial and later time points), supporting a semi-quantitative readout approach suitable for thresholding and trend monitoring.

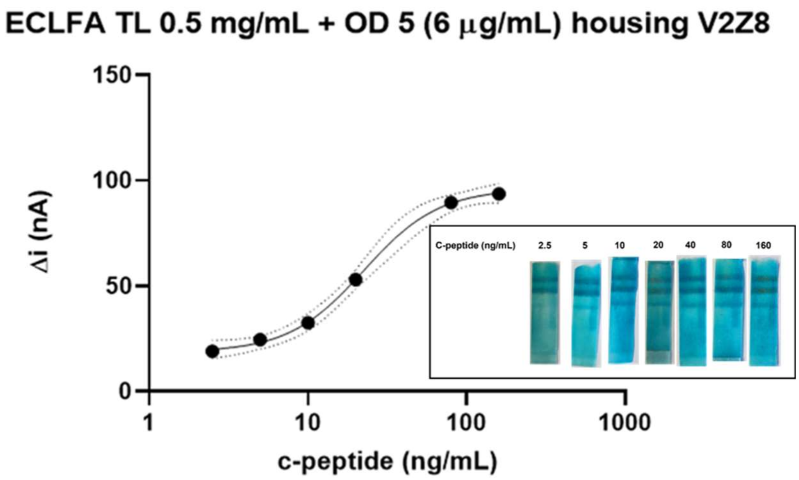


Figure 57: Calibration curve (n=1) of spiked c-peptide in running buffer of the electrochemical lateral flow assay with Gen 2 carbon sensors and version V2Z8 housing. Inset: image of the membranes after the assay.

3) Testing in urine matrix (proof of discrimination in pooled T1D urine)

The analytical performance was further assessed using urine pool samples from patients with Type 1 Diabetes Mellitus (T1DM), spiked with c-peptide at concentrations of zero and 80 ng/mL. A significant difference in Δi upon TMB addition was observed between the two conditions (Table 14), demonstrating the sensor's capability to discriminate between low and elevated c-peptide levels.

Table 12: Electrochemical lateral flow assay using sensor-only prints and housing with spiked c-peptide in pool of urine samples from Type 1 diabetes mellitus patients. (n=2)

Dilution 1/1 , urine/RB

c-peptide (ng/mL)	Mean $I_{0\ (nA)}$	Mean $I_{f\ (nA)}$	mean Δi (nA)	SD Δi (nA)
0	30.7	132	**101.3**	75.9
80	198.5	432	**233.5**	58.7

4) Electrochemical lateral flow assay for detection of creatinine (MEDUG, URV)

Due to its small molecular size, creatinine is not well suited to a sandwich immunoassay format, so a competitive assay was selected for electrochemical detection; in this configuration, the signal trend is inverted and current decreases with increasing analyte concentration. Securing highly selective anti-creatinine antibodies proved to be a major constraint during the project and required extensive screening and verification. Following the identification of a suitable antibody, the assay was optimized by tuning antibody and buffer conditions, and optical testing confirmed functional sensitivity within the target urine concentration range (see Figure 58). Based on the established electrochemical workflow used for C-peptide, the assay is expected to be transferable to an electrochemical readout with comparable implementation steps.

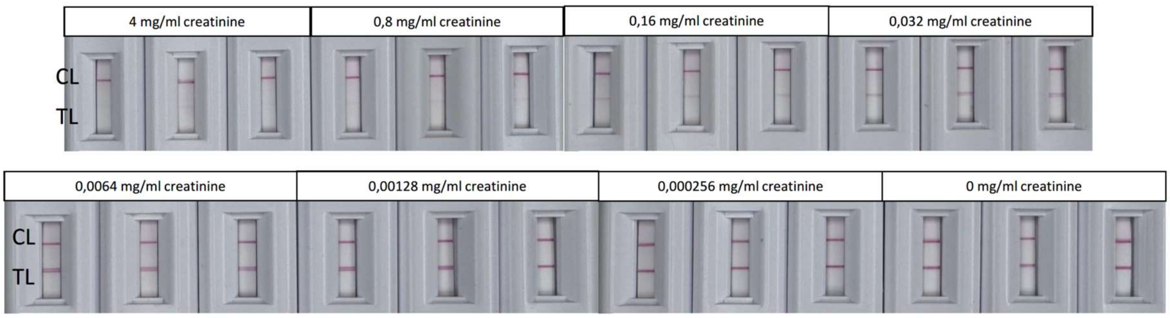


Figure 58: Lateral flow assay for the detection of creatinine

5) Competitive-based C-peptide detection

In collaboration, MEDUG and CBM contributed to the optimisation of a competitive-based C-peptide assay development, including colorimetric (ELISA-based) and optical (LFA) optimisation. Several parameters were evaluated, including nitrocellulose membranes, running buffers, and test line concentration, to establish suitable conditions for competitive C-peptide LFA. Following parameter optimisation, competitive-based LFA detection of C-peptide was performed using running buffer spiked at concentrations ranging from 0 to 1.25 µg/ml. The optimised conditions provide a basis for further evaluation and development of the competitive C-peptide LFA.

Relevance of UCPCR

CBM focused on the relevance of UCPCR as a biomarker for distinguishing between diabetic and non-diabetic individuals and the presence of diurnal variation depending on fasting and non-fasting status. To address these questions, samples from a longitudinal observational study were included in a propensity score-matched cohort to generate comparable diabetic and non-diabetic groups, as well as in a second cohort with sampling over time. In collaboration with MEDUG, gold-standard measurements of serum and urinary C-peptide, insulin, and urinary creatinine were performed in fasting patient samples (n = 62) and in samples collected at defined time points (n = 360). The data analysis confirms that UCPCR is a biomarker for glucose intolerance (for monitoring at risk-patients) but does not perform well in established diabetes under anti-diabetes medication. UCPCR is higher in non-fasting state.

Additional components for prototype integration in paper cup:

For potential later integration of the sensor platform in a smart and sustainable urine cup, alternative/additional components and technologies are essential and have been also addressed with Gen 3:

1) Paper fluidics and float barrier to enable integration of the LFD into the paper substrate (VTT):

The boundaries of the paper fluidic structures were printed onto analytical paper from TER using self-formulated beeswax-based inks (Figure 63-A). The backside of the paper was printed with flexography using un-coloured beeswax ink and the whole surface was covered with the ink. The actual fluidic channel patterns were screen-printed on the frontside of the paper with coloured beeswax ink. Fluidic channel patterns were successfully printed with well-defined edges onto the paper substrate. The printed layers had good and even coverage. Coloured water flowed quickly along the channel and no background staining outside of the channel area was seen.

2) Integration of printed electrodes on LFD membrane (CSIC):

CSIC has developed an approach to integrate electrochemical sensors directly into lateral flow diagnostic tests by screen-printing them onto the nitrocellulose membrane used in paper-based assays.

Conventional electrochemical detection methods require the separate fabrication of screen-printed sensors and additional steps to attach them to the paper test strip. The new integrated approach eliminates these extra steps by embedding the sensors directly into the test strip, thereby simplifying the manufacturing process (Figure 59 -B). Key advantages include improved sensor–biorecognition element contact, reduced risk of poor alignment or weak connections, enhanced reliability and reproducibility of results, and the potential for lower-cost and more scalable production.

3) Carbon-nanotube based sensors for detection of c-peptide (CAN):

CAN focused on the development of a semi-quantitative electrochemical biosensor based on carbon nanotube (CNT) sensors for urinary C-peptide detection, targeting a clinically relevant range of 0–300 ng/mL (see Figure 59 C). The work included establishing the assay concept on the CNT platform, functionalizing the sensor surface, and optimizing the measurement approach to enable reliable C-peptide readout. Sensor performance was evaluated in pooled Type 1 diabetic urine using representative C-peptide concentrations to demonstrate suitability for real sample matrices. A short-term storage study also indicated stable sensor sensitivity after room-temperature storage, supporting practical handling and use.

4) Additional electrochemical sensors via electrode functionalization (CSEM):

Functionalization of printed electrodes were achieved by applying selective membrane coatings to enable electrochemical detection of pH, potassium (K+), and sodium (Na+) on the Gen 3 cartridge platform (Figure 59D). The work included preparing multiple sensors sets across different printing configurations and evaluating their response characteristics to verify suitability for integration. The results demonstrated good reproducibility and an extended linear range, supporting reliable measurements across relevant concentration ranges for Na+ and acceptable reproducibility for K+.

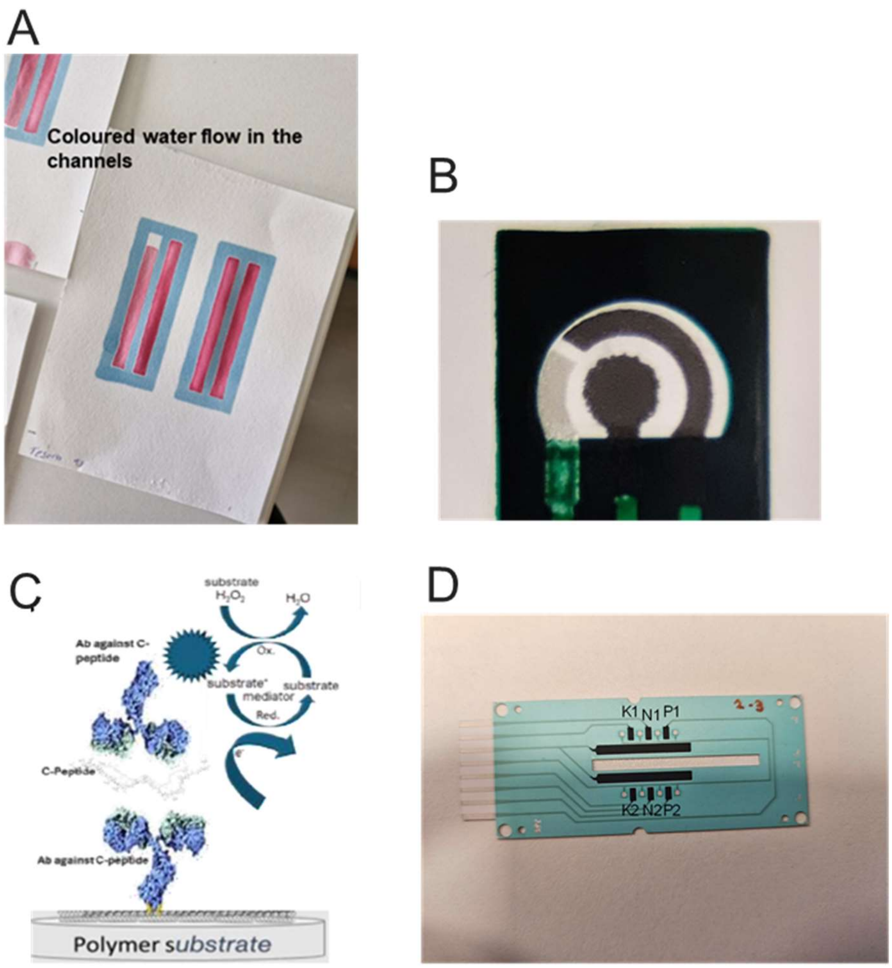


Figure 59: Additional components for prototype integration in paper cup.

Sustainability & social targets and their status in Gen 3:

The Life Cycle Assessment (LCA) compares the functional prototype (Gen 2) with the sustainable prototype (Gen 3) by updating the production model to reflect the main Gen 3 design changes while keeping the rest of the life-cycle modelling consistent. In Gen 3, copper-based ink is used instead of silver ink, the ASIC is integrated as a bare die via flip-chip bonding directly on paper, and the supercapacitor is redesigned to be more compact, reducing material use; these modifications are explicitly represented in the manufacturing inventory. Other life-cycle phases are modelled in the same way for Gen 2 and Gen 3, with only minor adjustments for differences in weight and material composition, so that differences in results mainly reflect the prototype design updates. The climate-change comparison shows that the largest reduction comes from the silver-to-copper ink replacement, while substrate replacement, the smaller supercapacitor, and bare-die mounting provide additional smaller reductions; overall, a ~30% reduction in manufacturing-related climate-change impact for Gen 3 versus Gen 2 is achieved and a reduction of over 90% in mineral use. Detailed results are presented in Deliverable 4.6,

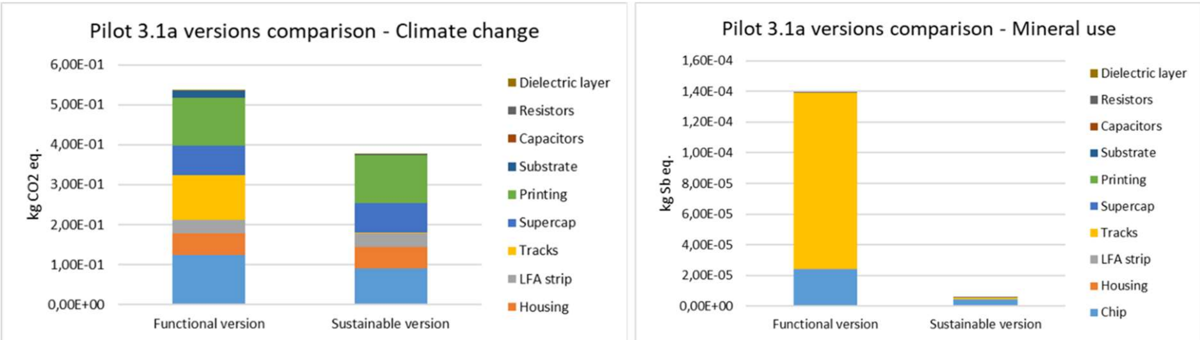


Figure 60: LCA for P3.1a including the climate change impact in kgCO2 and mineral use. Functional version (Gen2) is compared to the sustainable version (Gen3).

The handprint analysis reports the positive climate benefit achieved by moving to the sustainable SUSTRONICS device and its beneficial environmental impacts that reduce the footprints of others, evaluated through a global warming potential comparison across the defined scenarios (with impacts broken down by device parts and energy-related contributions). The reference scenarios are hospital tests, meaning patients travel back-and-forth to the hospital (reference 1) and home test and shipment of samples to the hospital/lab (scenario 2). Figure 65 shows the climate change impact for all scenarios including the functional and sustainable P3.1a prototypes. The Sustronics prototype provides clear benefits over reference 1 by avoiding transportation. Due to manufacturing contribution, the environmental performance of reference 2 remains slightly better. However, it is to be considered that reference 2 is an unlikely scenario and that the Sustronics solution remains the faster and more convenient (user-friendly) way to monitor urinary biomarker at-home.

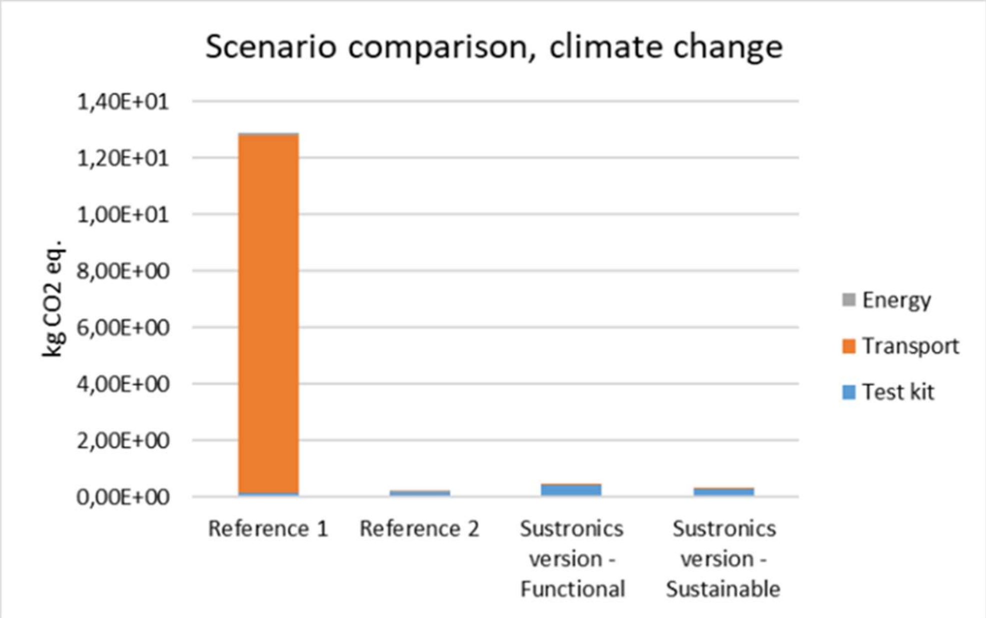


Figure 61: Handprint analysis of P3.1a.

End user engagement:

The UCPCR method was actively presented at multiple medical congresses across Europe (e.g., Berlin, Munich, Münster, Innsbruck, Salzburg, Graz, Girona), reaching key end-user groups including general practitioners, paediatricians, diabetologists, osteologists, dietitians, lab technicians, and journalists.

- **Level of interest:** Follow-up questions and requests after the talks indicate strong interest in the test. However, substantial additional awareness-raising and educational materials are needed to clearly communicate the clinical relevance and use cases of the UCPCR system to physicians (e.g., GPs, paediatricians).
- **Sustainability considerations:** Given the expected high volume of consumables per user and the general aversion some users have toward urine-based handling, single-use components are considered important. Clear labelling and guidance are required, including explicit instructions towards the sustainability of Pilot 3.1a.
- **Key barriers and usability requirements:** Main hurdles include reimbursement pathways (insurance coverage), formal recognition as a diagnostic tool (requiring broad clinical studies), and comparative measurement evidence. End-users expect high usability: a straightforward workflow, simple handling, easy-to-understand results, and clear instructions on next steps.

Pilot Achievements & key challenges in Gen 3:

Achievements

KPIs (pilot specific):

- Quantitative measurements of multiple analytes:
  Electrochemical assay for detection of c-peptide established and tested in spiked buffer and urinary samples. Detection of creatinine via lateral flow assay shown optically.
- Increased absolute and relative current measurement sensitivity: not applicable as sensors are newly developed. However, electrochemical signal performance was increased from Gen 2 to Gen 3.

- Duration of analysis <= 20 min: Overall duration of Gen 3 workflow for the user is roughly 15 min.
- Reduction of the required energy supply component by >50%: During measurement current consumption of the µchip was reduced by 50% and during wait time reduced by 30 %.
- Reduction in use of plastic materials: Paper substrate used instead of PET.

KPIs (project objectives):

- Number of integrated devices > 50: For lab-validation and clinical testing, 65 fully integrated and fully functional samples were prepared
- Number of external stakeholders involved: see end user engagement
- Manufacturing process yield >95%: Sample batch for clinical testing had a yield of 93%.

Key challenges

- Bare die fanout printing: Achieving the desired resolution and printing quality has proven to be challenging with screen-printing.
- Printing on paper: Printing on paper substrate caused the paper to bend which could be mitigated by double sided printing. Also, resistance of the conductive traces was very high when printing Cu on paper. Exchanging Ag with Cu is highly beneficial for the climate change impact, whereby using paper instead of PET only brings minor benefits. Hence, Cu-inks printed on PET could be a reliable alternative.
- Biochemical assay: Optimizing the sensitivity of the assay towards the relevant concentration range in urine and interfering matrix effect were the largest obstacles. Further improvement of the assay will be needed.
- Complex user workflow: Due to the complexity of the urine matrix and the assay, the user has to follow multiple steps which might be too demanding for a final product. Optimization of the assays and workflow would be needed.
- Measurement reproducibility of fully integrated prototypes: The currently implemented approach relies on mechanical fixation of the LFD strip on the printed electrode Ensuring a reproducible force induced via the 3D printed housing remains challenging.
-

Table 13: Pilot 3.1 Technology and sustainability readiness levels:

Technology and sustainability readiness levels:

	Gen 2	**Gen 3 final**
TRL	3/4	4
SRL	3	4

2.3.2. Pilot#3.1b Smart Skin Patch

Pilot Leader: ONA (Alfredo Ongaro) supported by SIGMA (Jacqueline Gómez)
Pilot Goal/Objective :

The Pilot 3.1b project aims to develop a platform that addresses the need for better diabetes management, more sustainably (Figure 63).

Figure 62: . Pilot 3.1b concept. Green leaf highlights the component developed/in development during the Sustronics Project

Diabetes poses not only a major global health challenge, affecting 1 in 10 people worldwide and causing 1.6 million deaths in 2021, but also a significant environmental burden. Diabetes management, particularly through continuous glucose monitoring (CGM) and finger-prick tests, generates substantial electronic and plastic waste. Annually, over 1.3 billion glucose test strips are used, contributing to the over 21 billion single-use items disposed of, with 80% of this device waste ending up in landfills. In addition, CGMs alone account for nearly 90% of electronic waste in this context. The environmental footprint of diabetes care is further exacerbated by emissions from travel, insulin supply chains, and healthcare energy use, adding up to 2.7 billion tons of greenhouse gases annually, with diabetes care alone responsible for 2–3% of global healthcare emissions. In response, an innovative and more sustainable solution is proposed: a Smart Skin Patch that continuously monitors glucose through sweat.

Effective diabetes management heavily relies on monitoring blood glucose levels to adjust medication, diet, and lifestyle accordingly. Currently, various solutions are available in the market (Figure 63). Traditional methods involve invasive techniques, such as finger-prick tests which can be painful, inconvenient, and may discourage regular monitoring. Finger-prick tests not only have poor practicability due to their invasive nature but also contribute to environmental waste. Each test requires a durable hardware device, a single-use test strip, and a lancet, with diabetic patients needing to test themselves 2 to 8 times a day. CGM devices are both invasive and generate significant environmental waste. CGMs, despite their advanced technology, have a short lifespan and consist of multi-material and complex disposable components.

Pilot 3.1b approach eliminates the need for single-use strips and sensors, thus reducing material waste while offering additional health insights through multi-parameter monitoring and lifestyle integration.

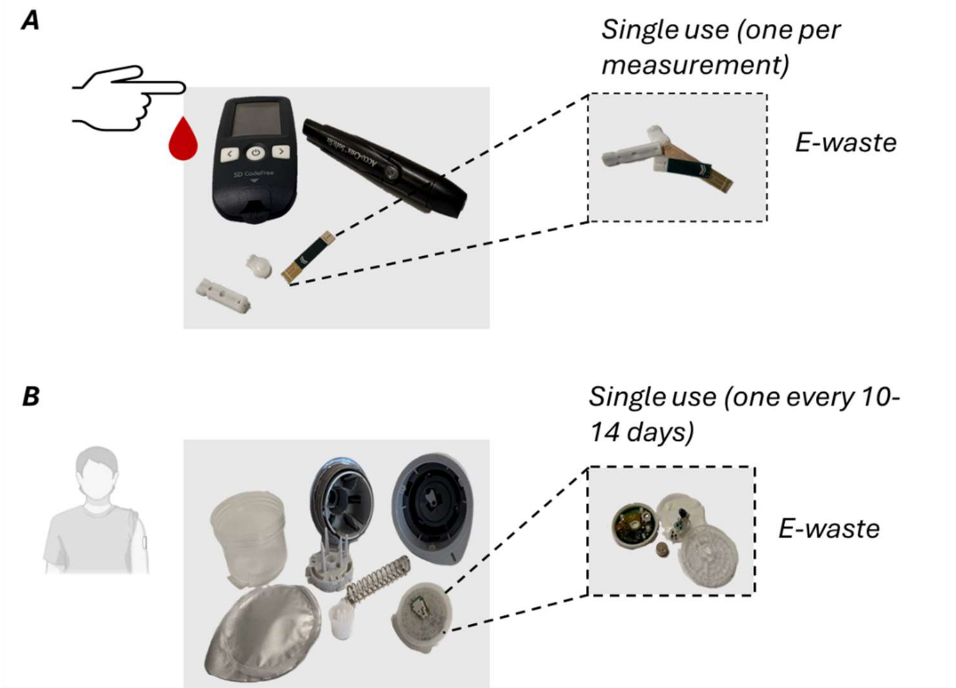


Figure 63. State of the Art glucose monitoring solutions: A) example of a traditional blood glucose monitoring device. It requires finger pricks and single-use test strips and lancets for each measurement; B) Example of a continuous glucose monitor (CGMs). It relies on disposable electronic sensors replaced every 10–14 days.

Updated Pilot Description for Gen 3

Building on the two parallel development tracks established in Gen 2; Gen 2a (electrochemical glucose sensing) and Gen 2b (optical diffuse-reflectance sensing), Gen 3 consolidates the most promising approach into a validated, integrated system. In light of the technical challenges encountered with the electrochemical route (salt-induced signal inhibition and hydrogel-mediated dilution effects), the Gen 3 architecture is centred on the optical detection platform (Gen 2b lineage), now fully coupled with an upgraded AI data platform and expanded in-vivo validation. This generation also completes the cradle-to-grave Life Cycle Assessment (LCA) of the device, incorporating results from D4.6 (Deliverable on LCA and Handprint Study).

Key advances with respect to D3.3 (Gen 2 description) include:

- Improved analytical and clinical performance of the optical sensor (MARD reduced from 17.28% to 12.44%).
- Expanded in-vivo validation cohort, now exceeding 1,831 paired data points including Type 2 diabetic subjects.
- Continuous sweat glucose monitoring at 1-minute sampling frequency, validated against CGM devices.
- Multimodal data integration: sweat glucose correlated with pulse rate, systolic/diastolic pressure, temperature, and CGM reference data.
- Time-In-Range (TIR) and Glucose Management Indicator (GMI) metrics computed from sweat data and benchmarked against CGM.
- Personalized AI-driven lifestyle recommendations validated for fidelity (3.5/5) and relevance (4.81/5).
- Completed cradle-to-grave LCA (D4.6) demonstrating a reduction of approximately 28 g CO_2eq per patch unit compared to the Gen 2 electrode-based design.
- Presentation of key results at the 19th ATTD International Conference on Advanced Technologies & Treatments for Diabetes (11–14 March 2026, Barcelona, Spain).

Technical Layout and Characterisation of Gen 3

Gen 3 System Architecture

The Gen 3 device retains the three-part architecture of Gen 2b: a disposable sweat-sampling patch (consumable), a reusable wristband, and a reusable optical reader (DM). The core sensing principle diffuse reflectance spectroscopy through sweat accumulated in a microfluidic chamber, is unchanged. The Gen 3 iteration focuses on system integration, extended in-vivo validation, and AI platform maturation.

The optical reader employs a multi-wavelength light source (developed at ONA) acting as a reflectance spectrophotometer. Glucose-dependent changes in reflected light intensity are processed by the on-device firmware and transmitted via Bluetooth Low Energy (BLE) to the mobile application, to the cloud, where the AI platform converts raw signals into blood glucose estimates and personalised recommendations.

A significant improvement in power management was achieved in Gen 3. The battery life of the reusable DM reader has been extended from approximately 24 hours in Gen 2 to one full week of continuous operation, under a 1-minute periodic measurement duty cycle. This 7× increase in autonomy was achieved through firmware-level optimisation of the measurement and transmission routines, including aggressive low-power sleep states between sampling events and duty-cycling of the LED illumination source. The extended battery life substantially reduces charging interruptions during daily use and supports uninterrupted multi-day monitoring periods, a prerequisite for clinically meaningful Time in Range and Glucose Management Indicator calculations.

In-vivo validation was extended to a cohort including Type 2 diabetic (T2D) subjects, in addition to healthy volunteers and subjects from earlier generations. Sweat glucose was sampled continuously at 1-minute frequency and compared with reference blood glucose measurements (SD CodeFree glucometer) and, in a subset of subjects, with a reference Continuous Glucose Monitor (CGM). The key performance metrics achieved in Gen 3 are summarised in Table 14.

Table 14 Analytical performance comparison between Gen 2b (D3.3) and Gen 3. MARD = Mean Absolute Relative Difference; MAE = Mean Absolute Error; CCC = Lin's Concordance Correlation Coefficient

Performance Metric	Gen 2b (D3.3)	Gen 3 (D3.4)
Mean Absolute Relative Difference (MARD)	17.28%	12.44%
Mean Absolute Error (MAE)	22.68 mg/dL (RMSE)	17.58 mg/dL
Pearson Correlation (r)	0.711 (CCC)	0.86
Paired data points (n)	>1,831	>1,831
Consensus Error Grid – Zone A	Most readings	Most readings

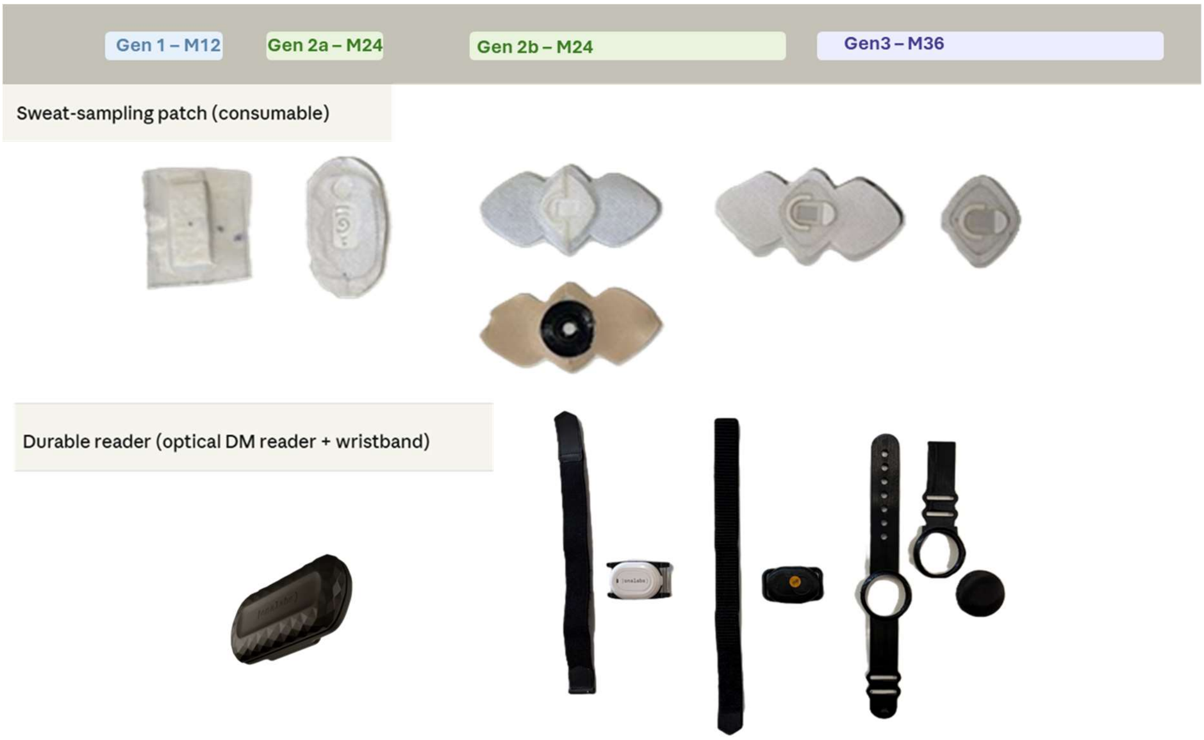


Figure 64 Consumable and Durable development. A journey through Generations

Continuous Monitoring and CGM Benchmarking

A key advancement in Gen 3 is the demonstration of continuous sweat glucose monitoring at a 1-minute sampling frequency over multi-day periods in real life. In a subset of diabetic volunteers and healthy subjects equipped with both the ONA sweat sensor and a reference CGM device, the following aggregate metrics were observed:

- Time in Range (TIR): Sweat sensor = 77%, CGM reference = 79% (within 2 percentage points).
- Glucose Management Indicator (GMI): Sweat sensor = 7.19%, CGM reference = 6.83%.
- Visual overlay of continuous sweat glucose (arbitrary units) versus blood glucose (mg/dL) trajectories demonstrated strong temporal concordance, capturing meal-related excursions and nocturnal patterns.

These results represent the first demonstration within the Sustronics project of CGM-level continuous glucose tracking from sweat, suggesting the clinical relevance of the platform for long-term, painless diabetes management.

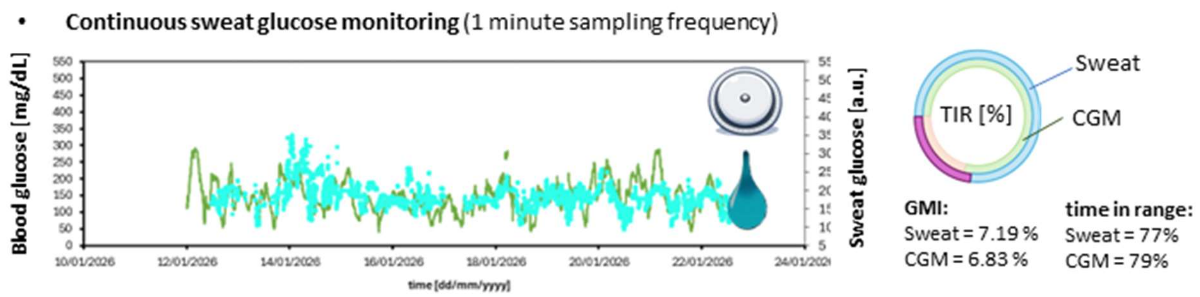


Figure 65 Continuous sweat glucose measurement and comparison with CGM

Multimodal Data Integration

In Gen 3, the cloud platform was extended to incorporate multimodal physiological signals alongside sweat glucose. The following parameters are simultaneously acquired and fused within the personalised recommendation engine:

- Sweat glucose (optical sensor, 1-min sampling)
- Pulse rate
- Systolic and diastolic blood pressure
- Skin temperature

This multimodal integration enables richer patient profiling and might enhance context-aware recommendations, allowing the AI to distinguish between glucose variations attributable to physical activity, diet, or physiological state.

Software: Gen 3 App and Cloud Platform

The mobile application underwent a substantial redesign in Gen 3, both in terms of its backend integration and its user-facing interface. Two major advances distinguish the Gen 3 software from the Gen 2 version described in D3.3.

Automatic Session-Based AI Recommendations via the Cloud Platform

In Gen 3, the AI recommendation engine has been integrated with the cloud platform, enabling fully automated delivery of personalised lifestyle suggestions. Previously, recommendations were generated on demand. In Gen 3, the workflow is triggered automatically: every time a user session ends and a new session begins, the system retrieves the session's glucose trajectory and multimodal physiological data, runs the patient characterisation and blood glucose prediction models.

The cloud platform handles data storage, user identity management, session orchestration, and the asynchronous triggering of the AI inference pipeline, providing a scalable and interoperable cloud backbone for multi-user clinical deployments.

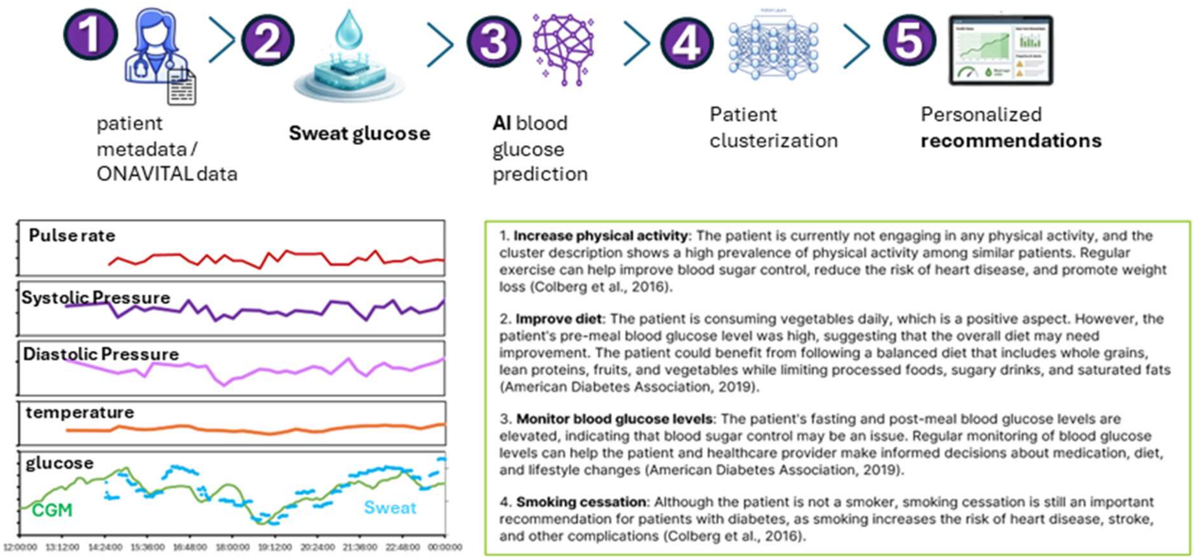


Figure 66 Multimodal Dataflow and AI personalized Recommendations

Updated App Interface and Integrated Health Metrics

The Gen 3 application introduces a redesigned home screen that consolidates continuous sweat glucose monitoring with a broader set of physiological and computed wellness metrics into a single, user-friendly view. This multimodal dashboard replaces the minimal pairing/measurement interface of Gen 2 and is intended to give the user an at-a-glance overview of their current metabolic condition. The metrics displayed are described below.

Sweat Glucose. The primary reading shown on the app home screen is the real-time sweat glucose value derived from the optical sweat sensor. Expressed in sweat glucose units (sgu), it is calculated within the algorithms embedded in the firmware current sweat optical. A continuous time-series graph of the active session is displayed alongside the numerical value, allowing the user to track glucose trends during physical activity, meals, or rest.

AI Platform, Gen 3 Performance

The AI data platform, developed by SIGMA, was further refined in Gen 3. The Retrieval-Augmented Generation (RAG)-based Diabetes Care Recommender was evaluated on a panel of expert reviewers against the 2025 ADA clinical guidelines, yielding:

- Recommendation Fidelity: 3.5 / 5 (alignment with clinical guidelines)
- Recommendation Relevance: 4.81 / 5 (pertinence to individual patient profile)

The patient clustering model (trained on a large public dataset) assigns each patient to a metabolic risk group based on clinical questionnaire data (BMI, blood glucose history, physical activity level, dietary habits). The blood glucose predictor, trained on >1,831 paired sweat–blood glucose data points and augmented with conditional Generative Adversarial Network (cGAN) synthetic data, demonstrated consistent improvement in prediction accuracy relative to Gen 2.

Sustainability Targets and Their Status in Gen 3

Life Cycle Assessment: Updated Results (D4.6)

A full cradle-to-grave LCA of Pilot 3.1b was conducted by Fraunhofer IZM (FHG) using Sphera LCA for Experts with the Sphera and Ecoinvent 3.9.1 databases, applying the EF 3.1 methodology (EF3.1 midpoint indicators). Results are reported in Deliverable D4.6. The functional unit is defined as one month of continuous sweat glucose monitoring (approximately 120 patch changes at 4-hour patch lifetime).

Baseline: Gen 3 (Optical Detection)

The Gen 3 LCA baseline corresponds to the optical detection architecture (DM reader + disposable sweat patch without printed electrodes). For a full month of use, the DM reader electronics constitute the dominant environmental contributor in most impact categories, reflecting the electronics-intensity of the reusable durable unit. The disposable patch accounts for approximately 30% of total impacts in most categories (exceptions: land use and water use, dominated by patch materials; mineral resource use, dominated by DM reader electronics).

Within the disposable patch unit, the rigid nylon aligner is the primary material contributor, followed by the salt-impregnated sweat-collection layer (modelled as polyester nonwoven).

Generations Comparison: Gen 2 Electrode-Based vs. Gen 3 Visual Detection

A direct comparison of the disposable patch unit between Gen 2 (electrode-based, copper-ink screen-printed sensors) and Gen 3 (visual detection, no printed electrodes) was performed for climate change (GWP), mineral resource use, and ecotoxicity impact categories. The elimination of the printed copper electrode layer in Gen 3 produces significant improvements:

- Climate change (GWP): Reduction of approximately 28 g CO_2eq per patch unit, equivalent to >3 kg CO_2eq per month of use.
- Mineral resource use: Substantial reduction driven by the elimination of copper ink (and its associated mining/processing burden), resulting in a decrease of approximately 80% in patch-level mineral resource impact.
- Ecotoxicity: Comparable magnitude of reduction, driven by the absence of metallic conductive inks.

These results confirm that the transition from electrochemical to optical detection not only resolves the technical challenges of the Gen 2a pathway (salt inhibition, hydrogel dilution) but also delivers substantial environmental co-benefits.

End-of-Life Strategy

Since sweat is a non-biohazardous analyte, the disposable patch is expected to enter the municipal solid waste (MSW) stream and be incinerated. The reusable DM reader is assumed to follow the WEEE pathway. Proposed end-of-life improvements for future generations include:

- Material separation for recyclability (rigid nylon aligner, optical window in recycled PMMA).
- Design for disassembly enabling mechanical component recovery.
- User-level disposal guidance aligned with current medical and e-waste regulations.

Table 15 Technology and Sustainability Readiness Levels for Pilot 3.1b.

	Gen 2 (D3.3)	Gen 3 (D3.4)	Gen 3 Objective
TRL	4	5	5
SRL	4	5	6

End User Engagement

The Pilot 3.1b results were presented at the 19th International Conference on Advanced Technologies & Treatments for Diabetes (ATTD 2026), held 11–14 March 2026 in Barcelona, Spain. The submission, titled "Sweat as Digital Biomarker for Non-Invasive and Continuous Glucose Monitoring", was presented as a poster by Ricardo Heredia, Fernando Espinoza, Jaime Punter-Villagrasa, Andrea Fajardo, Mario Gomez-Barea, Albert Alvarez, Xavier Muñoz-Pascual, and Alfredo E. Ongaro (Sigma Cognition / ONA).

The poster demonstrated the integrated system performance (MARD = 12.44%, r = 0.86, TIR alignment with CGM, multimodal data integration) and the AI platform capabilities (personalised recommendations aligned with 2025 ADA guidelines) to an international clinical and technical audience. Feedback from clinicians and diabetes care specialists confirmed the strong clinical relevance of the approach and the interest of the diabetes community in non-invasive continuous monitoring solutions.

Furthermore, the device was evaluated through comprehensive in vivo testing with a diverse group of volunteers representing both healthy individuals and those living with diabetes. Specifically. These participants assessed the device across multiple dimensions, rating its design, intuitiveness, ease of use, intrusiveness, hygiene, and speed. Their feedback and real-world usage data were instrumental in validating the system's analytical and clinical performance, confirming its strong potential for non-invasive continuous glucose monitoring in both clinical and everyday settings.

Participants rated the sweat-based glucose monitoring device across six usability dimensions on a standardized scale. All metrics scored above 5.5, indicating strong overall user acceptance. Intrusiveness achieved the highest rating (5.80), demonstrating that users found the device minimally invasive and comfortable for continuous wear. Hygiene (5.77) and Speed (5.60) also scored particularly well. Design (5.57), Intuitiveness (5.55), and Ease of use (5.53) received positive ratings, though slightly lower, suggesting minor opportunities for interface refinement. These results confirm strong user acceptance across all critical dimensions for wearable medical device adoption.

Pilot Achievements and Key Challenges in Gen 3

Achievements

- Optical glucose sensor validated in-vivo with >1,831 paired data points (MARD = 12.44%, MAE = 17.58 mg/dL, r = 0.86).
- Continuous sweat glucose monitoring demonstrated at 1-minute sampling frequency over multi-day periods.
- TIR from sweat sensor (77%) aligned with CGM reference (79%) in T2D subjects (N = 7).
- GMI from sweat sensor (7.19%) aligned with CGM reference (6.83%).
- Multimodal data integration (sweat glucose, CGM, pulse rate, blood pressure, temperature) implemented in Cloud platform.
- AI recommendation system evaluated: fidelity 3.5/5, relevance 4.81/5, against 2025 ADA guidelines.
- Implementation of sustainable inks (copper, graphite) in Gen 2a electrochemical sensor validated as green alternative.
- LCA (D4.6) completed cradle-to-grave: Gen 3 optical design reduces patch GWP by ~28 g CO_2eq/unit vs Gen 2 electrode-based design.
- ATTD 2026 poster presentation validated by international diabetes community.
- App (Android, Flutter) and BLE connectivity developed and operational; redesigned Gen 3 interface integrates estimated glucose (eGu), Metabolic State, Time in Range, Glucose Management Indicator, Glucose Stability, and remaining patch session duration into a unified user dashboard.
- Automatic session-based AI lifestyle recommendations implemented via the cloud platform: at every session end–start transition, personalised guidance is generated and delivered to the user without manual intervention.
- Battery life of the reusable DM reader extended from 24 hours (Gen 2) to one full week of continuous operation at a 1-minute measurement periodicity, enabling uninterrupted multi-day monitoring without recharging.

Consolidated Milestones, KPIs, TRL and SRL by Component and Generation

The table below consolidates the milestone achievements, performance KPIs, Technology Readiness Level (TRL) and Sustainability Readiness Level (SRL) for all five component groups of Pilot 3.1b across the three development generations. Work Package (WP) assignments are included for cross-reference with other Sustronics deliverables. Cells highlighted in orange indicate items where a sustainability statement is pending confirmation from SIGMA; please provide the relevant content for those placeholders.

TRL scale: 1=basic principles observed → 9=proven in operational environment. SRL scale: 1=basic sustainability requirements observed → 9=sustainable system proven in operational environment. SRL 5=validated in relevant environment; SRL 6=demonstrated in relevant environment (Gen 3 objective).

Table 16 . Consolidated milestones, KPIs, TRL and SRL for Pilot 3.1b by component and generation.

Components	Gen 1 Milestones	TRL/SRL	Gen 2 Milestones	TRL/SRL	Gen 3 Milestones	TRL/SRL
A. Sweat-sampling patch (consumable) — ONA (Gen1-2-3) / CSIC (Gen 1/2a)						
Microfluidic substrate & sweat collection	Layered sweat-collection substrate designed using renewable materials	TRL 3/ SRL 2	Salt inhibition issue identified; agarose-based hydrogel developed as passive sweat sampler; in-vitro and in-vivo proof of concept with conductivity sensor	TRL 4/ SRL 3	Optical patch: no screen-printed electrodes; nylon rigid aligner + sweat-metering layers integrated;	TRL 5/ SRL 5
Electrochemical glucose sensor (Gen 2a)	Screen-printed Ag/AgCl enzymatic sensor on PET; 1st prototype fabricated; calibration initiated	TRL 3/ SRL 2	Graphite & copper inks validated as Ag/AgCl alternatives; calibration R^2=0.82; in-vitro performance confirmed; salt-induced signal loss ~50% identified	TRL 4/ SRL 4	Paused — superseded by optical route. development continues as secondary track only.	TRL 4/ SRL 4
Optical glucose sensor (Gen 2b / Gen 3)	Not applicable	—	Diffuse reflectance spectroscopy system built; multi LED (R/G/IR); linear calibration R^2=0.82; first in-vivo cohort (10 healthy + 1 T1D + 1 T2D); MARD=17.28%, CCC=0.711; Consensus Error Grid Zone A	TRL 4/ SRL 3	Extended cohort; MARD=12.44%, MAE=17.58 mg/dL, r=0.86; TIR sweat=77% vs CGM=79%; GMI sweat=7.19% vs CGM=6.83%	TRL 5/ SRL 5
Sustainable electrode inks & LCA (patch)	Silver-based inks baseline; cradle-to-gate LCA: electrodes = 60–90% of impact; patch GWP = 0.149 kg CO_2e	TRL 3/ SRL 3	Copper & graphite inks validated — equivalent electrochemical performance; significant reduction in GWP, ADPe, FAETP vs Ag inks; cradle-to-gate LCA updated with Fraunhofer (WP4)	TRL 4/ SRL 4	No screen-printed electrodes in Gen 3 optical patch: ~28 g CO_2e saved per unit vs Gen 2 electrode design; >3 kg CO_2e/month reduction; ~80% drop in mineral resource use;	TRL 5/ SRL 5

B. Durable optical reader & wristband (ONA)						
PCB, optical housing & wristband	PCB designed; energy consumption characterised; ECG sensor included;	TRL 3/ SRL 2	Functional optical reader prototype (multi-λ LED + photodetector); BLE PCB operational; wristband in TPU; 3D-printed PLA housing; BLE pairing with app confirmed	TRL 4/ SRL 3	Full system integration; recycled PMMA optical window; modularity: disposable patch + reusable reader separable for end-of-life routing (MSW vs WEEE)	TRL 5/ SRL 5
Battery & power management	Energy consumption characterised; power budget defined for sensor and BLE	TRL 3/ SRL 2	~24 h battery life demonstrated at operational duty cycle	TRL 4/ SRL 3	Battery life extended to 1 week at 1-minute periodic measurement (7x improvement); achieved through firmware-level duty-cycling of LEDs and BLE transmission; eliminates daily recharging interruptions	TRL 5/ SRL 5
C. Bluetooth connectivity (BLE) ONA						
BLE communication stack	Not applicable — connectivity not yet implemented	—	BLE stack developed; secure encrypted health-data transmission from reader to Android app; permissions for location & BLE configured	TRL 4/ SRL 3	BLE operational in production; session end/start handshake triggers AI inference pipeline in cloud; low-power BLE duty-cycling contributes to 1-week battery life	TRL 5/ SRL 5
Sustainability — BLE & connectivity	Not assessed	—	BLE chosen over Wi-Fi specifically to minimise power draw and avoid always-on radio; local encrypted storage reduces cloud data transfer	SRL 3	BLE duty-cycling directly enables 1-week battery autonomy, reducing charging frequency and associated energy consumption; low-power radio protocol aligned with eco-design objectives of WP4	SRL 5
D. Mobile application (Android / Flutter) ONA						
App framework & architecture	Not applicable	—	Flutter (cross-platform) framework; hexagonal architecture; GitHub version control; Android 10–14 support; BLE pairing; local encrypted storage (flutter_secure_storage)	TRL 4/ SRL 3	Redesigned Gen 3 UI	TRL 5/ SRL 5
Cloud integration	Not applicable	—	Cloud data pipeline architected; data storage and user identity management defined	TRL 3/ SRL 2	Cloud platform operational: session orchestration,	TRL 5/ SRL 5

Sustainability — App & cloud	Not assessed	—	App uses local encrypted storage to minimise data transfers; BLE-only connectivity limits radio energy; no always-on cloud polling	SRL 2	Offline-first, BLE-only architecture with local encrypted storage and session-based cloud sync minimises data-transfer energy. GDPR-compliant anonymisation minimises data retention.	SRL 5
E. AI data platform (SIGMA)						
Patient characterisation model	6 public datasets related to diabetes identified & analysed; model architecture selected; synthetic data strategy defined	TRL 2/ SRL 1	Model trained on large public dataset; patient risk-group clustering operational; questionnaire-based inference validated	TRL 4/ SRL 3	Multimodal inputs: sweat glucose + volunteers Metadata	TRL 5/ SRL 5
Blood glucose predictor	Architecture defined; first synthetic dataset generated via public data analysis	TRL 2/ SRL 1	cGAN synthetic data augmentation; n>1,831 real paired sweat/blood glucose points; first model trained and validated; MARD=17.28%, CCC=0.711	TRL 4/ SRL 3	Continuous 1-min inference; MARD=12.44%, MAE=17.58 mg/dL, r=0.86;	TRL 5/ SRL 5
RAG recommendation engine	Not applicable — architecture only defined	—	RAG system built; aligned with 2025 ADA guidelines; personalised recommendations generated for each patient profile; clinician dashboard demo (clinical overview, patient profile, recommendations tabs)	TRL 4/ SRL 3	Automatic session-based delivery via Cloud; recommendation fidelity=3.5/5; relevance=4.81/5;	TRL 5/ SRL 5
Sustainability — AI platform	Not assessed	—	cGAN synthetic data generation reduces need for resource-intensive clinical data collection; model compression considered to minimise inference compute	SRL 2	Inference energy (CodeCarbon v2.x, WP2): 0.00207 kgCO_2e per query. GPTQ 4-bit quantization reduces GPU compute by ~75%. Benchmark vs GPT-5 (Univ. Rhode Island 2025): 51% lower emissions, 76% lower energy per query. Self-hosted deployment on renewable-energy cloud	SRL 5

					eliminates grid and network overhead.	

Exploitation of Results:

ONALABS will pursue the commercialization of its Generation 3 (Gen 3) technology by initially entering the consumer electronics sector as a wellness device, enabling faster market access while building user adoption and data validation. In parallel, the company will continue technological development and actively seek support from the European Innovation Council (EIC) to advance toward Software-as-a-Service (SaaS) medical certification, specifically targeting the validation of algorithms that convert sweat glucose measurements into blood glucose estimations.

The algorithmic component will be leased from Sigma, ensuring robust data processing capabilities while maintaining flexibility for future integration. Furthermore, cost-efficiency and sustainability improvements achieved in Generation 2a (Gen 2a) will be leveraged, incorporating knowledge and results obtained in collaboration with CSIC into the consumable components of ONALABS' product, ONASPORT.

From a dissemination and validation perspective, early-stage results have already led to one published scientific paper, with additional work accepted and presented at relevant conferences, reinforcing the scientific credibility of the approach.

Finally, ONALABS has secured intellectual property protection through the patenting of its combined optical and patch-based measurement system, establishing a strong foundation for competitive advantage and future market expansion.

2.3.3. Pilot#3.2 Smart hygiene

Pilot Leader: ESS (Shabira Abbas and Tilak Lakshmana)
Pilot Goal/Objective:

This pilot introduces an innovative single-use sensor label designed for incontinence products, aimed at enhancing patient comfort and optimising healthcare efficiency. The label integrates advanced sensors to monitor temperature, humidity, enzyme activity, and also pH for refined enzyme response analysis.

The thin and flexible sensor label connects to a reusable wearable device that wirelessly transmits the collected sensor data to the cloud or local storage via a base station or mobile phone. Leveraging AI-driven analytics, the system interprets the data and delivers actionable insights via a user-friendly smartphone application. The concept is illustrated in Figure 67.

Figure 67. Illustration of the complete P3.2 Smart Hygiene system.

This prototype represents the SmartCare Change Indicator — a sustainable digital health technology solution. By attaching sensor labels directly to absorbent products, the sensor system notifies caregivers when a product change should be considered, promoting timely care and reducing unnecessary product usage.

Updated Pilot Description for Gen 3:

Two alternative architectural designs, called A and B, have been explored across all three generations of the sensor label system. The main differences between these two designs lies in how the sensors on the sensor label are read out and how the sensor label connects to the transmitter:

- Design A – Wired connection: This version features a sensor label that is physically connected, via a flexible flat cable connector, to the transmitter that also houses the sensor readout electronics.
- Design B – Wireless connection via NFC: This version introduces a fully wireless interface between the sensor label and the transmitter, utilising NFC for both data transmission and power delivery. The passive, or battery-less, sensor label includes an ASIC for readout of the sensors and a printed antenna coil for wireless data transmission and power harvesting via NFC.

Most effort has been put on design A as it has been identified as the most commercially viable option, due to lower complexity, lower cost and better sustainability. For design A, Gen 2A has been carried forward as Gen 3A with further improvements of performance and sustainability. For design B, the sensor label design from Gen 2B has been reused for Gen 3B and efforts have mostly focused on firmware development and sensor readout. Components used in Gen 2A/3A and 3B are shown below in Figure 68 and Figure 69, respectively.

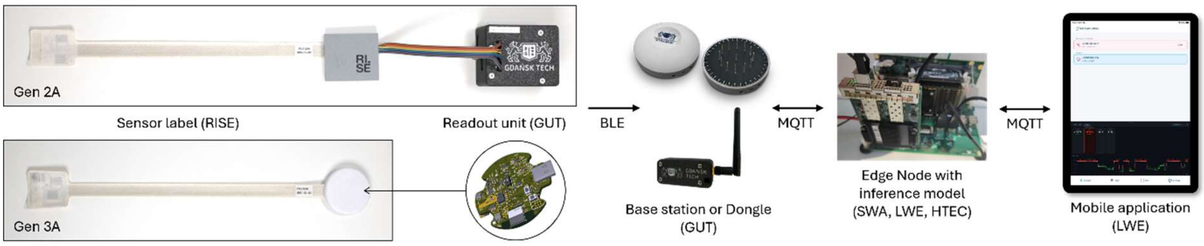


Figure 68. Data flow in Pilot 3.2 Gen 2A and 3A.

The data flow through the system in Design A (Gen 2A and 3A) is shown in Figure 68. The printed sensor label is attached to the incontinence product and connected to the readout unit using a flexible flat cable connector. The sensor values are read out and transmitted over BLE to a dongle or base station that acts as a gateway, forwarding the sensor data to the edge node within the nursing/care home. The edge node runs the inference model that produces the result, informing if there is a need to change the incontinence product or not. The graph on the dashboard (in engineering mode) shows the plot for the chosen sensor. This dashboard seamlessly displays the results for both Design A and B.

The system in Design B (Gen 2B/3B) is shown in Figure 69. The sensor label is powered using the energy from an NFC reader unit, in this case an NFC-enabled smartphone. The sensors are read out by the ASIC integrated on the sensor label, which then are transferred to the smartphone and further relayed to the edge node. The data then flows through the rest of the chain similarly to Design A. In a realistic use scenario, the smartphone would be replaced with a small and wearable readout unit, just as in Design A. It was decided not to develop such a customized reader within the project, but instead prioritize a reader for Design A.

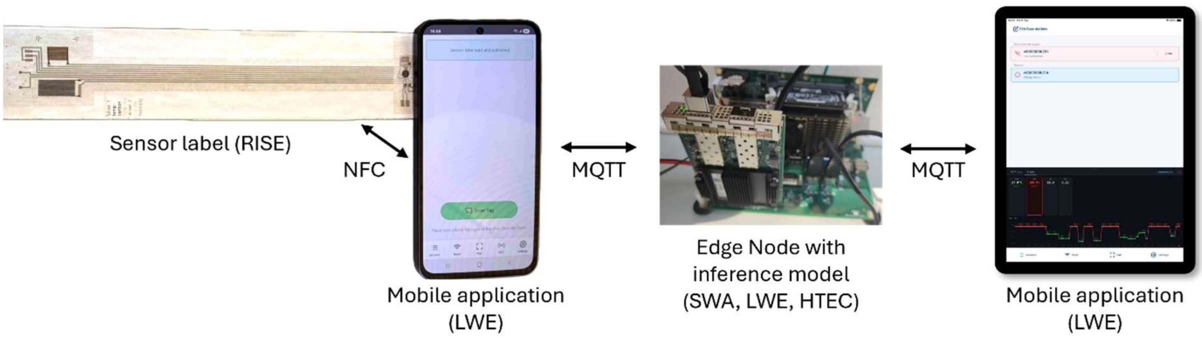


Figure 69. Data flow in Pilot 3.2 Gen 3B.

Work Carried Out: Gen 2 and Gen 3 Overview:

LCA analysis

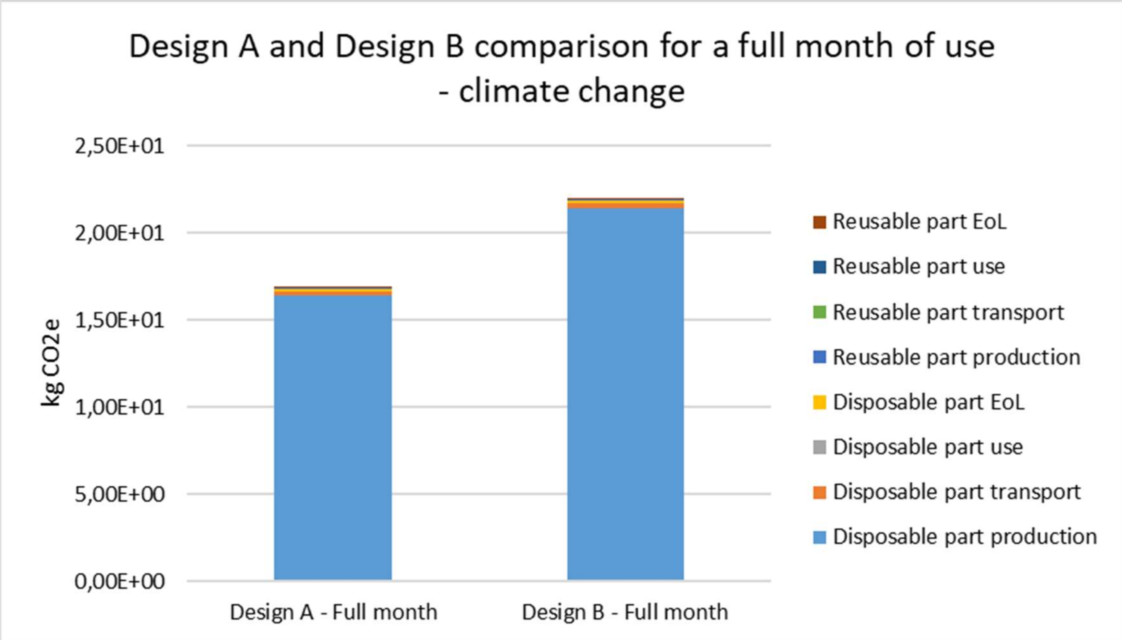


Figure 70. Comparison of LCA results for Design A and B by FHG.

LCA analysis shows that the kg of CO2e is comparable between these design approaches (see Figure 70). Design A produces lower footprint compared to Design B. The sensor label in Design B is passive meaning that it does not include any energy storage device, such as a supercapacitor. Thus, the chip on the sensor label is powered by the NFC reader in the transmitter unit. It can be noted in the above Figure 70, that the carbon footprint is dominated by contribution from the manufacturing of the single-use sensor labels.

Technologies involved and role of project partners in Gen 3:

The roadmap and actions leading to the development of Gen 2 and 3 were successfully executed across several key areas, including:

- Subsystem Design
- Sensor Label Development and Manufacturing
- Data Handling and Processing
- Testing of Gen 2 and Gen 3 Prototypes
- Sustainability and Life Cycle Assessment
- Comprehensive Reporting

Each of these components contributed to the overall success of the pilot. The contributions from all partners involved are detailed in Table 17.

Table 17. Partners involved in Pilot 3.2 and their contributions.

ACC	pH sensors
BEN	Upscaled manufacturing of Design A sensor labels by roll-to-roll screen printing
CSEM	Electronic design and pH sensors
ESS	Leading this pilot and testing of prototypes in mannequin and water bath
FHG	Life cycle assessment across generations
IFAT	Microchip (ASIC) and associated firmware for Design B
GUT	Readout electronics for Design A; base station and related firmware. Data visualization mid-way in the data flow

HTEC	Data handling, inference model
LWE	Mobile application for both iOS and Android, Edge node configuration, Cloud Platform for push notifications, user management and sensor calibration
RISE	Sensor label design and manufacturing on sheet, temperature and humidity sensors and inks, printed electrodes for enzyme sensor, assembly of components and membranes, environmental testing of sensor labels
SWA	Implementation of edge node
TER	Supplying paper substrate in sheet and roll format
UGOT	Two electrode trypsin enzyme sensors for simplified readout
UPM	Application of adhesive and release liner
VTT	R2R component assembly at proof-of-concept level

Technical layout and characterisation of Gen 3:

Trypsin enzyme sensor

A sensing gel formulation composed of porous silicon dioxide particles, a conducting polymer, and an electrolyte, was designed by UGOT specifically for the detection of the enzyme trypsin that is present in faecal. This gel is applied to a two-electrode system, initially consisting of a gold working electrode and a silver/silver chloride reference electrode. The number of electrodes in the sensor have been reduced from three to two, which significantly reduces the complexity of the readout electronics and its associated firmware. The enzyme sensors are integrated in the sensor labels as assembled sticker components with backside contacts. Optionally, the sensor electrodes could potentially be printed directly on the sensor label. In both cases, the sensors use screen-printed carbon working electrodes and silver/silver chloride reference electrodes that were developed and prepared by RISE. Monolithic integration with printed electrodes directly on the sensor label could have several advantages in decreasing the number of process steps and reducing material usage. The developed enzyme sensor response addresses the technical requirement that the enzyme can be detected within 1 minute.

Temperature sensor

The fully screen-printed resistive temperature sensors from RISE that were used in Gen 1 and Gen 2 were also used in Gen 3. The metal content in the sensing layer was further reduced, making the sensors even more sustainable and increasing the sensor resistance, which simplifies readout and improves the robustness of the sensor. The temperature sensor has a very linear response within the prioritised range from 15 to 40 °C, with a positive temperature coefficient of 0.24%/K, and the response time is within seconds. Since the change in resistance with temperature is smaller than the variation in the resistance of the printed temperature sensors, the temperature sensors require individual calibration. However, a one-point calibration is sufficient, making the calibration procedure fast and simple.

Humidity sensor

The sensor label includes a fully screen-printed capacitive humidity sensor from RISE. The sensor includes carbon interdigitated electrodes and a lignin-based sensing layer, making the component highly sustainable. A water vapour permeable membrane from ESS is attached on top of the sensor using a transfer adhesive from UPM that completes the device. No changes were made in the sensor for Gen 3 compared to Gen 2. The sensors allow for measurement of relative humidity (RH) in the targeted range from 30% RH to 100% RH, and the response time is just a few seconds, meeting the requirements set by the use case. The sensors allow for batch calibration. The sensors have a slight temperature dependence, so the temperature sensor value is therefore used in the calculation of the humidity.

pH sensor

ACC contributed Gen 2 SMD-style potentiometric pH sensor stickers for continuous pH monitoring to the pilot. The sensing system consists of two separate sticker components: a pH electrode sticker and a reference electrode sticker. The sensors are manufactured on flexible polymer substrates using screen printing and other additive fabrication processes.

The pH sensor stickers from ACC are based on a modular sensor concept designed for integration into different application environments. This approach allows the sensor function to be added to a target substrate via dedicated contact pads. The sensor stickers are mechanically attached and electrically contacted to the sensor label by applying pressure.

The potentiometric response of the pH sensor was characterised by ACC in pH step tests by sequential transfer into buffer solutions with different pH values. The sensors showed a linear response in the range from pH 3 to pH 8, with an approximate slope of -50 mV/pH. After assembly onto the paper sensor labels, additional 24-hour tests confirmed adhesion to the label substrate and continued signal output over time, confirming capability for continuous pH monitoring. A microscopy image of assembled components and electrical characteristics for the pH sensor are shown in Figure 71.

The pH sticker components were selected as the main approach in the pilot. As a potential alternative integration route, RISE and CSEM have explored fully screen-printed pH sensors for monolithic integration into the sensor label. This approach offers the potential advantage of reduced material usage by eliminating the need for separately assembled pH sensor components. In parallel, the modular SMD-style sensor sticker approach offers specific advantages for multiparameter sensing systems, including independent sensor manufacturing, pre-characterisation, transferability across different substrate layouts via dedicated contact pads. This is particularly relevant when different sensor types require different material systems, processing, functionalisation or curing conditions. By manufacturing the sensor elements separately from the final substrate, the SMD sticker concept can reduce the risk of cross-interference between different sensor manufacturing steps and enables functional sensor components to be selected before integration. This can improve substrate area utilisation during sensor manufacturing and may reduce material losses associated with integrating non-functional sensor elements into final systems.

Both the SMD-style sensor sticker approach and the directly printed sensor approach therefore represent relevant routes for integrating pH sensing into smart hygiene sensor labels, with the final choice depending on manufacturing strategy, integration requirements, performance and sustainability assessment.

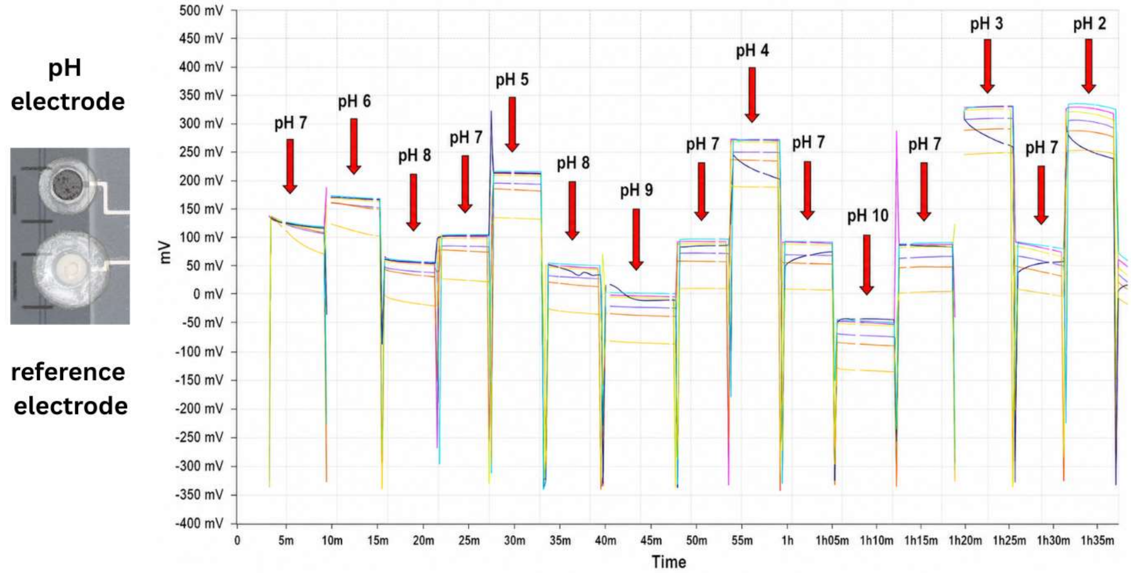


Figure 71. ACC Gen 2 SMD-style pH sensor stickers for the smart hygiene pilot. Left: pH and reference electrode sticker components on the test substrate. Right: representative pH step test showing the sensor response during sequential transfer into buffer solutions with different pH values (n=8).

Sensor labels

Layout and processes for manufacturing of the sensor labels of both design A and B were developed by RISE. A paper from TER was selected as substrate. An adhesive coating and a release liner was applied to the backside of the paper by UPM. The adhesive was selected to give appropriate adhesion for attachment of the final sensor labels to the targeted hygiene products from ESS. Using a paper with precoated adhesive as substrate also simplified the handling of the substrate during the manufacturing, i.e. during printing and conversion. This was especially helpful in the R2R manufacturing, where the substrate is under tension, since the stack also provided additional strength to the substrate.

The layout for screen printing of the Gen 3A sensor labels, having a wired connection to the readout electronics, is shown in Figure72a. The layout includes four different variants of the sensor labels, each having either six or seven printed layers. A photo of a fully printed sheet with Gen 3A sensor labels is shown in Figure72b. In all variants, the temperature and humidity sensors are printed directly on the paper substrate. The pH and enzyme sensors are either integrated as assembled sticker components or as directly printed components on the paper. The latter alternative requires one additional screen-printed layer and functionalisation steps for the sensor surfaces. This approach may allow for reducing separate component assembly steps and material use associated with additional sensor carrier components. However, a comparative sustainability assessment would also need to consider manufacturing yield, substrate area utilisation, process losses and the rejection of non-functional sensor elements during system integration. In this context, assembled SMD-style sensor stickers can also offer sustainability-related advantages. The sensor stickers can be manufactured in dense sheet-level layouts, supporting efficient substrate utilisation and parallel production. In addition, functional sensor components can be pre-characterised and selected before integration into the final sensor label, which may reduce material losses associated with integrating non-functional sensor elements into complete demonstrators or products.

The pH and enzyme sensor components are manually assembled on the sensor label after completed printing. Layers of semipermeable and permeable membranes, and absorbent materials, all from ESS, are thereafter laminated on top of the label using transfer adhesive from UPM. A plastic stiffener is also attached to the contact tab to make it compatible with the flexible flat cable connector on the readout unit. The sensor label is thereafter cut to its final shape. Photos of the sensor label after component assembly and a completed sensor label are shown in Figure 73.

For Gen 3B, the sensor label with wireless sensor readout and communication via NFC, no changes were made to the sensor label layout compared to Gen 2B. The sensor label includes an ASIC from IFAT that allows for sensor readout and NFC communication. The ASIC as a bare die and capacitors as SMD components were assembled on the sensor label using pick-and-place and anisotropic conductive adhesive. Enzyme and pH components from UGOT and ACC, respectively, were assembled by hand. A Gen 3B sensor label after completed component assembly is shown in Figure 74.

(a) (b)

Figure 72. Gen 3A of the smart hygiene sensor label. (a) Layout for screen printing. (b) Photo of a screen-printed sheet with six sensor labels.

(a)

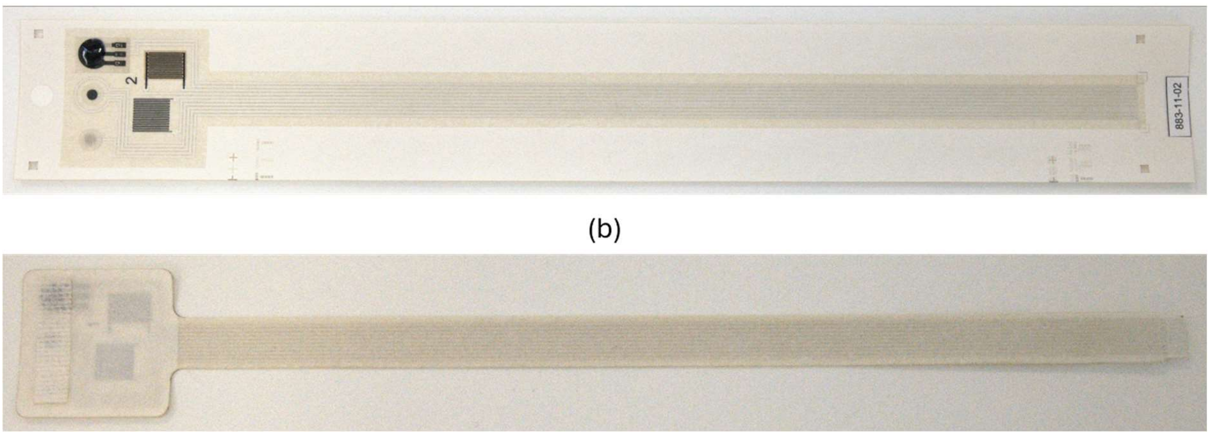


Figure 73. (a) Gen 3A sensor label with assembled pH and enzyme sensor components. (b) A completed Gen 3A sensor label with laminated membrane layers.

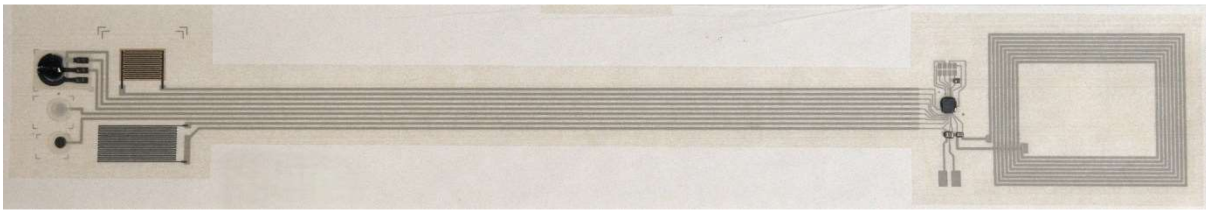


Figure 74. Gen 3B sensor label with assembled ASIC, pH and enzyme sensor components.

Special attention was given to the assembly of the pH sensor sticker components from ACC to the printed paper sensor label, since this part of the sensor label will be exposed to liquids during use, which poses certain technical challenges. After assembly of the components onto the paper labels (see Figure 75), 24-hour tests were performed to assess adhesion to the label substrate and the ability of the sensors to continue providing signals over time. These tests confirmed the feasibility of integrating the pH sensor sticker components into the smart hygiene label concept.

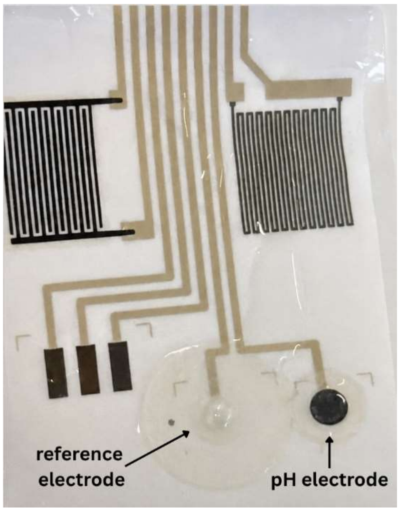


Figure 75. ACC SMD sensor sticker on Sensor Label.

Scaled-up manufacturing by R2R screen printing and assembly

BEN has acted as the scale-up partner for the manufacturing of the sensor label developed at RISE. The company has provided expertise in screen printing, converting, lamination and die-cutting, enabling the transition from prototype development to scalable production. Using printable substrates supplied by TER and functional ink from RISE, BEN has produced sensor labels on a two-station flatbed screen-printing machine (see Figure 76). The manufacturing process consists of six printed layers of functional inks, applied in a R2R compatible workflow. As a result, fully functional sensor labels have been produced with the required precision and quality. The delivered printed electronics components are suitable for component assembly and system integration.

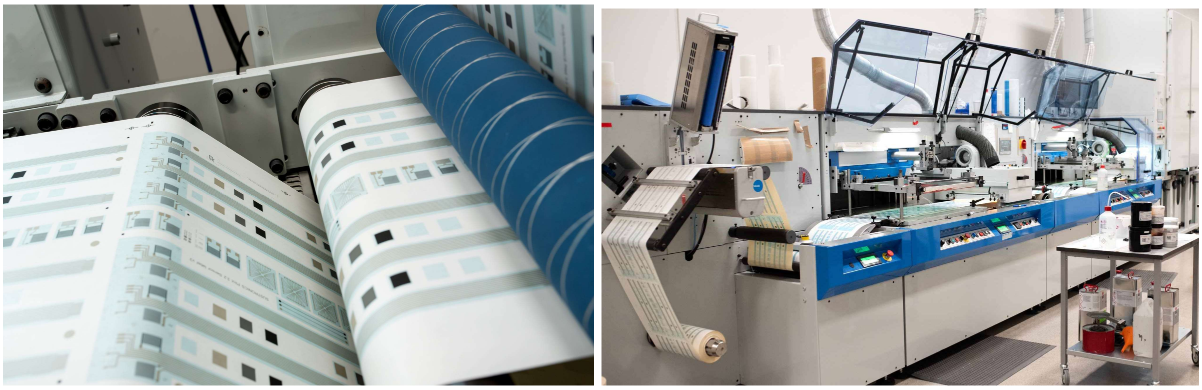


Figure 76. R2R flatbed screen printing of sensor labels at BEN

A proof-of-concept demonstration of R2R component assembly was done using a converting line at VTT that is shown in Figure 77. It is based on a Delta ModTech R2R line equipped with two robotic arms. A roll with R2R printed sensor labels manufactured by BEN was installed on the converting line. The machine vision view of the assembly area on the printed web is seen in the monitor at the upper left corner of Figure 77. Sensor components with specific PET carriers were placed on the tray pointed out with a white arrow. This approach is useful when the enzyme sensor and the pH sensor are not yet functionalized and integrated into the sensor label.

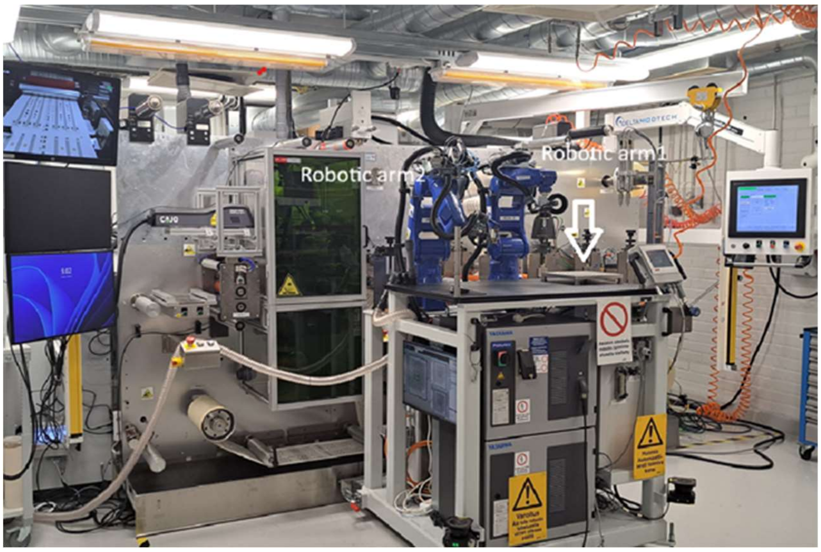


Figure 77. Proof-of-concept demonstration of R2R assembly of sensor components on printed sensor labels by using a converting tool and robotic arms at VTT.

Readout electronics

The readout electronics for the Design A sensor labels have been redesigned and miniaturised for Gen 3A, taking the learnings made from the testing performed with sensor labels and redout electronics from Gen 2A into account. This work has been done by GUT with support from CSEM and RISE. GUT has also developed firmware including optimised sensor readout protocols.

Communication platform

The communication platform developed by LWE enables distributed deployment, device registration, scalability, management of end users and calibration of the sensors.

Connected devices need to have a registration to the correct location, for authentication and authorization of data transmission. This registration process is handled through the mobile application, that connects the device to a specific edge node, provided by SWA. When completed, the registered device can receive push notifications when the inference model produces a positive result, thru an API request from the inference service directly to the communication service. The result is then communicated to all registered devices for that edge node.

Calibration of the sensors are carried out thru QR-code scanning of the sensor labels and mapping are done according to the persisted sensor characteristics for that batch of sensors, where the cloud service has the records for each batch and are mapping them to the transmitted values. This functionality combined ensures a reliable process for enrolling both new devices and deployments.

Sensor label testing

The resulting sensor label platform was used for further evaluation within the smart hygiene pilot, including climate chamber, mannequin and water bath tests for the relevant integrated sensor functions.

In Figure 78 below, a sensor label is attached on product material that is equivalent to the incontinence product. The sensors are placed on a water bath at fixed temperature inside a climate chamber. Notice that commercial reference sensors were placed close to the sensors on the label and also outside the product for referencing the conditions in the climate chamber. This water-bath simulates the micro-climate conditions of the skin. The tests were conducted for more than 8 hours, and the sensor labels remained functional throughout the tests. This satisfies one of the technical requirements.

Figure 78. Testing of sensor labels with water-bath at ESS. (left) A sensor label mounted on the incontinence material. (right) Reference temperature and humidity sensors attached near the sensors on the sensor label and outside the incontinence material.

In Figure 79, a sensor label was attached to the inside of an incontinence product and then mounted onto a mannequin in a climate chamber where the temperature and humidity were well-controlled to simulate a typical nursing home environment. Synthetic urine was pumped to the mannequin to simulate urination. For this test, the quantity and duration were fixed.

Figure 79. Testing with mannequin at ESS. The fixture shows pumping synthetic urine into the mannequin with the read-out electronics.

Upon completion of the mannequin test, a close-up view of the sensors in contact with synthetic urine can be seen in the below Figure 80. It can also be seen that the distribution of the urine is not homogenous on the sensor label. Depending on the placement, different sensors are sensing differently. Figure 81 shows the changes in temperature and humidity with dosing of synthetic urine inside the mannequin. The pattern resembles the reference sensor.

Figure 80. Left: A close-up of the dispersion of the urine inside the incontinence product where the sensor label and reference sensors are placed. Right: A view after the test.

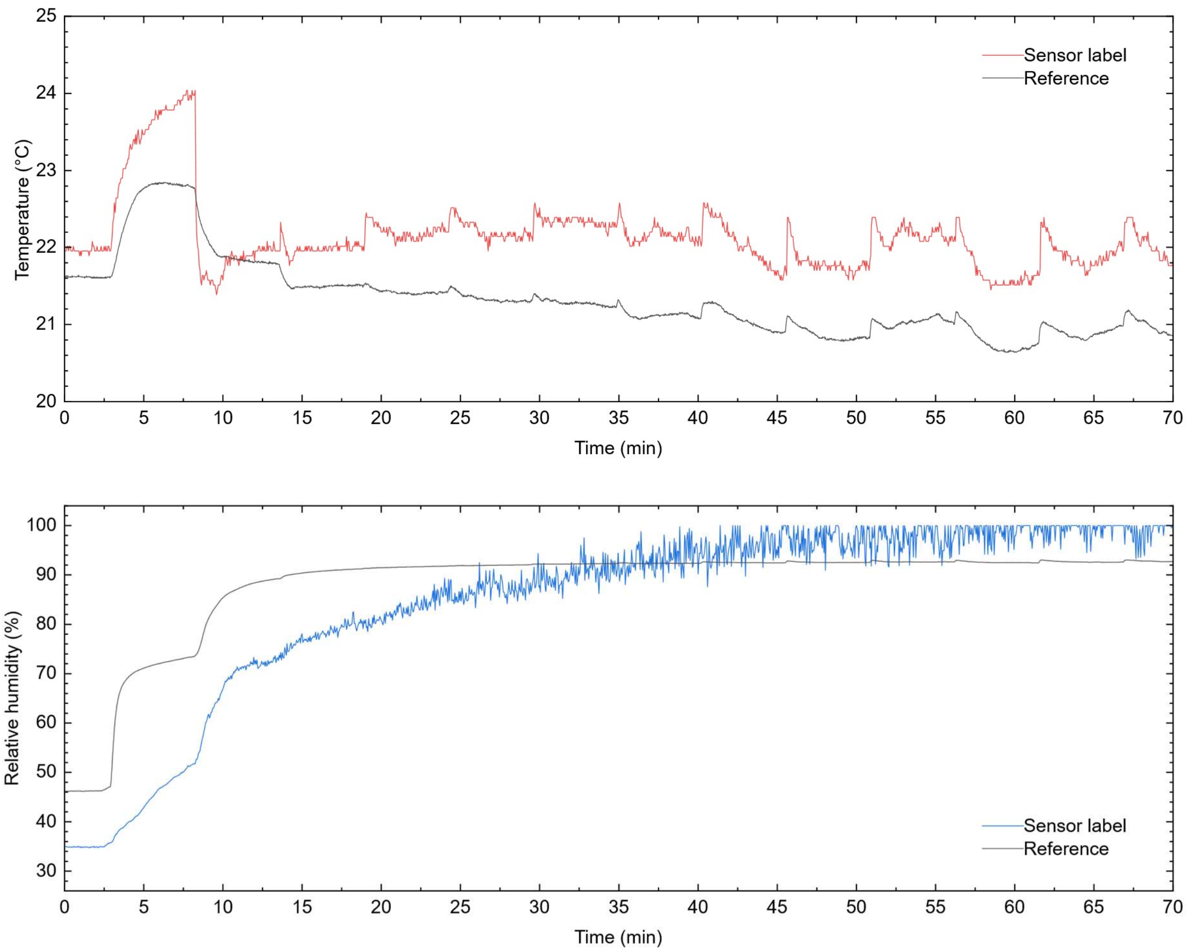


Figure 81. Shows the changes in temperature (top) and relative humidity (bottom) with dosing the mannequin with synthetic urine.

Inference model

Based on the synthetic data generated in this framework, an AI model has been developed to evaluate individually each of the sensor measurements (RH, T, pH and enzyme) since each of them behaves differently. The accuracy of each of these models using the test synthetic dataset can be found in Table 20.

Table 18. A summary of the accuracy of different models based on the sensor type.

	RH model	Temp model	pH model	Enzymes model
Accuracy	99.2%	89.1%	100%	85.2%

Table 18 shows how the trained models achieve a high performance suitable for this pilot. It is possible to observe how all these models achieve high accuracy results where the lowest is the Enzymes model with an accuracy of 85.2%. Regarding the pH model, it achieves a perfect accuracy, which usually could mean a problem during the training phase. However, this result is due to the usage of a synthetic dataset where the separation of pH classes was easier than the rest of the sensors. During the training of all 4 models, early stopping was used by splitting the training data into train and validation subsets. This also ensures that the accuracy of the pH model is not due to overfitting, which is also confirmed by the fact that above table show accuracy results on test dataset rather than during training.

During the evaluation and development of these 4 models as well as the whole AI module, a modularized approach has been followed to ensure no extra resources will be wasted during its execution, for example when not all sensors are available. Similarly, during the training of the models, the early stopping technique ensures no extra training epochs were used if not needed, so that energy is not wasted during the training process.

After the evaluation of the data with those 4 models, a final aggregation algorithm takes the outputs from those models and returns the prediction. This is notified to the healthcare professional regarding the necessity to change the product or not. This module has been programmed in a way that it can be used even if some of the sensors are not working. This way, the final AI model is more flexible, and it can be adapted to different scenarios including the ones where sensors may not perform as expected. This technique has been deployed on SWA's edge node to ensure its correct performance in the desired hardware platform for this pilot.

When engineering mode is enabled in the nurse's app as shown in the below Figure 82. The MQTT logs from the sensor can be seen. Choosing a particular sensor label, the sensors in that label can be viewed as a graph.

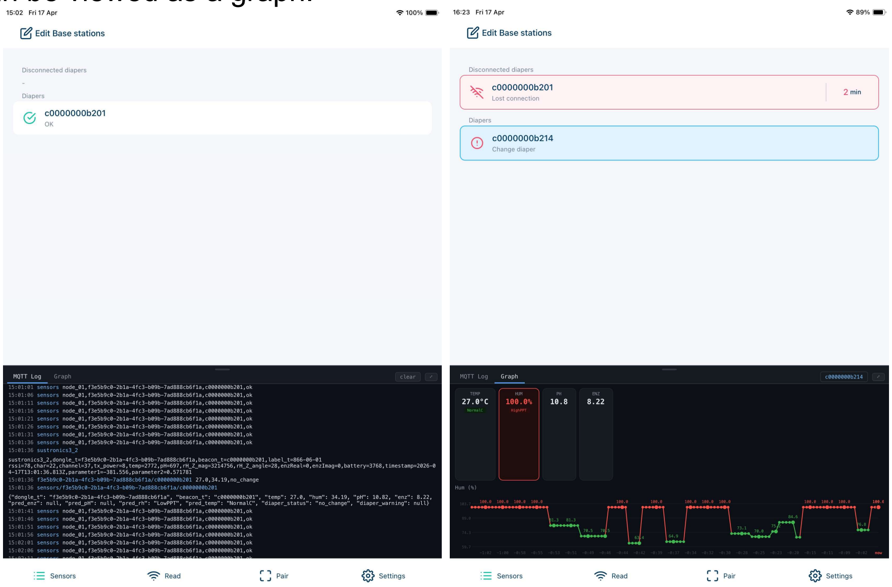
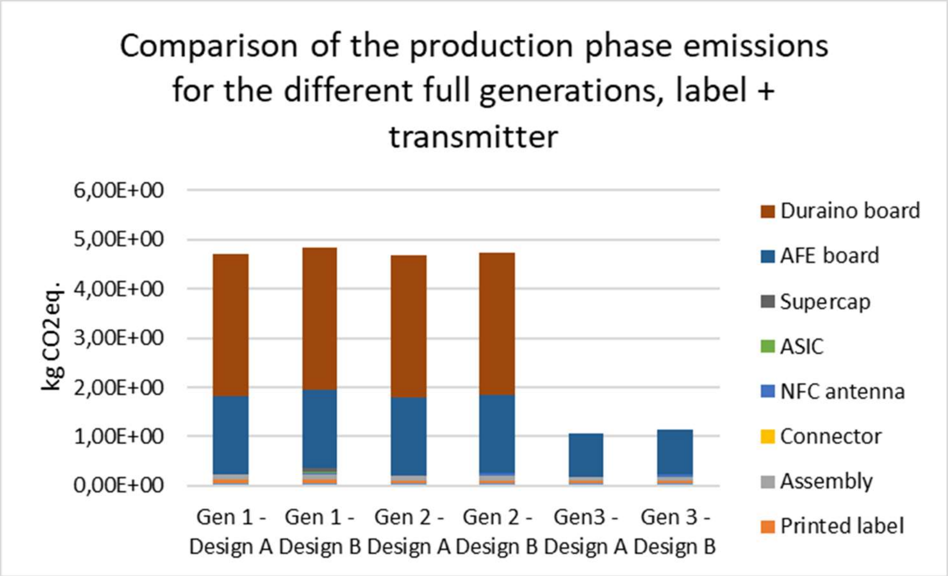


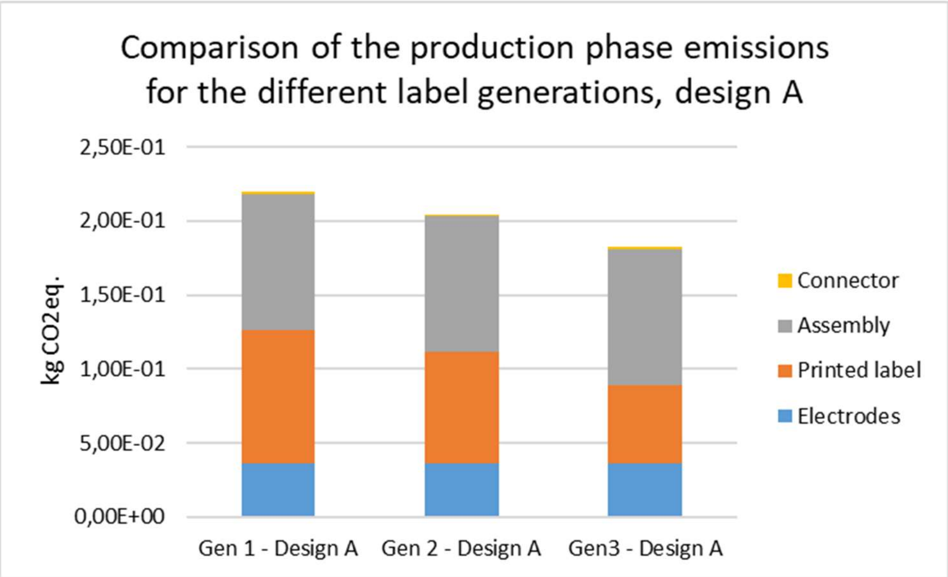
Figure 82. The sensor data appearing the dashboard of the nurse in engineering mode where the left picture shows the MQTT messages from the edge node to the app and in the right picture, sensor label from Design A (blue) and Design B (red) can be viewed. The app is developed by LWE.

Sustainability & social targets and their status in Gen 3:

- SmartCare Change Indicator is a sustainable digital health solution for continence care, featuring a sensor label that attaches to absorbent products and alerts caregivers via a smartphone app when a change should be considered.
- The system includes a single-use sensor label with printed temperature and humidity sensors, and assembled pH and enzyme sensors.
- Both wired and wireless system architectures were explored, with the single-use label interfacing to a reusable and wearable readout unit that collects data and transmits it wirelessly to cloud or local storage via a smartphone or base station.
- Life cycle assessment shows that device manufacturing dominates environmental impact, emphasizing the importance of modular design, as the disposable label remains the main contributor to emissions.
- The pilot targets improved patient comfort, reduced healthcare costs, and a cost increase below 10%, enabled by printed electronics, sustainable materials, additive manufacturing, and flexible bio-based substrates, with physical or wireless connection to the wearable unit.

- Figure 83 below shows significant reductions in equivalent kgCO2 in the final Gen 3 for both architecture designs A and B for the smart hygiene pilot. Manufacturing is still the major contributor where design A is slightly better than design B as the ASIC with the NFC antenna are not integrated in the single-use label.





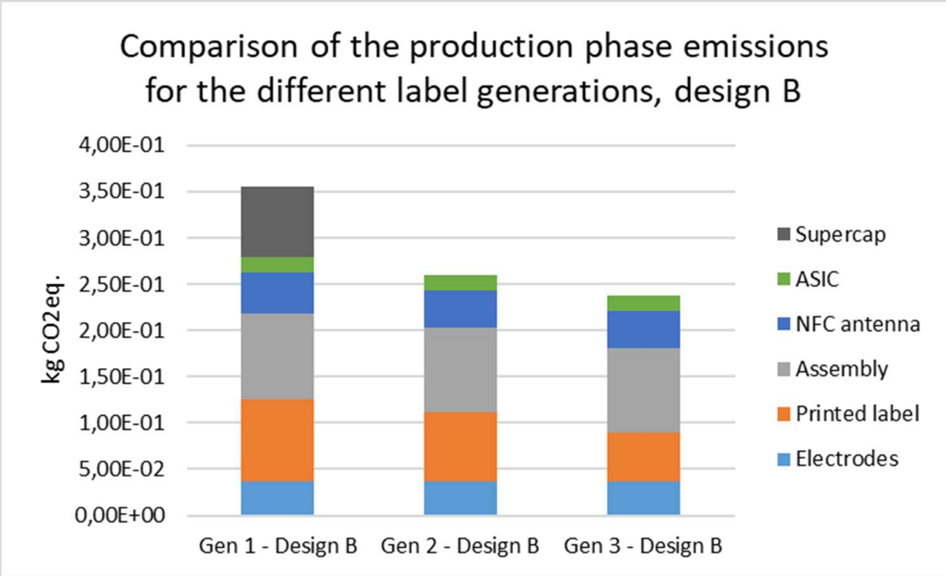


Figure 83. Comparison of emissions across generations by FHG. Top: Generational improvement in both Design A and B with the label and the transmitter. Focusing on the sensor label for a given design, assembly and printing process consumes most of the energy where middle and bottom plots capture Design A and B, respectively.

End user engagement:

There is a market need for the sensors in incontinence care products where the end-user is the elderly care group. For this, ESS plans to demonstrate the final generation of Design A and B to the stakeholders so that a feasibility project can be started towards commercialisation. This is expected to occur in Autumn 2026.

Pilot Achievements & key challenges in Gen 3:

Achievements

- Paper-based sensor labels including four sensors for sensing temperature, humidity, pH and trypsin enzyme developed and tested
- Upscaling of sensor label manufacturing from lab-scale sheet-to-sheet printing to high-volume roll-to-roll printing successfully demonstrated
- A wireless NFC-based version of the sensor label was developed
- Electronics and firmware developed for readout of all four sensors
- End-to-end system validation completed through simulated body and mannequin-based testing, demonstrating functional performance and data transmission under representative conditions, as shown in Figure 84.

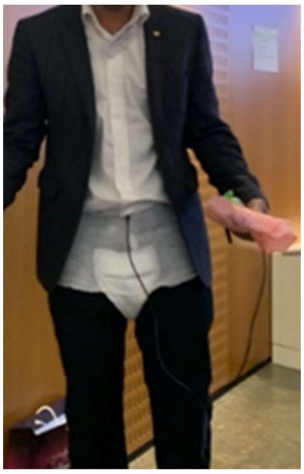


Figure 84. Pilot leader demonstrating the sensor label system at the Sustronics General Assembly meeting in Barcelona 2026.

Key challenges

- Using paper as substrate for the sensor label involved several challenges:
  - When using the thin paper alone as substrate, it easily got distorted and nonplanar during printing. This could be resolved by adding the adhesive (and backing paper) to the backside of the paper substrate before printing, which made the substrate more robust and easier to handle.
  - Conductive traces printed on paper using copper inks did not give acceptable electrical performance and stability. Further development will be needed for replacing silver inks for conductive traces on paper substrates.
  - The paper substrate changes dimensions with moisture content and temperature, making layer-to-layer alignment during printing more challenging. It also affects the sensor characteristics.
- Device-to-device variation in the printed sensors affecting accuracy. Resolved by implementing individual or batch-wise calibration depending on sensor.
- Performing accurate sensor measurements with ASIC integrated in the passive sensor label in design B was challenging, requiring further development and optimization.
- Initially challenges with establishing reliable bonding and electrical connection of the pH sensor sticker components on the paper sensor label, but this was later resolved by a redesign of the sensor components.

Technology and sustainability readiness levels:

Table 19: Pilot 3.2 Technology and sustainability readiness levels

	Gen 2A	Gen 2B	Gen 3A	Gen 3B
TRL	4	3	5	4
SRL	4	3	5	3

2.3.4. Pilot#3.3 Smart wound dressing

Pilot Leader: IFAG (Moritz Schlagmann)
Pilot Goal/Objective:

Pilot 3.3 aims to research an intelligent wound dressing. It involves the measurement of temperature and pH levels, with the objective of enhancing wound treatment by allowing early detection of infection. Sustainability improvements and PCB replacement is at the heart of the pilot. By minimising unnecessary dressing changes, the initiative seeks to improve medical care, reduce medical waste, and lessen the burden on both patients and healthcare providers. This lowers the environmental impact holistically. Given the highly innovative and intricate nature of this endeavour, the project is divided into eight distinct building blocks: ASIC, system integration, sensors, communication, energy management, data processing, materials/sustainability, and application. Additionally, on all this building blocks sustainability improvements are developed, e.g. system integration with sustainable PCB materials, low power communication, higher reliability and efficient AI algorithms. This modular approach ensures efficient progress across the different components.

In means of sustainability also the End-of-Life management is a crucial fact. As we are dealing with a medical application which is directly in contact with body fluids the disposable wound dressing itself needs to be treated as contaminated. That means it is medical waste and will be burned accordingly at elevated temperatures. Nevertheless, the reusable read-out unit, which contains the electrical components, will be reused for the overall treatment of one patient, to keep the material need as low as possible. After the healing of the wound the read-out unit will be reused after cleaning. The concept is shown in Figure 85 and the prototype in Figure 86.

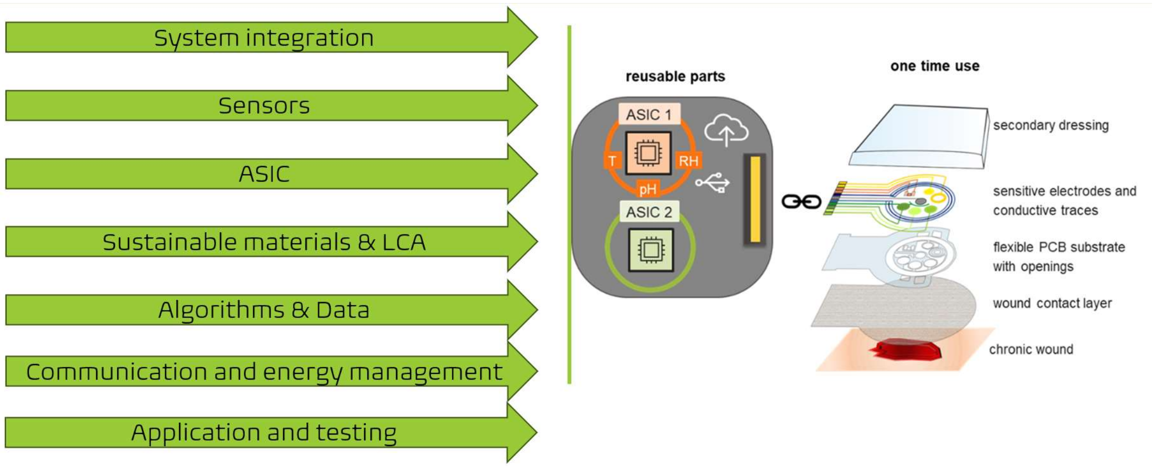


Figure 85. Concept of building blocks that ensures innovative development of smart wound dressing. The dressings have an exchangeable part for one time usage and a reusable part.

Figure 86 In blue reusable readout unit and on flexible PET the research platform for sensor integration comprising more than seven positions for sensors.

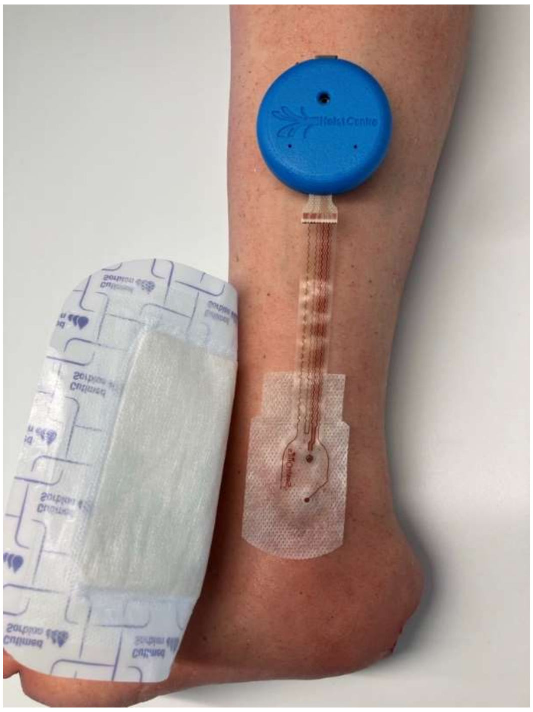


Figure 87 Pilot 3.3 Gen 3 demonstrator on artificial leg model with flex PCB, sensors and reusable readout unit.

Updated Pilot Description for Gen 3

For Gen 3 pilot 3.3 committed to the most sustainable solution for remote wound monitoring. The final version of the flex PCB design was used to test the final version of the sensors under relevant conditions at Essity artificial wound model. For the final Generation 3 iteration, the previously established generative AI framework was further refined and improved, enhancing the quality of synthetic skin temperature and pH data used to train the wound healing prediction AI model, which achieved an accuracy of over 95%, while an algorithm for sepsis detection was in parallel developed and integrated into a mobile app readout.

The results are shown in the following subsections.

Work Carried Out: Gen 1 and Gen 2 Overview:

The first generation of the pilot focused on establishing a solid foundation. Despite the complexity of defining the precise use case and requirements, all building blocks delivered their initial results within the planned timeframe, culminating in the completion of a comprehensive demonstrator. On the hardware side, flexible patch substrates were developed using TPU and copper layers, integrating pH, temperature, and humidity sensors, with substrates distributed among partners for testing. The development work also surfaced several important challenges to be addressed in subsequent generations, including reliable sensor contact within wound dressings, the lack of real clinical data, integration and communication protocol design, sterilization and storage requirements, and the need for a finalised design to support a robust Life Cycle Assessment (LCA) as a key sustainability milestone for the project.

Generation 2 built directly on these findings, delivering progress across all key areas, with sustainability as a central design principle. A significant step forward was the exploration and testing of bio-based materials for flexible PCBs, alongside the development of a novel flex PCB with paper substrate and carbon ink, representing a tangible move towards more environmentally responsible electronics. Thinner substrate materials were also adopted,

reducing overall material consumption. Beyond hardware, a generative AI framework for synthetic data generation was established and first AI models were trained, complemented by the incorporation of real user data. Signal integrity was enhanced through improved shielding, and LoRa communication was prepared as a low-energy wireless technology, contributing to a reduced energy footprint.
Together, these two generations demonstrate steady and structured progress, balancing technical innovation with a clear commitment to sustainability, laying the ground for Generation 3.

Technologies involved and role of project partners in Gen 3:

As already mentioned, the work in the Pilot 3.3 is divided into Building Blocks. The technologies involved are listed below for each building block:

- ASIC (IFAG, VULPES, ACC, TUHH, TNO, FHG, WUR, SWA, GUT)
    - Harmonise Component systems in one ASIC – Firmware
    - Sensing
    - Data collection
    - Communication (BLE and LoRa module)
- Sensing (ACC, BSN, TNO, HTEC, IFAG, FHG, CSEM)
    - pH-Sensor (potentiometric, 2 electrode system, in form of SMD-style sticker components and directly printed by CSEM with a different formulation of pH sensor reference and work electrode), Temp Sensor (resistive NTC), Uric Acid Sensor (amperometric, 3 electrode system)
    - Lifetime of Sensors for Gen 1 set to 7 Days
- Communication (TUHH, IFAG, GUT, SWA, VULPES, TAU, TNO)
    - General connection between the ASIC on the wound dressing and a phone or base station via NFC or BLE, respectively
    - Demonstrator for LoRa + WuRx as an low-energy alternative/addition to BLE for data transmission from sensor node to a base station
- Data (HTEC, VULPES, BSN, ACC, SWA, IFAG)
    - Generative AI framework for skin temperature and pH synthetic data generation including healthy, wound and infection scenarios.
    - Preparing, refining and classification of hospital data to meet the input requirements of the sepsis model.
    - Development of an initial, first version of the AI model for early sepsis detection using hospital clinical data from Intensive Care Units (ICUs).
    - Final version of Generative AI framework to generate synthetic temperature data validated statistically with collected data.
    - Final AI models for wound status prediction trained with generated synthetic data.
- Application (BSN, VULPES, WUR, HTEC, TAU, IFAG, ACC)
    - Develop and build new and additional test stands for gen 3 testing, based on gen 1 results
    - Final setup and align test plan
    - Conduct gen 3 prototype tests
- Materials / Sustainability (FHG, IFAG, TNO, SWA, TAU, ACC, VULPES, GUT, BSN, TUHH, WUR)
    - Two approaches under evaluation for flex PCB
        - subtractive (Cu on TPU) & printed (Ag on PET)
    - Analysed in means of functionality and sustainability
    - Collecting sustainability data while production
    - Generation 3 demonstrator on bio-based TPU substrate foil
    - Defined Use Case for LCA
- System integration (TNO, WUR, IFAG, FHG, SWA, VULPES, HTEC, TAU, ACC, GUT)

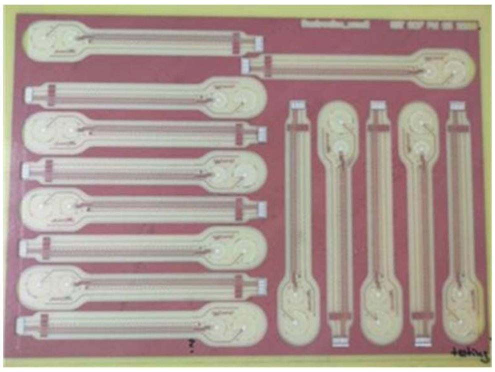
- Gen 1 and 2 will consist of a functional flex with temp and pH sensor integrated
- Redesign of the flexible PCB in Gen 3
- Removal of moisture sensors
- Assembly of sensors with low temperature solutions
- Connected to breadboard for signal amplification and further system improvements
- Tested final AI model in Swiss Vault edge node to ensure correct performance

Technical layout and characterisation of Gen 3:

Sustainable materials and integration

In the Gen 3 demonstrator a design and sensor consolidation was implemented: The humidity sensor was removed since it is not necessary for the target application, besides the temperature- and the pH-sensor (reference and measure electrode) only one further position for uric-acid measurements were maintained on the stretchable substrates. Furthermore, since data recorded using shielded versus non-shielded data lines on the flexible substrates did not show a significant difference in noise level in the lab environment in which experiments were carried out, shielding was not further implemented in the Gen3 demonstrator for the subtractive technology. For the application skin contact might be a source of noise as identified earlier as well as environments with complex medical equipment. For further product development shielding is to be further considered also for product safety. for the subtractive technology. For the application skin contact might be a source of noise as identified earlier as well as environments with complex medical equipment. For further product development shielding is to be further considered but for this TRL level it became obvious, that quality of the sensors and their interconnection to the substrates for this stage of development have a much larger influence on signal quality. Given the lower number of sensors, the stretchable substrates were reduced in size.

Subtractive Cu/TPU technology (FHG and WUR): Data collection with Gen 1 substrates was hampered by the substantial noise that was coupled into the rather long connectors between sensors and read-out. As noise is typically mitigated by shielding of the critical data lines, the flexible and stretchable substrates were equipped with additional shielding layers for Gen 2. In case of the subtractive technology two addition etched copper layers were implemented around the signal lines. Both shielding layers were connected using a conductive silver paste (in order to avoid plating processes). Different types of copper mesh structures were investigated. Subsequent measurements using the shielded substrates yielded a much better signal to noise ratio, as expected. A drawback of the implemented shielding structures is an increase of substrate thickness by approximately 150 µm and a respectively stiffer substrate. The material requirement of additional layers is compensated by thinner material.



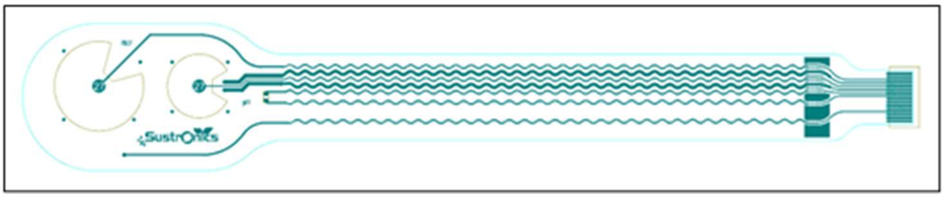
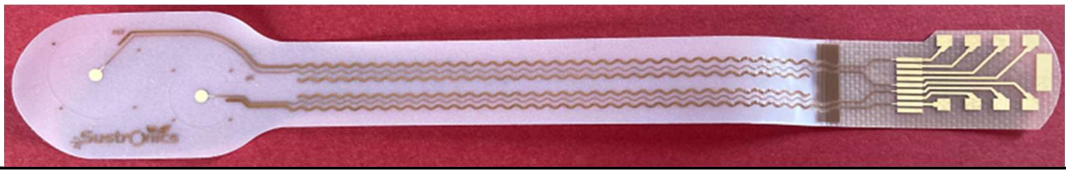


Figure 88.Gen3 consolidated design and manufactured substrates.

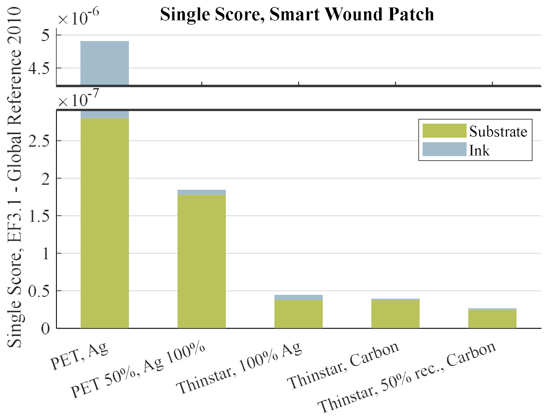
Initially, a relative humidity sensor (RH) was planned for tracking sufficient wetness of the pH electrodes. It became clear that this measurement is not meaningful in its current form and under the given conditions, as the target application involves continuously exuding wounds. Since the presence of liquid exudate is inherent and persistent, an RH sensor does not provide actionable or additional information. Consequently, the humidity sensor was removed from the list of requirements. The design of the single-use part was modified due to the removal of the sensor. The design for the single-use part of Gen 3 was split into 3 variants:

Figure 89: V1. without uric acid sensor, V2. with uric acid sensor and V3. without uric acid and with another plug connection.

V1	
V2	
V3	

Additive technology by printing solvent-based inks (TNO):

For the additive manufacturing approach, more sustainable materials were selected. A carbon ink for printing conductive lines is selected. The white coated paper from TER was selected as a paper-based substrate. By adjusting the materials choices, the environmental impact of the printed flex could be reduced significantly as expressed as a single score in Figure 91.

	
Figure 90 Smart wound flexes printed on paper with carbon inks	**Figure 91 Environmental impact of materials**

Furthermore, for generation 3, direct printing of pH sensor materials was tested by Add Sensors and CSEM on directly printed flexes to avoid the integration issues with the sticker sensor foils and simplify the manufacturing process. Also, the reduction in material usage for the flex not incorporating sticker sensors represents a sustainability gain. The materials from CSEM yielded the results given in Figure 92 although this was a first trial batch of CSEM to print onto the flex. Further improvements are expected with future research opportunities.

Note that the flexes included shielding features by printed layers as with additive technologies the shielding functionality could be more readily implemented and in the use case in which flexes will be in contact to the patient via wound exudate, noise will be introduced to the sensor signals. Further research is needed and consideration of implementation as business decision.

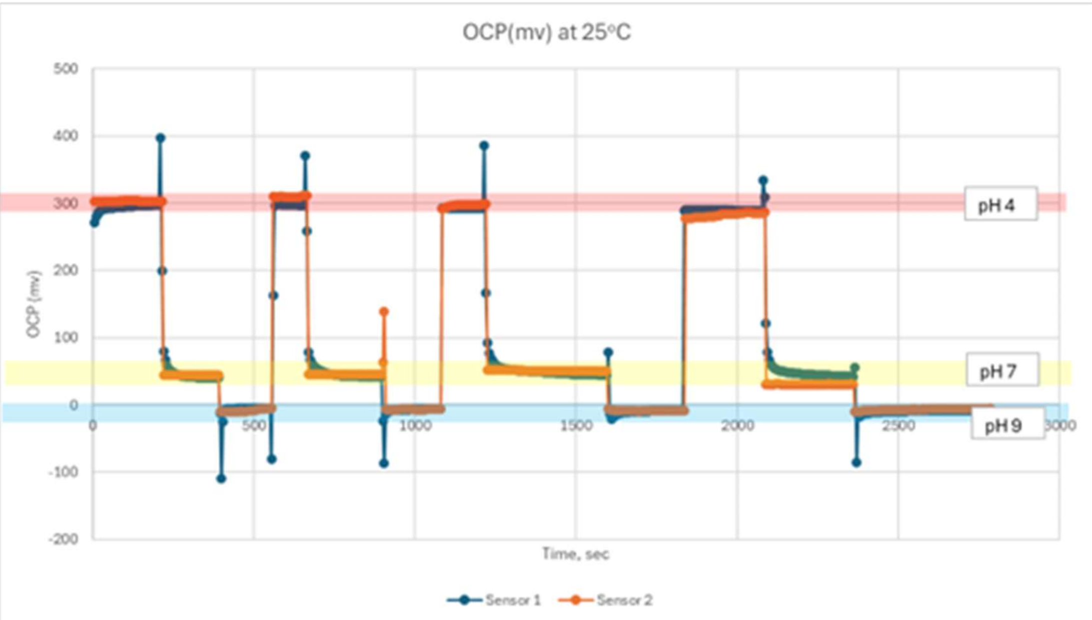


Figure 92 pH Sensor measurements as open circuit potential (mW) over time (sec) for three buffer solutions of 4, 7 and 9 showing repeatability with the directly printed pH sensors.

The temperature component (NTC negative temperature coefficient) that was mounted onto the printed circuitry gave reliable and repeatable results as shown in Figure 93.

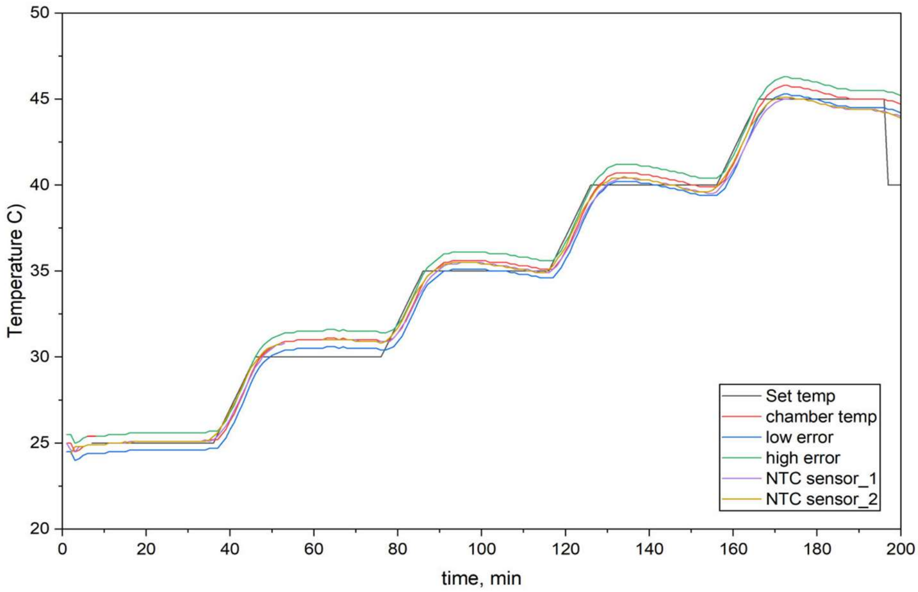


Figure 93 Temperature measurements in the domain from 25 to 45 °C for the Negative Temperature Coefficient sensors (NTC) mounted onto the additively printed flex

ASIC

The application specific integrated circuit (ASIC) was developed and implemented in the reusable readout unit. For this highly integrated, reusable readout unit the ASIC firmware was further debugged and low-level driver updated to ensure a reliable usage.

Communication

For energy efficient communication from the sensor node to a base station TUHH developed and tested a demonstrator including a LoRa transceiver in combination with a wake-up receiver. The additional receiver reduces the power consumption in an always-on receiving mode to the single digit µW domain eliminating the necessary synchronization in standard LoRaWAN implementations. This comes at the expense of a reduced sensitivity w.r.t to standard LoRa implementations as the usage of active components such as low noise amplifiers in the receiver frontend is limited to further reduce power consumption.

The node can be addressed by a LoRa transceiver that uses an additional layer with on-off-keying modulation (e.g. in a base station, in the current implementation this is a PCB connected to the PC), a wake-up is triggered and initializes the sensor readout. While the sensor on the PCB is a digital temperature sensor, generally, any other type of sensor data (e.g. the voltage value provided by an ADC as in the readout unit) would work. The data is transmitted via LoRa back to the base station/PC.

For data storage and access the general implementation of an MQTT publisher is done to send data to the EDGE Node provided by SWA.

The data transmission from gateway to Edge Node solutions was deployed. The sensor readout-unit and gateway are further integration in the system architecture of SWA.

An overview of the dataflow can be seen in Figure 94.

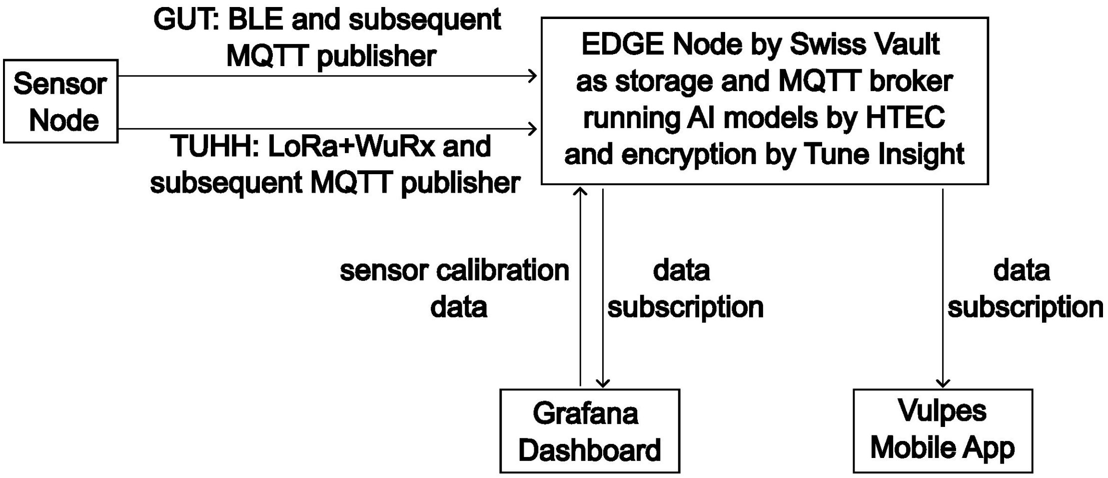


Figure 94: dataflow in pilot 3.3

Wireless Communication and Data Infrastructure (GUT):

Gdańsk University of Technology (GUT) contributed to Pilot 3.3 by developing and validating the wireless communication architecture for the Gen 3 smart wound dressing demonstrator. The work focused on establishing a reliable and energy-efficient data transmission pipeline between the wearable sensor node, the base station, and the backend infrastructure.

The implemented communication architecture was based on Bluetooth Low Energy (BLE), enabling wireless transmission of sensor measurements from the wearable wound dressing to the gateway device. The overall system architecture developed within Pilot 3.3 is shown in Figure 100. The gateway infrastructure was integrated with MQTT-based backend communication to support real-time monitoring, visualization and further data processing.

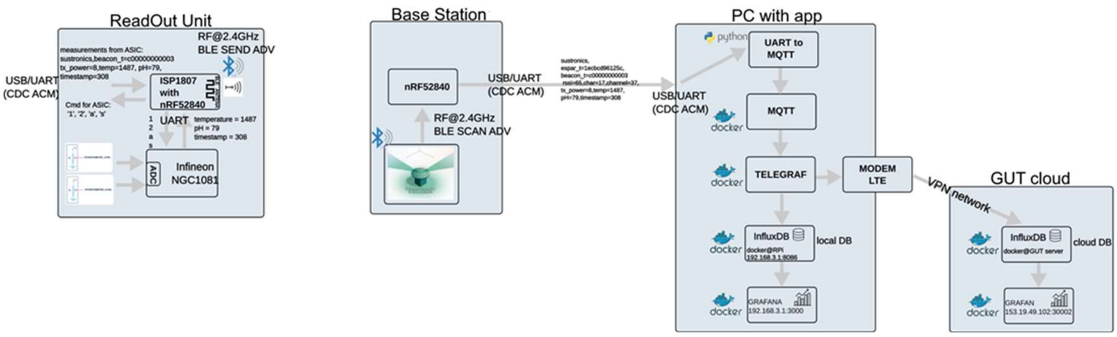


Figure 95: Wireless communication architecture developed by GUT for the Gen 3 smart wound dressing demonstrator, including BLE communication, gateway infrastructure and backend integration.

The developed communication chain consisted of:

Sensor Label → ReadOut Unit → Base Station → MQTT Application → Grafana Dashboard

The BLE communication layer enabled stable wireless transmission between the wearable sensor platform and the base station while maintaining low power consumption suitable for wearable sensing applications. Subsequently, the base station forwarded acquired data to backend systems using secure WebSocket (WSS) communication and MQTT publishing mechanisms.

A Serial-to-MQTT bridge was implemented to support seamless integration between the BLE communication layer and cloud/edge infrastructure. Data were published to dedicated MQTT topics and integrated into the overall Pilot 3.3 system architecture. The implemented BLE-to-MQTT communication pipeline is presented in Figure 101. In addition, a dedicated simulation mode was implemented to support testing and validation of the communication pipeline independently from the availability of complete sensor hardware.

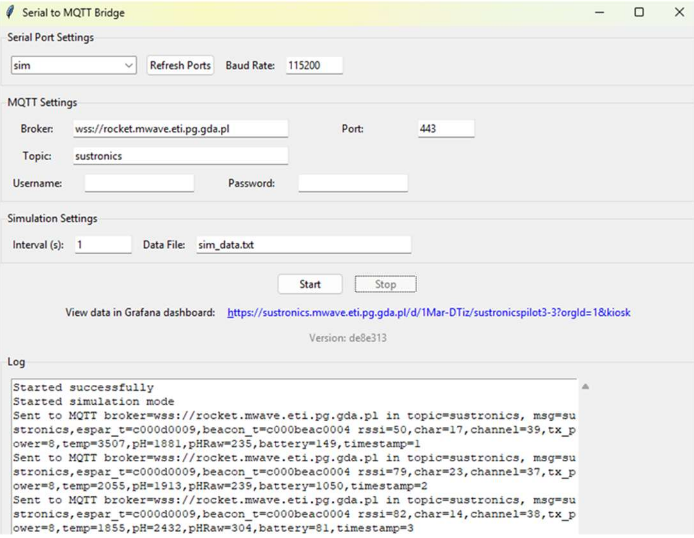


Figure 96: MQTT bridge application enabling secure BLE-to-MQTT data forwarding between the wearable sensor base station and backend infrastructure.

To support functional validation activities, a real-time monitoring environment based on Grafana dashboards was developed. An example of the developed monitoring environment is shown in Figure 101. The dashboard infrastructure enabled visualization and monitoring of:

- pH measurements,
- temperature measurements,
- voltage signals,
- battery status,
- calibration curves,
- multi-device comparison data.

The visualization environment supported communication verification, anomaly observation and validation of the complete sensor-readout workflow during laboratory-scale experiments and integration activities.

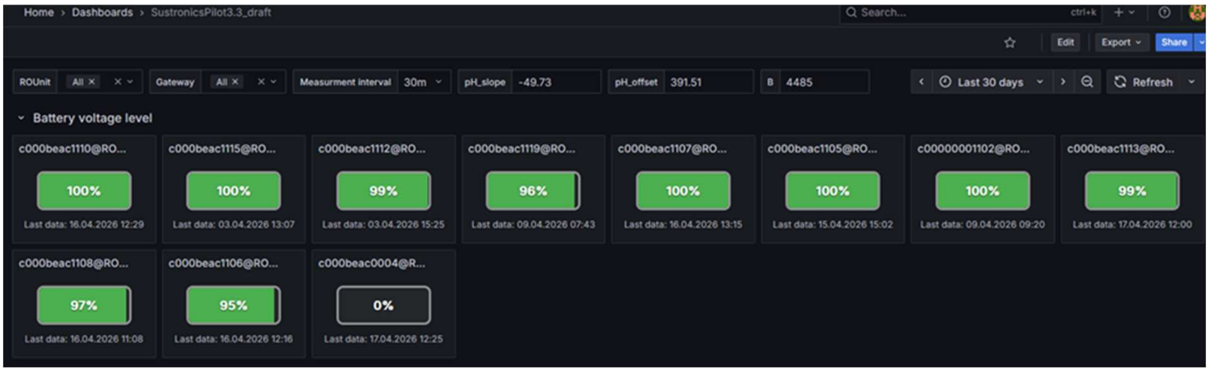


Figure 97: Real-time monitoring dashboard developed for Gen 3 validation, including visualization of pH, temperature, voltage and battery data.

Within Gen 3 validation activities, GUT performed:

- BLE communication stability validation,
- real-time data transmission tests,
- MQTT data integrity verification,
- integration with Grafana and Edge Node infrastructure,

- support for laboratory-scale functional validation experiments.

The developed infrastructure demonstrated reliable end-to-end wireless communication and provided a scalable and modular architecture suitable for future platform integration and further development of the smart wound dressing ecosystem.

Sensing

The sensing work in Pilot 3.3 focused on the integration and evaluation of pH and temperature sensing, complemented by a uric acid sensor variant. ADD developed and contributed SMD-style potentiometric pH sensor stickers for integration into the smart wound dressing demonstrator. For Generation 3, two complementary pH sensor integration approaches were evaluated: modular SMD-style pH sensor stickers and direct printing of pH sensor materials onto flexible substrates. Direct printing can simplify the substrate architecture by reducing additional carrier components and assembly steps. In parallel, the SMD sensor sticker approach provides specific advantages for multiparameter sensing systems, including modular sensor integration, independent sensor manufacturing and pre-characterisation, and transferability across different flexible substrate layouts via dedicated contact pads.

The SMD sticker concept is particularly relevant when different sensor types require different processing, functionalisation or curing conditions. By manufacturing the sensor elements separately from the final substrate, the approach can reduce the risk of cross-interference between different sensor manufacturing steps. It also enables dense sheet-level fabrication of the sensor components, improving substrate area utilisation during sensor production compared with direct printing onto application-specific flex layouts that include larger interconnect areas, contact pads and unused layout spaces. This can support higher production throughput and reduce material losses before system integration. In addition, the modular sticker concept may enable future circularity strategies at sensor-component level. Since the sensor element is provided as a separate sticker component, delamination from the carrier substrate after use and subsequent re-functionalisation could be explored as a potential refresh-and-reuse approach. This may be particularly relevant for electrochemical sensors using noble metals or other resource-intensive electrode materials, where reuse of the electrode component could provide an additional sustainability benefit compared with fully integrated, directly printed sensor layouts.

Based on the findings from Gen 1/2 testing, the SMD-style pH sensor stickers were redesigned to improve the robustness of the sensor–substrate interface under wet conditions. Both the redesigned SMD sensor sticker approach and the directly printed sensor approach represent relevant development routes for future smart wound dressing applications, with further optimisation required depending on the final manufacturing strategy, integration requirements and application environment.

Temperature was measured using resistive temperature sensors, while uric acid sensing was addressed as an amperometric three-electrode sensor concept. The sensor set was evaluated on flexible substrate variants and in artificial wound model tests under wet, application-relevant conditions.

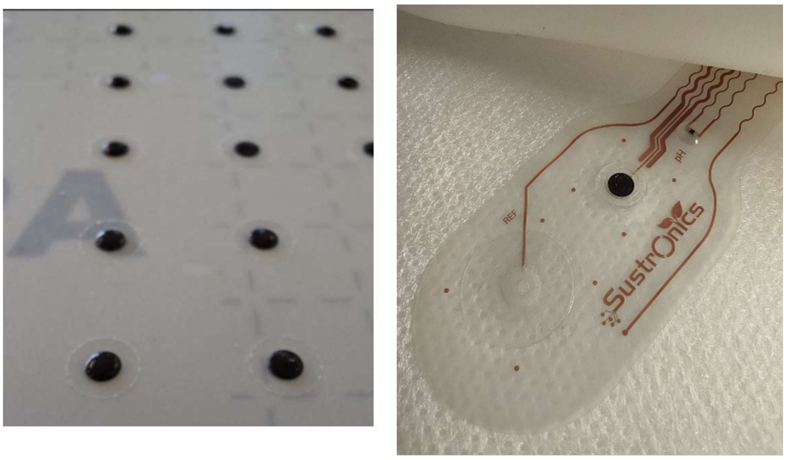


Figure 98: Redesigned ACC SMD-style potentiometric pH sensor stickers for Pilot 3.3. Left: pH sensor stickers on the fabrication sheet. Right: integrated pH sensor sticker assembly on the flexible Pilot 3.3 substrate manufactured by Fraunhofer IZM.

Characterization and application

Partners worked collectively on the characterisation of Gen 3

The sensors can be tested in beakers using heating plates and pH buffer solutions. These tests give the best results in regard to sensor accuracy and range. Nevertheless, these tests are emulating the use case and do not consider the additional challenges of real wound environments like for instance the human body as noise source or complexity of the chemicals to be sensed and monitored. To have an intermediate test setup, that gives insights into how these prototypes behave in more advanced environments, five artificial wound leg models have been built by BSN. These feature circular transparent tubes integrated with a heating mat and controller as well as a system to pump artificial wound exudate into the circular wound site. Seen in figure 98. Initially multiple artificial exudates have been developed.

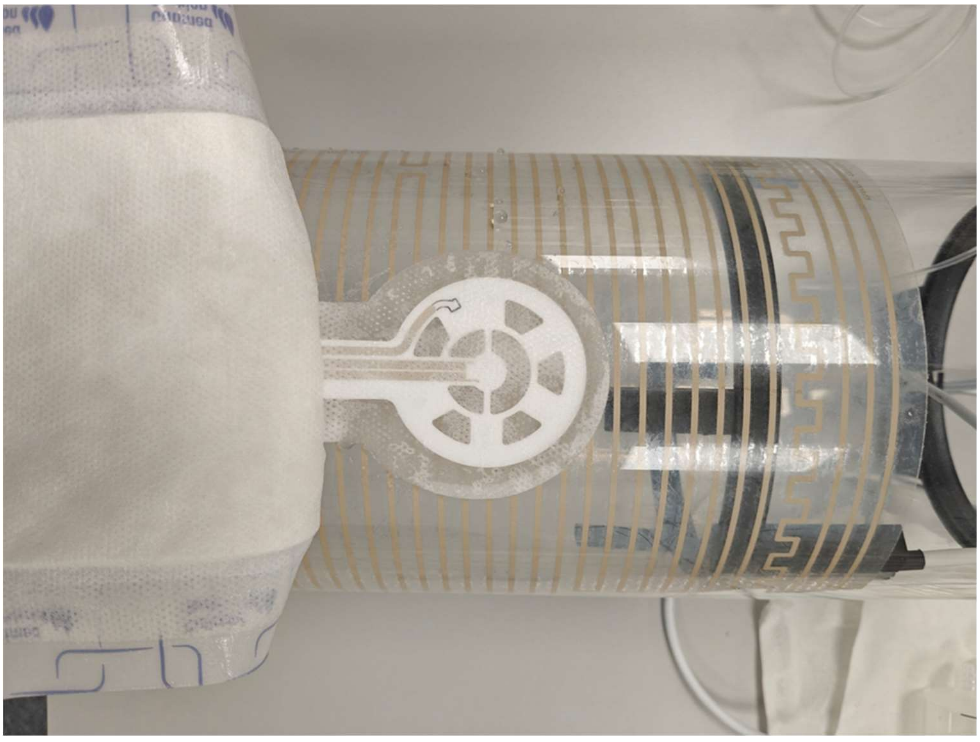


Figure 99: Artificial wound model after use with 15 ml of transparent viscous buffer solution, covered by a wound contact layer, followed by a sensor flex by additive manufacturing by TNO and a superabsorbent, self adhesive wound contact layer, which has been peeled back. The heating mat can be seen covering most of the surface of the transparent tubing.

Due to challenges in the manufacturing of gen 3 prototypes and the resulting very tight time constraints during the end of the project, we focused on using buffer solutions which have been altered by adding plant fibers to make them more viscous and closer in regard to viscosity to the real wound exudate. These have been available with a pH of 9, 6 and 4.

With the described test stands and artificial exudates we were able to run several tests with the following settings:

- Pump in viscous buffer pH 9 @ 3 ml / h for 1 h
- Run a temperature ramp from 33 to 37 °C in 1 °C increments over the same timeframe
- Change artificial exudate to viscous buffer pH 6 and repeat
- Change artificial exudate to viscous buffer pH 4 and repeat

These tests have been repeated for the final additively manufactured flex (by TNO with a directly printed CSEM pH sensor figure 100 as well as the final ADD pH sensors on a Würth/FhG substrate figure 101 three times each. One initial concern was that by pumping more exudate into the artificial wound covered by the superabsorbent secondary dressing, it would only be possible to measure the accumulated pH of all exudates having entered the wound site. This does not seem to be the case, as the measured pH reflects the currently pumped pH quite well. There could be multiple causes for this. One could be, that the superabsorbent dressing has a strong pull effect and locks the absorbed buffer solution in firmly.

Figure 100: pH and temperature curves of TNO / CSEM sensor flex. The sensors are able to detect the pH and temperature levels quite well. Jagged lines on the temperature measurements might be due to the controller of the heating elements overshooting slightly.

The yellow temperature sensor broke during the first cycle

Figure 101: pH and temperature curves of addsensors / Würthsensor flex.

The sensors are able to detect the pH and temperature levels very well. Jagged lines on the temperature measurements might be due to the controller of the heating elements overshooting slightly. The difference between the yellow and green temperature curve during the first cycle is partially due to the temperature sensor of the controller being misplaced slightly. That has been fixed in second cycle and led to more accurate results immediately.

All in all, both flexes performed well on the artificial wound model. While the yield of the ACC flexes is not optimized yet, the working samples were able to measure stable results. This demonstrates the feasibility of the redesigned SMD sensor sticker approach. The direct printed CSEM sensors showed a already a high yield and good results. Going forward additional tests with exudates containing proteins in the form of albumins would be desirable. These could lead to insights concerning biofouling and would be a good next step in increasing the complexity of the testing conditions.

Temperature Sensor Integration

To ensure a safe and controlled sensor application process, the temperature sensors were assembled first, before the pH and reference electrodes were attached. Two different interconnection technologies were evaluated, both yielding very good and reproducible results.

Isotropic Conductive Adhesive (ICA): For smaller-scale production, NTC components for temperature sensing were mounted using an isotropic conductive adhesive. The adhesive was dispensed onto the corresponding pads, the components were placed, and the adhesive was cured in an oven for 30 minutes at 80 °C. This process is well-suited for batch production, enabling a high number of substrates to be processed simultaneously.

Low-Temperature eutectic SnBi Soldering: The panel layout produced by Würth was used to demonstrate that low-temperature soldering with SnBi eutectic solder paste is also applicable to TPU substrates. The solder paste was automatically jetted using a MyCronic MY700 system, components were placed with an ASMPT SiPlace CA4V2 pick-and-place machine, and the full board was processed in a reflow oven with a maximum temperature of 155 °C. A total of 16 components were mounted with this method. Both technologies are well understood and deliver reliable, robust interconnections.

To ensure a smooth surface over the mounted SMD components — important both for protecting the components from test liquids and for compatibility with the artificial wound model — BECTRON AR 4820 conformal coating was applied.

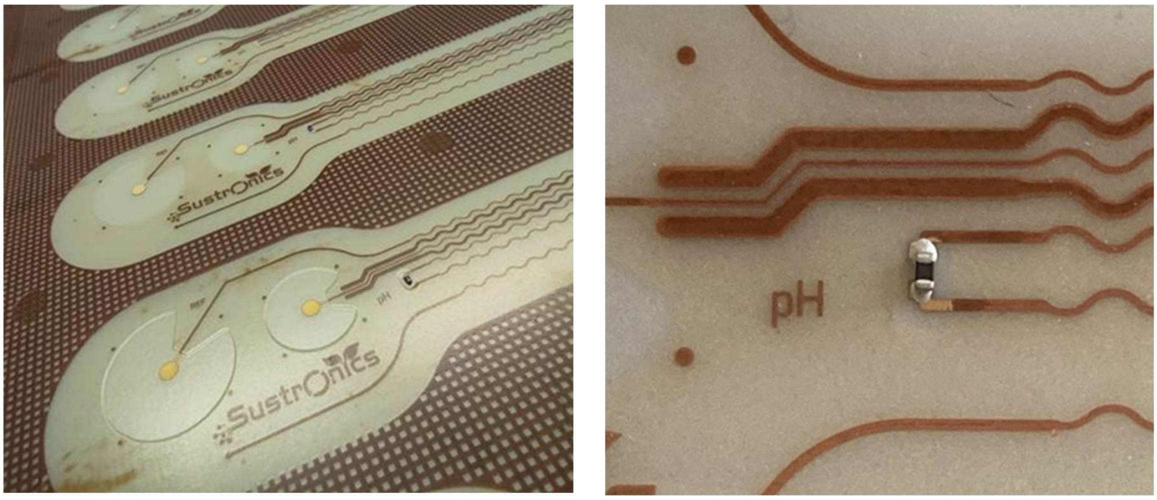


Figure 102: Temperature sensing components on Würth substrates panel, SnBi soldered (left), conductive adhesive (right)

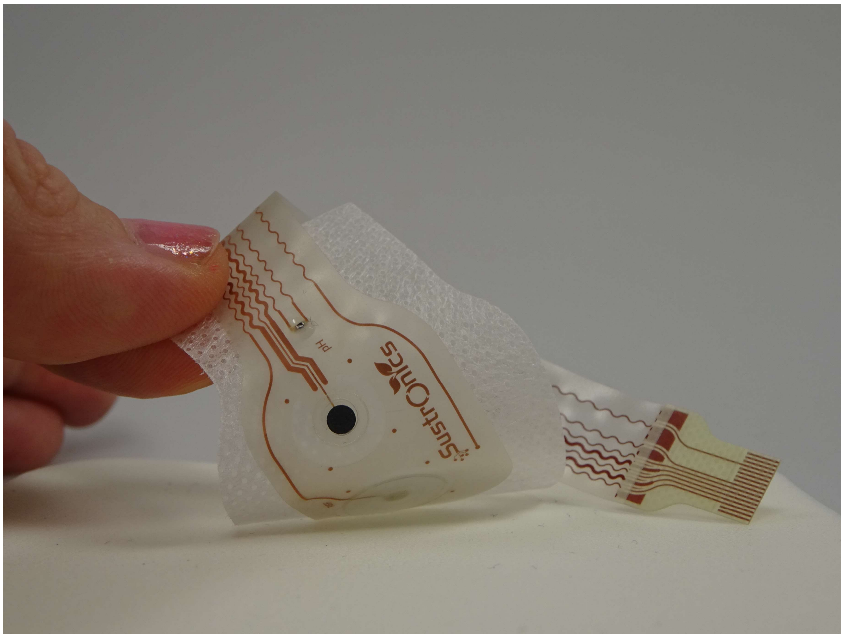


Figure 103: TPU substrate for smart wound dressing with integrated pH sensor, reference electrode and temperature sensor

Mechanical Reliability Testing

Torsion testing was performed at Instron E10.000 to assess the mechanical robustness of the TPU substrates under conditions representative of real-world use.

Testing was conducted at ±30°, 2 Hz, for a total of 110.000 torsion cycles - simulating 12 days of use at 9,000 footsteps per day. The resistance of the temperature sensor line, the pH sensor line, and the reference electrode line were continuously monitored throughout the test. Results confirmed the mechanical robustness of both the substrate and meandered Cu traces.

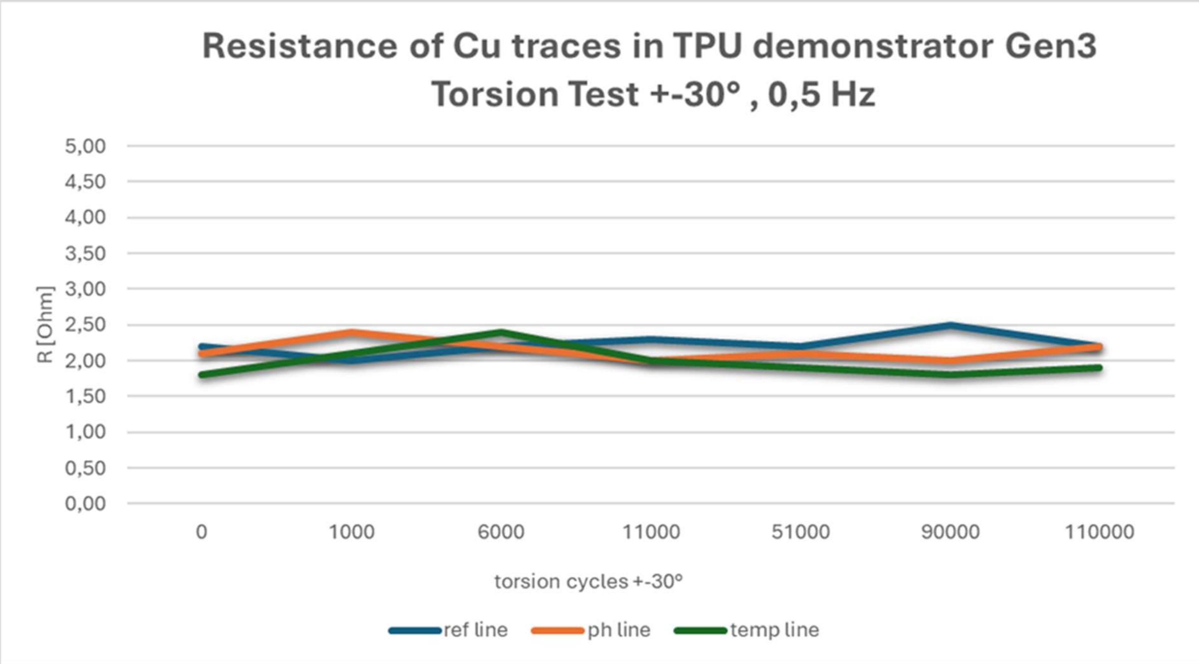


Figure 104: Diagram depicting the resistance values of Cu traces in TPU substrate in torsion test up to 110.000 cycles @ ±30°, 2 Hz

Data and AI

For Gen 3, the generative AI framework for high quality synthetic skin temperature and pH data generation has been further improved by including more performance metrics to better understand its results. At the same time, this framework has been retrained to further improve its accuracy. A sample of this synthetic data is shown in Figure 105.

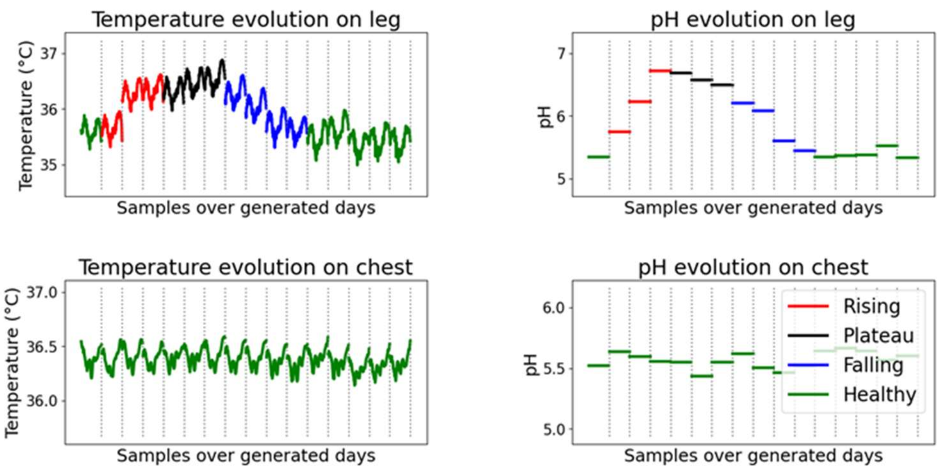


Figure 105. Results of synthetic data to develop AI algorithms.

Based on this synthetic data, a model for wound status prediction has been trained and developed. This model is based on a fully connected neural network that takes as input the evolution of the pH and temperature measurements to predict the current healing status. During the training, multiple topologies were evaluated and the most efficient, using the trade-off between performance and memory footprint to reduce the resource consumption of the model, was selected. The selected topology was evaluated, and it achieved an accuracy of over 95%.

The topology of this model can be found in Figure 10606.

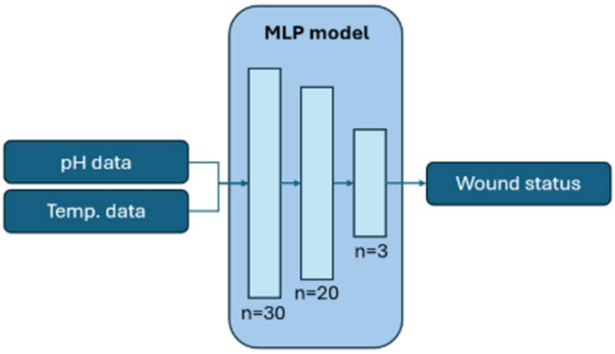


Figure 106. Topology of neural network for healing status prediction.

Complementing this work, Vulpes developed a supervised AI model trained on both clinical and synthetic data, achieving a precision of approximately 89% for early warning detection (yellow alert) and 96% for critical warning detection (red alert), demonstrating the potential of AI-driven monitoring for timely clinical decision support. Alongside the AI model, Vulpes also designed a mobile application tailored to meet the distinct needs of both patients and clinicians, ensuring that actionable insights are accessible and meaningful for all end users, see Figure 107.

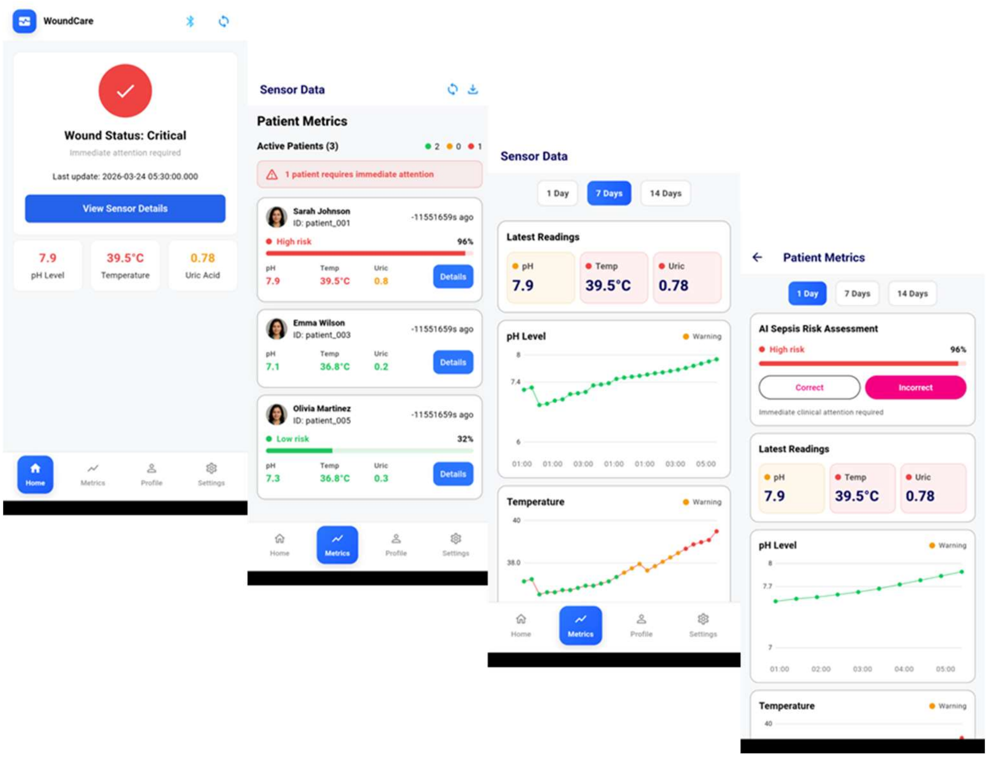


Figure 107 Mobile app to track sepsis warning.

Sustainability & social targets and their status in Gen 3:

The primary goal of the sustainability workstream was to closely guide the Eco²Design process in parallel with the product development of the smart wound patch. To achieve this, iterative

Life Cycle Assessments (LCAs) were conducted at both system and component levels, enabling continuous improvement of the product's overall environmental footprint across development generations.

In the first generation, a fast-screening LCA was conducted to inform early design decisions, identifying the main electronics — including active components such as ICs, OpAmps, the battery, and AFE components — as the dominant environmental hotspots. In response, a partly reusable design strategy was adopted, in which the main electronics unit is retained and reused throughout a single patient's treatment cycle, minimising the need for repeated manufacturing of high-impact components. With the reusable strategy established, the single-use sensor strip emerged as the next critical hotspot, shifting the focus of Generation 2 towards sustainable design solutions for the flexible PCBs.

For subtractive manufactured PCBs, hotspots were identified in the manufacturing process, substrate, and conductive traces. Key mitigations included the introduction of a copper recycling process for manufacturing waste, the use of a bio-based TPU substrate offering 20% lower CO_2 emissions, and an optimisation of the PCB size. Together, these measures achieved a 47% reduction in environmental impact at the component level. For additive manufactured PCBs, the conductive ink was identified as the primary hotspot. This was addressed through the use of silver ink from secondary materials and carbon-based ink, combined with a PET substrate containing 50% recycled content and a paper-based alternative, resulting in a 44% reduction in GWP and a 98% reduction in material resource consumption. These results confirm the KPI that sustainable materials were used for more than 50% compared to the baseline systems.

Furthermore, analysis of the main electronics identified electricity consumption in IC manufacturing as a key hotspot Sourcing renewable energy for ASIC production was shown to reduce component-level GWP by 43%.

At the overall use case level, i.e. from cradle-to-grave, the most significant environmental hotspot lies in the use phase, where caregiver travel associated with each dressing change contributes considerably to the total footprint. By extending dressing wear time through the smart wound patch's continuous monitoring capabilities, the frequency of dressing changes and associated logistics are substantially reduced. The LCA confirms a positive environmental handprint, with reductions of 40% to 60% compared to standard care.

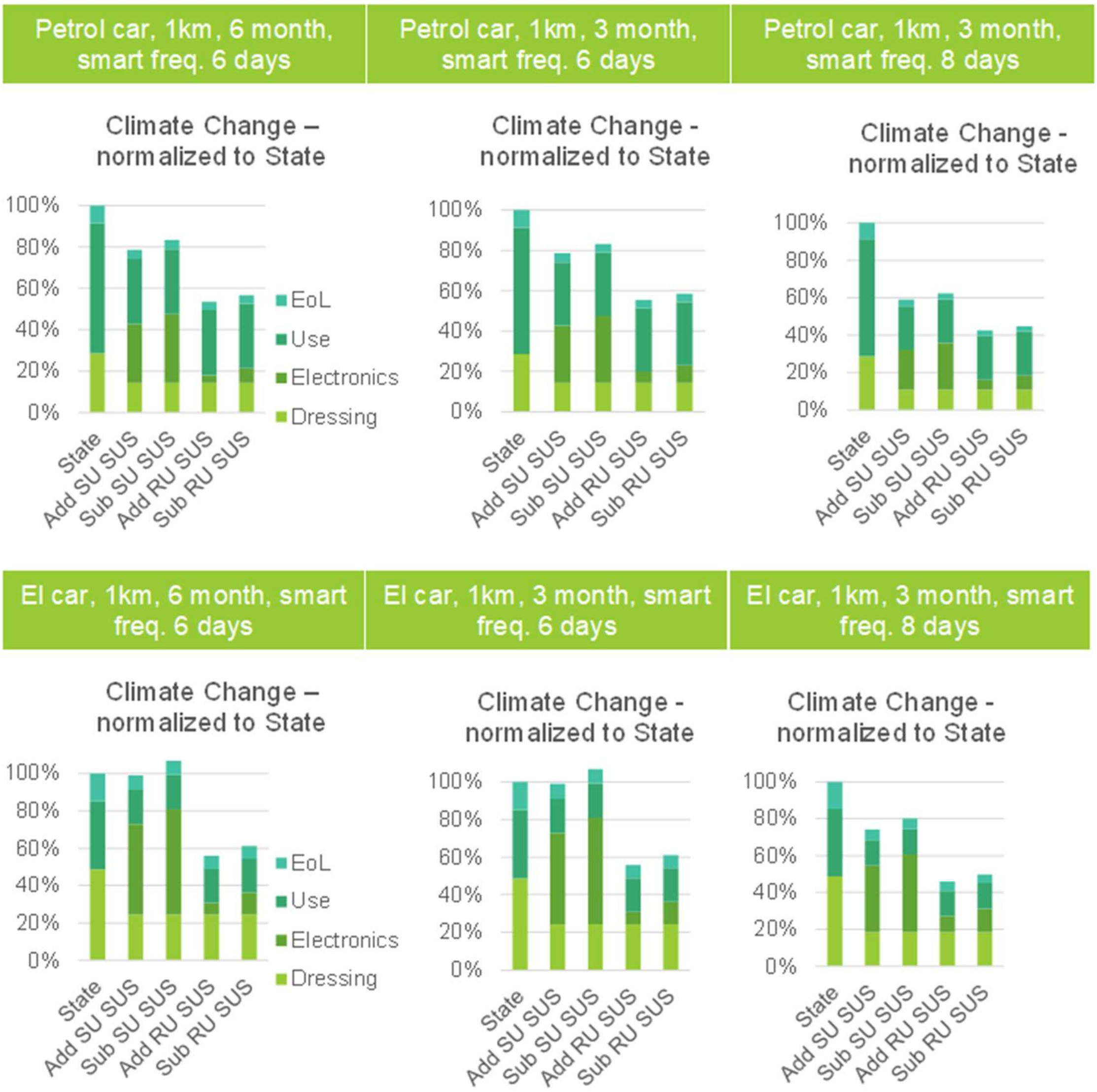


Figure 108. LCA conducted for Pilot 3.3 comparing state-of-the-art wound dressing with single use and modular smart dressing.

End user engagement:

Although Pilot 3.3 did not include a formally designed end-user study, end-user input was gathered through regular discussions with clinical experts, healthcare-experienced colleagues, and interdisciplinary peers. Feedback indicated that the Sensorflex demonstrator was generally perceived as particularly flexible and pleasant to the touch, with very limited concern regarding potential pressure-related issues during use.

The use of a reusable readout unit, compared to a fully single-use system, was noted to slightly increase complexity in handling. However, there was broad agreement that this minor disadvantage is outweighed by improvements in cost efficiency, performance, and sustainability. Placement of the Sensorflex underneath a secondary wound dressing was found to be straightforward and could be performed without difficulty, even by colleagues without prior training.

Overall, a positive consensus emerged regarding the concept and its anticipated usability. At the same time, it was clearly acknowledged that the pathway towards a final product remains substantial, particularly with respect to further technical maturation, clinical data acquisition, and compliance with regulatory requirements.

Pilot Achievements & key challenges in Gen 3:

The Gen 3 demonstrator is presented in Figure 109.

Figure 109 Generation 3 of Pilot 3.3 demonstrator on the artifical wound model with wound dressing.

Achievements

- Generative AI framework for synthetic data generation improved
- Thinner substrate material for flex PCBs
- Biobased materials tested for flex PCBs
- Flex PCB with paper substrate with carbon ink developed and tested
- LoRa+WuRx communication for use case developed

- Water ingress issue from Gen 1/2 addressed by redesign of the SMD-style pH sensor stickers solved
- Functionality demonstrated on artificial wound model with regards to temperature and pH

The following section presents the **Key Performance Indicators (KPIs)** defined for Pilot 3.3, providing a structured overview of the targets set at the outset of the project and the results achieved across the three generations of development.

Table 20: Pilot 3.3 Key Performance Indicators (KPIs)

#	KPI Description	Category	Target / Success Criterion	Comment
1	Classification accuracy	Technical	≥ 80%	More than 90% achieved for wound healing model, 96% for red sepsis events
2	Wound healing process phase identification and assessment	Technical	All 4 phases identified and assessed	Done with synthetic data by HTEC
3	Sensing elements for temperature, moisture and pH	Technical	TRL advancement from TRL 2/3 to TRL 5	TRL 5 partly achieved, in relevant environment, but reduced complexity (no protein). To be discussed with EB. Moisture sensor was discontinued, as discussed. Uric Acid sensor: TRL 4 Temperature: TRL 5
4	Complete data computing from multiple sensors	Technical	Capture of complete data from up to 7 sensors	More than 7 sensors tested and data captured in Grafana and computed to temperature and pH values. pH is even dependent on temperature.
5	Sustainability of material stack for single-use electronics	Environmental	≥ 50% of currently used materials replaced with more environmentally friendly alternatives	Subtractive: Reduced TPU thickness and biobased TPU Additive: Paper based substrate instead of PET and Carbon based ink instead of Ag ink
6	Power consumption for remote telemetry connection	Technical	Reduction from ~100s µW to single-digit µW (reduction factor of ×100)	TUHH: Wake-up receiver significantly reduced power consumption in an “always receiving” mode. Receiver section is in the single-digit µW range at the expense of reduced sensitivity compared

				to conventional LoRa implementations.
7	Wire bonding assembly reliability on stretchable substrates	Technical	0% failure rate for wedge lifting of bond pads on 2 different surfaces	Not achieved on TPU, because TPU is not suitable because of its stretchable properties. No wire bonding was selected in Pilot 3.3. Alternatives are assessed in KPI #8.
8	SMD assembly reliability on stretchable substrates	Technical	0% failure rate for 0402 components; < 20% failure rate for 0201 components	Achieved for low temperature solder and conductive adhesive
9	Life cycle environmental impact quantification	Environmental	Demonstrated reduction of ≥ 50% in relevant impact categories (minimum: GWP) vs. conventional solution	Achieved as shown in Fig. 113
10	Identification of environmental hot spots via LCA	Environmental	Minimum 5 environmental hot spots identified	Achieved, see hot spots below
11	Ecodesign solution alternatives per hot spot	Environmental	Minimum 2 alternative ecodesign solutions identified per hot spot	1. **Main Electronics**: Reduced design or reuse (2 variant) --> reuse better 2: **Substrat**: TPU vs bio TPU, PET, Paper, recyc PET (3 variant) 3: **Inks**: Ag, recyc Ag, Cu, recyc of CU, Carbon (3) 4: **IC**: energy consumption in manuf.: use of renewable electricity (1 variant) 5: **Transportation**: reduced dressing change frequency

Technology and sustainability readiness levels:

Table 21: Pilot 3.3 Technology and sustainability readiness levels:

	Gen 2	Gen 3
TRL	4	5
SRL	4	5

3. Technical - Final Pilot System Specifications and results

This chapter presents the final system specifications and corresponding results for each pilot in tabular form, reflecting their technical implementation and performance.

The Gen1 / M12 column outlines the specifications of the initial implementation. The Gen2 / M24 and Gen3 / M36 columns describe the evolution of the system towards subsequent generations, with Gen3 / M36 capturing the final specifications and achieved results, demonstrating the technical maturity and performance of the pilots.

3.1. System Specification Use Case #1 Circular electronic devices

3.1.1. Pilot#1.1 Green and circular image guided therapy systems

Table 22: Specifications Pilot#1.1 Green and circular image guided therapy systems

	Gen1 / M12 Implementation	Gen2 / M24 Implementation	Gen3 / M36 Implementation
Technical Specifications			
Reduce energy consumption by 30%	Concept-design available with the following properties: ≤ 50% of power consumption in low-power state Low-power state available for at least 3 hours per day on average Clinical workflow not interrupted Automatic shut-off of entire system possible after a configurable number of minutes of idle time and Time from low-power to ready to scan: less than 1 minute	Feature split into two parts: Early introduction for automatic shut-down and display stand-by sub-features. Tube stand-by to be investigated further before introduction.	Prototype with integrated power saving mode including automatic triggers. Expected average energy saving is 42%.
Reuse 25% of material in remanufactured systems	Concept of remanufactured Azurion 3.0 created with following properties: Lifetime of reused parts extended by	Packaging / Installation tools tested for reuse; maximum number of reuses estimated 80% of packaging reusable	Remanufacturing discontinued

	10 years (total 24 years) Material reused in remanufactured system ≥ 25% (currently 60-70%, but based on results from risk analysis parts may be replaced instead of reused) Functionality and reliability same as in new Azurion 3.0 All components are compliant with the latest standards and regulations (RoHS, REACH, MDR, FDA, etc.)	Remanufacturing discontinued	
Reuse installation frames	Not implemented	1x reuse of installation frames demonstrated	1x reuse in place, pilot executed with logistic partner.
Material reduction in new lightweight geometry design	Not in scope for Gen 1	Initial prototype of new light-weight geometry concept. Functioning imaging chain, including X-ray tube, detector, X-ray generator, collimator	Solution for passive modular end effector for lightweight geometry
Sustainability Requirements			
Lower LCA score by 10%	CO2 emission evaluated	Evaluation of impact lightweight geometry design to baseline Azurion. Evaluate other environmental categories (most relevant to be defined).	Final LCA of innovations in Gen 3.
Improve LCA/LCI processes and tooling	Data storage, LCA methodology compliant with CSRD Data model available within Windchill PLM BOM structure	All materials and weights available for lowest level in BOM Recommendation for granularity of data in mixed components (e.g., PCBAs)	Prototype tool for one-click LCA based on BoM created.

	For lowest level of tree material weight and type available (proxy used for components for which composition is unknown). Data collection started, to be completed in Gen2	Template and process for collection of sustainability data at suppliers established	

3.1.2. Pilot#1.2 Sustainable system integration and product design of personals health products

Table 23: Specifications Pilot#1.2 Sustainable system integration and product design of personals health products

	Gen1 / M12 Learn	**Gen2 / M24 Fast Iteration+Test**	**Gen3 / M36 Integration**
Technical Specifications			
Alternative technologies must achieve same functional requirements as current PCBA	Agree on requirement set from Central PCBA Team	Selection criteria used to choose Alternative technologies	Alternative technologies developed, integrated and tested in final Gen 3 PCBA
Sustainability Specifications			
Improve environmental impact assessment	New methods for assessing environmental impact explored. Final method selected.	Detailed PCBA LCA performed on simple PCBA.	Detailed PCBA LCA performed on Baseline and new Gen 3 PCBA.
Reduce environmental impact	PCBA Hotspots identified.	Alternative technologies to reduce impact tested.	Final Gen 3 PCBA developed and assessed. The environmental KPI impact reduction Targets on PCBA Level are achieved. The KPI Target on Product Level was not achieved.

NOTE: *Due to confidentiality, details on the targets and technologies are not shown in this deliverable. All detailed results are presented in the sensitive deliverables.*

3.1.3. Pilot#1.3 Sustainable luminaire

Table 24: Specifications Pilot# 1.3 Sustainable luminaire

	Gen1 / M12	Gen2 / M24	Gen3 / M36
Technical Specifications			
Slim lighting luminaires: Reduction of thickness of all layers and reduction of weight	For the light module, three different options investigated: a paper, ridged, and a flex light source. For all three options first, functioning samples were made and tested	Functional sample sustainable material on ridged (RGB)WW	Functional sample ridged and flex
Sustainable casing and diffusors	Housing: two different bio-based PLA filament materials tested, and small size demos realised Optics: different foam samples tested and evaluated	3D printed housing from standard materials, full size semi-functional demo 3D printed housing from sustainable materials, small size semi-functional demo Diffusor: small size demo from sustainable materials	3D printed housing from sustainable materials, full size demo, including diffusor from sustainable materials
Eco design and modularity	Different samples for housing, optics, and light module realised and tested/evaluated. Designs enabling modularity, consisting of single material components and reversible connections	Luminaire: small size demo Light module: renewable material glued/ reversible	Luminaire: full size, modular demo Light module: renewable material reversible
Sustainability Specifications			
Dismantling and separation to component level	Not included, as Gen1 focused on the separate luminaire components. However, easy dismantling and separation to component level are included in	End of life: 40% recovery of materials	End of life: 80% recovery of materials

	designing the Gen1 architecture		
Reduce material use	Additive manufacturing techniques used for housing (3D printing) and light module (printed electronics)	Additive manufacturing with renewable materials	Weight reduction light module by 25%
Lowest possible LCA	For all luminaire components, more sustainable, renewable materials are used, which has a positive impact on the LCA. Further, additive manufacturing techniques are used for the housing (3D printing) and the light module (printed electronics) which results in lower material and energy use during manufacturing. This also results in a lower LCA	Energy reduction soldering processes: not included in Gen 2 LCA reduction: additive manufacturing (3D printing), with renewable materials	Reduction of 10% of energy for soldering processes Overall reduction of LCA of 10%

3.2. System Specification Use Case #2 Sustainable manufacturing for electronics

3.2.1. Pilot#2.1 Embedded electronics for EEG monitoring

Table 25: Specifications Pilot 2.1 Embedded electronics for EEG monitoring

	Gen1 / M12	Gen2 / M24	Gen3 / M36
Technical Specifications			
Sustainable sensor interface and electronics	First test pilot done	Second test pilot of electrode samples, sample 126W paper based is pilot -ready & first PoC of EEG LDS sensor	Third test to EEG LDS sensor prototypes, sample 3 validated as a functional prototype, 3D design and development ongoing to reach the final prototype
Reliability	Use of PLUX hub	Use of PLUX hub	Use of PLUX hub

Bluetooth streaming	Included in the Hub	Included in the Hub	Included in the Hub
Signal acquisition & visualisation	Use of the PLUX EEG sensor and the Biosignals Studio software for the visualization of data	Use of the PLUX EEG sensor and the Biosignals Studio software for the visualization of data	Testing the final EEG LDS sensor prototype with electrode sample 126W and using Biosignals Studio software for data visualization

3.2.2. Pilot#2.2 Wearable health monitoring

Table 26: Specification Pilot 2.2 2 Wearable health monitoring

	Gen1 / M12	**Gen2 / M24**	**Gen3 / M36**
Technical Specifications			
Use more sustainable materials	Substrate material changed from PET to more sustainable ones. Silver printed conductive traces replaced with copper and carbon traces	Best materials from Gen1 selected for next print round without silver and PET	Best materials from Gen2 selected for final prototype(s)
Solution for multi-use electrode	Materials suitable for multi-use electrode printed	Samples with best materials from Gen1 selected for next print round	Multi-use electrode for ECG measurement made and tested
Shelf lifetime	No testing at Gen1	Samples to be tested for lifetime at MOV	There was no sufficient time to test the shelf lifetime of made electrodes
ECG and bio-impedance signal quality	ECG signal measurements with Gen1 prototypes to be made by MOV. Bioimpedance signal measurements for monitoring respiratory patterns will be conducted using state of the art electrodes and a measurement setup developed by EDI	ECG signal measurements with Gen2 prototypes to be made by MOV. Bio-impedance signal measurements with Gen2 prototypes to be made by EDI	Both ECG and bio-impedance electrode measurement made and signal quality proven to be suitable for intended use
Bioimpedance acquisition and	Stationary setup: Zurich Instruments MFIA + PC, 4 gold-plated polyimide	Compact wearable front-end prototype validated against MFIA using Gen 2	Final wearable bioimpedance node integrated with Gen 3 down-selected

respiratory-parameter software	reference electrodes;. Python peak-detection algorithm on PC extracts onset of inspiration/expiration, breathing rate and dynamic range	sustainable electrodes; algorithm ported toward embedded target and accuracy benchmarked vs. Gen 1	sustainable electrodes; < 5 W total; embedded respiratory-parameter and signal quality index algorithm running on the node, accuracy within agreed tolerance vs. Gen 1.
Standardised interconnect fabric with sensor-network software (mapping, communication, calibration, reprogramming)	Baseline MCMT jacket with wiring/electronics embedded as a separate manual second step; nodes programmed with fixed firmware before sealing	Fabric with integrated wiring patterns simulated and manufacturing guidelines prepared; mapping/communication/calibration/reprogramming methods implemented in software and lab-tested on benchtop nodes	Garment-scale fabric with wiring embedded during fabric manufacture; sensor placement decoupled from wiring; software library integrated so nodes are auto-mapped, calibrated and re-flashable post-deployment
Sustainability Specifications			
LCA and functional comparison	Preliminary LCA for materials selected for Gen2	LCA for materials and processes used on Gen2	Final LCA comparison between Gen3 and reference electrodes made Preliminary LCA for EDI energy and material efficient wearable bioimpedance system on interconnect fabric.

3.2.3. Pilot#2.3 Sustainable dashboard for automotive

Table 27: Specifications Pilot 2.3 Sustainable dashboard for automotive

	Gen1 / M12	Gen2 / M24	Gen3 / M36
Technical Specifications			
Eco design and circular design to enable component disassembly and material recovery	Done with standard materials in Gen1 as a reference	Reuse of Gen1 design	Reuse of Gen1 design
Bio-based substrate, inks and	Gen1 done with standards materials	Evaluate bio-based substrates from	Gen 2 substrate

conductive adhesives for injection		partners: for functional and decorative films (printability - thermoformability) as well as pellets (injection)	
Include functions: Dynamic lighting, touch buttons, sliders	Design and printing of all functions to achieve the IME functionalities and the constraints imposed by the automotive environment need to be respected has been done	Same as Gen1	Same as Gen1
Sustainability Specifications			
Evaluation of sustainability of IME technology for automotive	LCA performed by VTT, based on BOM data	Assessment of impact of using bio-based materials on LCA and comparison with LCA of Gen1 to propose recycling/reuse solutions (discussion with other partners)	Application of the guidelines defined by LCA on Gen2
Disassembly solutions (conductive and non-conductive adhesive)	Planned on Gen 3	Planned on Gen 3	Evaluate the implementation of dismantling solutions of foils and/or components from technical film using materials from partners or commercially available, while respecting automotive constraints.

3.3. System Specification and results Use Case 3 Environmentally compatible single use electronics

3.3.1. Pilot#3.1a In Vitro Diagnostics

Table 28: Specification Pilot 3.1a In Vitro Diagnostics

	Gen1 / M12	Gen2 / M24	Gen3 / M36

Technical Specifications			
Biodegradable substrate for printed electronics	Plan implemented; Function achieved good performance also with paper	Further tests of paper substrates for new electronic layout	Different strategies for using paper substrate tested and functional samples achieved
Biodegradable substrate for lateral flow microfluidics	LFA pressed down on PET substrate (fluidic barrier not yet investigated)	Options investigated: 1. single substrate as electrode carrier and microfluidics channel (defined by hydrophobic barriers) 2. two parts pressed onto each other (Paper based microfluidic substrate instead of nitrocellulose)	Focus on option 2, as the initial results were more promising, which is the analytical paper from TER as sustainable alternative to nitrocellulose established.
Sensing two analytes in single system	No sensor functionality on fully integrated system smart card (no analyte selectivity), maybe first results regarding standalone sensors	Combination of two sensors from one sample source	Full integration of two analyte testing not yet achieved. Individual testing shows promising results
Smartphone app	plan implemented, Function over achieved, demonstrate fill detection of strip, analog measurements of current over LFA	custom App with basic functions, simple operation of sensor measurement phases (error detection, fill too slow/not enough sample)	User-friendly app (guided measurement procedure, storage features, plot history, send to doctor, privacy) Distribution via Files (No AppStore publication)
Firmware	GUI firmware capable of running two 3-electrode measurements: 1. fully separated, 2. with parallel WEs, 3. by time interleaved activation of WEs (ahead of what was	Firmware able to measure available sensors, send results to smartphone	Firmware optimized for electrode operation and power consumption: sample taking averaging, power down times between measurements

	planned as Gen 2 previously)		
Electrodes	Fully integrated system with first guess carbon electrodes (to reduce material cost, no gold as sensor design not settled)	LFA electrodes realization with focus on gold WEs. 3 WE per LFD strip	Carbon-based electrodes established as sustainable alternative to Au.
Functionalisation	No functionalisation on pilot demo (full system)	First electrochemical tests with c-peptide assay	Successful integration of c-peptide assay, proof-of-concept for creatinine
Circuitry printing	Design for packaged chip, filling start and fill detection sensing, placement of components done	Select combinations of sensor choices to full card, adapt antenna and LFA localization to suit use case scenario, bare die mounting	Design for bare die (get rid of plastic package of microchip) sustainable printed circuit lines
System Housing / Protection Layer	3D printed plastic, to hold components LFA in place and press down onto electrodes	Change shape from credit card to stick. Design housing according to sensor requirements.	Full layout housing for stick-design available.
Super Cap	Bought project external	From TAU tested for the use case for functional and sustainable prototype versions	Operation with the one designed from TAU, adapted to the needs of the sensing scenario. Further optimized towards sustainability.
Sustainability Specifications			
LCA	Bill of Materials (electric components) of Gen1 available, submitted to FHG	LCA for Bill of materials of (electric components, biochemical components, inks.)	LCA for whole system including options for circular waste management.
Quality/ Extend shelf life	Not implemented yet	Chip response check, maybe humidity detection exposure	Shelf-life of assembled strip (electronic components) tested for at least 3-4 months. Functionalized LFD strips need to be stored in fridge.

Biodegradability	Not implemented yet	Sustainable vs functional prototype concepts evaluated	Focus on sustainable prototype

3.3.2. Pilot#3.1 b Smart Skin Patch

Table 29: Specification Pilot 3.1b Smart Skin Patch

	Gen1 / M12	**Gen2 / M24**	**Gen3 / M36**
Technical Specifications			
Biosensors on the sensing cartridge: Glucose	1st version fabrication ready for 06/2024. Invitro tests on 1st Gen sensor	**Gen 2a:** Cu/graphite inks replace Ag/AgCl; calibration R^2=0.82; salt pad → agarose hydrogel mitigation **Gen 2b:** Optical diffuse reflectance sensor; first in-vivo cohort (10 healthy + 2 diabetic); MARD=17.28%, CCC=0.711	Optical sensor fully validated in vivo; extended cohort 120 T2D; MARD=12.44%, MAE=17.58 mg/dL, r=0.86; continuous 1-min sampling; Consensus Error Grid Zone A; electrochemical route paused
Biosensors on the sensing cartridge: Creatine	Creatinine sensor included in scope of Gen 3 scope. Definition of R&S	*OBSOLETE. not carried forward*	*OBSOLETE. not carried forward*
Electronics cartridge must be reusable for other skin patches	PCB designed; energy consumption characterised; BLE not yet implemented; ECG sensor included in Gen 1 scope; wristband concept in TPU defined; fabrication end of 2024	**Gen 2a:** Electrochemical reader PCB; 3D-printed PLA housing; TPU wristband; ~24 h battery life **Gen 2b:** Multi-λ LED optical reader (R/G/IR reprogrammed from PPG); functional optical prototype; BLE pairing confirmed	Full optical reader integration; recycled PMMA optical window; 3D-printed PLA housing; TPU wristband; modular design (reader → WEEE EoL); BLE operational; session-handshake triggers AI pipeline in Cloud Platform
ECG Layer Substrate made of renewable, flexible and hypoallergenic materials	1st version - Fabrication End of 2024	OBSOLETE — not carried forward	*OBSOLETE — not carried forward*

Printed Electrodes on the sensing cartridge made of renewable materials (Carbon base inks)	1st version - Fabrication End of 2024	Cu/graphite inks replace Ag/AgCl; calibration R^2=0.82; salt pad → agarose hydrogel mitigation	*OBSOLETE — not carried forward*
Layered collecting sweat substrates for sweat Collection made of renewable materials	Salt-impregnated layered substrate designed; first fabrication ready 09/2024; sweat collection characterised in bench tests	Gen 2a: high salt content caused sensor inhibition; agarose-based hydrogel developed as passive sampler — in-vitro and in-vivo proof of concept validated with conductivity sensor	Optical patch: nylon rigid aligner, salt-impregnated nonwoven polyester layer, sweat metering layers, double-sided adhesive tapes (skin + spacer), interrogation chamber, reflecting bed. No screen-printed electrodes. Modular EoL: patch → MSW
Printed antenna at the electronics cartridge level	Functional version of printed antenna.	Not implemented	Not implemented
Battery life / power management	NA	~24 h battery life demonstrated at operational BLE duty cycle	Battery life extended to 1 week at 1-minute measurement periodicity (7× improvement); achieved via firmware-level LED duty-cycling, BLE power optimisation, and low-power sleep states between sampling events; eliminates daily recharging
Smartphone APP should connect to the electronics cartridge and get readings reliably and provide means of analysing energy and performance of the sensor	NA	Flutter (Android 10–14); hexagonal architecture; BLE pairing; encrypted local storage (JWT + keychain); login, pairing, measurement, bad-positioning alert; GitHub version control; GDPR-compliant	Redesigned Gen 3 UI: estimated glucose (eGu) time-series, Metabolic State label, Time in Range (TIR), Glucose Management Indicator (GMI), Glucose Stability, session countdown; cloud integration; automatic session-triggered AI recommendations (no manual intervention)
Cloud platform integration (BioT) — session management, data security, GDPR	NA	Cloud data pipeline architected; user identity management defined; JWT +	Cloud platform operational: session orchestration, async AI inference pipeline, JWT token-based

		encrypted storage secured API endpoints; 10,000+ concurrent uploads stress-tested with zero data loss	authentication, role-based access, GDPR-compliant anonymisation; APIs enable interoperability with third-party health tools; platform reusable for telemedicine, sports, and wellness
Predictive AI model & Training database should predict and analyse glucose profiles	6 public diabetes datasets identified and analysed; model architecture selected; cGAN synthetic data strategy defined; feature importance analysis approach designed	RAG-based Diabetes Care Recommender built; aligned with ADA 2025 guidelines; personalised recommendations generated per patient risk cluster; clinician dashboard demo (clinical overview, patient profile, recommendations tabs)	Automatic session-triggered delivery via BioT — no manual intervention; recommendation fidelity=3.5/5; relevance=4.81/5 (expert panel evaluation vs ADA 2025 guidelines); per-query footprint 0.00207 kgCO_2e (CodeCarbon validated)
Sustainable materials for sensing cartridge	NA	New Design with more sustainable materials	Final sustainable design finished and ready for production
Sustainability Specifications			
Redesign of the smart patch to achieve the lowest possible number of single-use items	Baseline design with salt-embedded pad and Ag/AgCl screen-printed electrodes; LCA initiated; electrodes identified as 60–90% of environmental impact; patch GWP = 0.149 kg CO_2e (cradle-to-gate)	Gen 2a: Cu and graphite inks validated as Ag/AgCl replacements; updated LCA (WP4/Fraunhofer IZM); GWP, ADPe, FAETP significantly reduced. Gen 2b: optical design removes electrodes entirely from disposable patch	Optical patch: zero screen-printed electrodes; nylon aligner + sustainable sweat layers; recycled PMMA window in reader; modular EoL strategy (patch → MSW; reader → WEEE); final sustainable design validated and ready for steady fabrication processes
Replacements of polluting materials	NA	Cu and graphite inks tested and adapted for glucose and sweat rate sensors; equivalent electrochemical performance confirmed; silver largely eliminated	Final materials processing tuned; optical design eliminates all metallic conductive inks from disposable patch; −28 g CO_2e/unit, −80% mineral resource use vs Gen 2 electrode

		from Gen 2a sensor fabrication	design; >3 kg CO_2e/month saved; copper recycling from subtractive route modelled (D4.6)
AI & software energy efficiency — sustainable digital health platform		BLE-only architecture; local encrypted storage reduces cloud data transfers; no always-on radio; GDPR anonymisation minimises redundant data retention; platform designed for multi-tenant reuse	AI: GPTQ 4-bit quantisation (−75% GPU compute); 0.00207 kgCO_2e/query; −51% CO_2e vs GPT-5; −76% energy vs GPT-5 (CodeCarbon, WP2). App: 28% BLE TX reduction; 18% device lifespan increase (WP2 validated). Cloud on renewable energy; shared infrastructure avoids local server e-waste
Lowest possible LCA	Cradle-to-gate LCA completed for Gen 1 design; electrodes = 60–90% of impact across categories; baseline GWP = 0.149 kg CO_2e/patch; silver-based inks identified as primary hotspot	Gen 2a LCA updated (WP4/Fraunhofer IZM); Cu and graphite ink alternatives assessed; GWP, ADPe, FAETP reductions quantified; first design with comprehensive LCA analysis available	Gen 2a LCA updated (WP4/Fraunhofer IZM); Cu and graphite ink alternatives assessed; GWP, ADPe, FAETP reductions quantified; first design with comprehensive LCA analysis available
Other Specifications			
Investigation on availability of public data sets related to glucose measurements on sweat	Identified 6 public datasets related to diabetes. Results on the analysis of the datasets studied	First tests of the generated/available datasets to train the AI models	Models trained with real and public/ synthetic data
In vivo testing of glucose sensor	NA	First in-vivo cohort designed and recruited; 10 healthy volunteers + 1 T1D + 1 T2D; optical sensor Gen 2b validated vs SD CodeFree glucometer; MARD=17.28%, CCC=0.711;	MARD=12.44%, MAE=17.58 mg/dL, r=0.86; continuous 1-min monitoring over multi-day periods; TIR 77% (sweat) vs 79% (CGM); GMI 7.19% vs 6.83%; ATTD 2026 presentation (Barcelona)

		Consensus Error Grid Zone A	

3.3.3. Pilot#3.2 Smart hygiene

Table 30: Specifications Pilot 3.2 Smart hygiene

	Gen1 / M12	**Gen2 / M24**	**Gen3 / M36**
Technical Specifications			
Sensors: Temperature, humidity, enzyme, pH	Sensor label including printed temperature and humidity sensors, and pH sensor as mounted component. Trypsin enzyme sensors were not included in the sensor label in Gen 1, but these were evaluated separately.	Sensor label including printed temperature and humidity sensors. pH and enzyme sensors mounted as separate components.	Sensor labels including all four sensors. Temperature and humidity sensors printed directly on the label. Enzyme sensor modified to work with two electrodes, simplifying readout. Integrated either as sticker component or directly printed. system. Redesigned pH sensor with improved adhesion for component assembly. Alternative with fully printed pH sensor. pH signal output over 24 h. T, RH verified to be functional for several days in climate chamber tests and after 8 h in body water-bath.
Wireless readout	Wired connection between sensor label and readout electronics. Wireless transmission of data from readout electronics via Bluetooth.	Two versions of the sensor label with either wired or wireless (NFC) readout of the sensor labels with readout electronics.	Wired readout of the sensor label in design A. Wireless readout of the sensor label via NFC in design B,

	Readout electronics including first version of analog front-end for readout of sensors and otherwise using existing electronics from RISE.	Wireless communication between readout electronics and the cloud via either base station or mobile phone.	demonstrated with smartphone. Wireless communication by BLE between readout electronics and the cloud via either base station or mobile phone. Partial inference model validation based on the real sensor data was performed on the mannequin for T and RH.
Wireless energy harvesting	NA	Wireless energy transfer (and communication) between sensor label and readout electronics using NFC	Same as in Gen 2. The harvested energy is not stored in the label. It is instantaneously used.
Sustainable materials for substrates and inks	Sensor label using a paper substrate. Biobased ink for humidity sensor. Carbon ink used for electrodes in humidity sensor. Ink for temperature sensor with reduced metal content. pH sensor component including printed carbon and Ag/AgCl electrodes on PET substrate	Same as in Gen 1. Enzyme sensor component including printed carbon and Ag/AgCl electrodes on PET substrate.	Same as in Gen 2. pH and enzyme components replaced with fully printed sensors in one label variant. Reduced metal content in temperature sensor ink. Replacing silver with copper for printed conductors not successful with the selected substrate. More work needed. Sustainable adhesive chosen.
Use of printing and other additive technologies ≥75% of sensor system	Screen printing used for conductors, insulating layers, contacts, temperature and humidity sensors. Lamination used for protective layers and stiffener at contacts	Same as in Gen 1. Pick-and-place and dispensing used for design B.	Same as in Gen 2. Sensor label variant with only printed sensors.
Sensor label size		Small in size so that absorption in hygiene	Similar to Gen 2.

		product is still acceptable	Sensor area and component footprints reduced somewhat.
Sustainability Specifications			
LCA	Initial LCA for the system	LCA for the Gen 2 has been extended to include all life stages of the system.	Improved LCA models providing accurate results.
Materials in sensor label ≥90% sustainable (by weight)	Cellulose-based substrate. Humidity sensor including biobased materials and carbon electrodes.	Replacement of materials in sensor label with more sustainable alternatives.	The final design had materials chosen such that they are more than 90% sustainable by weight by design.
Other Specifications			
Minimal cost increase	Not implemented yet Focus on functionality but low-cost methods and materials anyhow used in manufacturing.	Cost considered in selection of designs, materials and processes.	Optimisation of material and energy use during manufacturing.
Suitable for body/skin contact	Not implemented yet	Will be considered when selecting materials for sensor label.	Already considered in Gen 2.

3.3.4. Pilot#3.3 Smart wound dressing

Table 31: Specifications Pilot 3.3 Smart wound dressing

	Gen1 / M12	Gen2 / M24	Gen3 / M36
Technical Specifications			
Parameters for wound classification	ADC are used to operate and read out sensor electrodes. Temperature: - resistive - moisture - capacitive - pH - potentiostatic	pH, Temp	Main sensors for smart wound dressing are pH, Temp, uric acid sensor. Investigation and development of supporting MEMS sensors with digital interface done.
Sustainable materials for components	Benchmark LCA for first Gen1 serves as reference for improvements at system and component level.	First parts realised in more sustainable material, but not all components	System demonstrators build with more sustainable material

Modular concept	Sensor elements attached to flexible PCB - read out and processing in separate breadboard	First HW realised for modules	final concept realised
Smartphone app with automatic alarm	contact-less communication interface NFC (PICC according to ISO/ IEC 14443 Type A); Is prepared as add on communication to minimise high energy consuming BLE communication;	App and warnings defined	App including automatic alarm working
Automatic data analysis and generation	AI-based data processing, Reduced data gathering and data exploration for synthetic data generation purposes	Data analysis done with simulated data	AI trained partly on real data
Data security	Embedded security (AES hardware accelerator; true Random Number Generator (TRNG));	Data management defined	Data transfer securely realised
Biocompatible, flexible, permeable PCB and electrodes	Compare 2 different flexible PCB variants in terms of functionality and sustainability (additive vs subtractive)	Material selection finalised	Electronics manufactured on biocompatible (bio TPU or paper), flexible aPCB
Wearable system	Flex PCB wearable and integrable into wound patch - tests with demonstrator of Gen1	1st wearable system with bigger form factor	Final system with small form factor
Lifetime minimum 14 days	Gen1 with lifetime of 7 Days	Lifetime 14 days realized	Lifetime +14 days not achieved
Resistant against sterilisation	Gen1 Demo ready for testing and concept design	First packaging approach under evaluation	System packaged to fulfil this requirement
Technical results			
Flexible PCBs	Functional development and design of flexible PCBs tailored to use case requirements Substrate target thickness ~120 µm	Printing: testing of sustainable materials (cellulose based) and inks compliant with regulations of health care. Substrate target thickness ~60 µm (without shielding)	Compare functionality of different material (i.e. bio-based) with respect to processing. Compare to sustainability achievements → focus on most

		Implementation of shielding structures Improve manufacturing regarding LCA results → e.g. less substrate waste	reliable and sustainable solution
Firmware	Define system architecture	Increase energy efficiency by defining stand by domains	Decrease energy consumption by adjusting firmware to limits of use case requirements (measurement frequency vs sending data to base station)
Read out unit	Develop functional circuitry with flexibility in testing different design options and sensors	Decrease size of PCB 25% Work on more sustainable materials for PCB	Focus on most sustainable solution regarding the use case (results taken from component LCA) and further improve layout
ASIC	Functional development regarding use case requirements	Evaluation of packaging variants in terms of sustainability	Testing of integration possibilities of the packaging variants on new PCB technologies (e.g. bare die)
Communication	BLE Chip for continuous data transmission to base station	Reduce BLE chip to smaller BLE module to decrease environmental impact. Prepare NFC interface as save and energy efficient add on communication	Adjust sending rate to limits of use case requirements to save energy → define specific communication protocols that define which way of communication is used in which scenario and defines the respective parameters
Sensing	Temperature off shelf; first iteration of pH and moisture included	1st generation of enzyme sensor (uric acid), Include printed Temperature sensor to decrease environmental impact Improve pH	Optimise Mult sensing system and decrease any unwanted interaction between single sensors

Housing and connection for read out	Plastic housing as benchmark	Use LCA results as guideline for new materials. Test biodegradable materials in terms of longevity and sterilisation process. Remove ZIF connector and work on different solutions (e.g. magnetic connection)	Focus on best solution in terms of functionality and sustainability and improve with help of precise LCA results
Data management	Reduced data gathering and data exploration for synthetic data generation purposes	Integrate more sensor measurements in synthetic data and development of AI algorithm for wound healing monitoring. At the same time, the integration of AI algorithm in edge device will be researched	Further development of AI algorithms including the sepsis detection algorithm as well as the optimisation based on results from Gen2 and integration in edge device
Application of the sensor flex to the wound site - tail	Simple tail that slightly sticks out underneath the wound dressing	Longer tail allows for easier application of the readout unit and hopefully leads to more comfort	Evaluate trade-off between longer tail and thus easier application versus the increased noise
Optimisation of sensor flex layout	Big design with multiple sensor slots for easier testing and ability to test multiple sensors	Reduction to necessary sensors – reduce footprint of the sensor patch as much as possible so that wound, and exudate flow are not inhibited	Further improvement on Gen 2. Hybrid shielding solutions for better sustainability.
Meeting MDR requirements	Not considered (technology exploration)	Initial regulatory screening of functional concept	Regulatory considerations maintained and adapted in line with prototype evolution

4. Sustainability - Final Pilot Design

This chapter describes the requirements and corresponding contributions from other work packages (WPs) for the design and implementation of each sustainability pilot. The information is presented in a structured tabular format, linking required inputs to their role in enabling pilot deployment and impact.

The column Gen1 / M12 summarizes the deliverables provided by other WPs that supported the initial implementation of the pilots and established the baseline for sustainability-related functionalities.

The columns Gen2 / M24 and Gen3 / M36 present the requirements for the subsequent generations, reflecting the progressive evolution of the pilots towards higher levels of maturity. In particular, the Gen3 / M36 column captures the final implementation status and highlights the achieved results, demonstrating how the pilots contribute to the project's sustainability objectives and overall impact.

4.1. Advances vs. Gen1 Use Case #1 Circular electronic devices

4.1.1. Pilot#1.1 Green and circular image guided therapy systems

Table 32: Sustainability Development Cycle Pilot 1.1

	Gen1 / M12 Implementation	Gen2 / M24 Implementation	Gen3 / M36 Plan	M36 Implementation Achievements
Sustainability Development Cycle				
Reduce energy consumption by 30%	Concept-design available with the following properties: ≤ 50% of power consumption in low-power state Low-power state available for at least 3 hours per day on average Clinical workflow not interrupted Automatic shut-off of entire system possible after a configurable number of minutes of idle time and	Feature split into two parts: Early introduction for automatic shut-down and display stand-by sub-features. Tube stand-by to be investigated further before introduction.	Automatic triggers for low-power and auto-shutdown implemented Low-power triggered by closing a patient or manually via UI Wake up via UI or by selecting patient for acquisition Automatic shutdown after configurable idle time, activated within configurable time slots (for example, outside working hours)	Prototypes of automatic shutdown and AI-triggered low-power states realized for happy flow scenarios. Patient/procedure closing not selected as trigger. Automatic patient detection used instead. Results in 42% reduction of energy consumption.

	Time from low-power to ready to scan: less than 1 minute			
Reuse 25% of material in remanufactured systems	Concept of remanufactured Azurion 3.0 created with following properties: Lifetime of reused parts extended by 10 years (total 24 years) Material reused in remanufactured system ≥ 25% (currently 60-70%, but based on results from risk analysis parts may be replaced instead of reused) Functionality and reliability same as in new Azurion 3.0 All components are compliant with the latest standards and regulations (RoHS, REACH, MDR, FDA, etc.)	Packaging / Installation tools tested for reuse; maximum number of reuses estimated 80% of packaging reusable Remanufacturing discontinued	Remanufacturing discontinued	Remanufacturing discontinued
Reuse installation frames	Not implemented	1x reuse of installation frames demonstrated	5x reuse of installation frames	1x reuse in place, pilot executed with logistic partner.
Material reduction in new lightweight geometry design	Not in scope for Gen 1	Two robotic arms on linear tracks, one ceiling track, one floor track.	User interface; monitor, controller Patient table	Achieved significant material reduction (~660 kg) through a lightweight new geometry

		Functioning imaging chain, including X-ray tube, detector, X-ray generator, collimator	Active tool changer with tool rack Several end effectors; different X-ray detectors for example	design, demonstrating that core imaging functionality can be realized with fewer components and reduced mass, while improving sustainability and preserving scalability for future system integration. This is complemented by the introduction of a passive tool-changer concept with a tool rack, enabling modular exchange of end-effectors without adding complexity to the system architecture. If including packaging and ceiling construction: ~1810 kg.
Sustainability Development Cycle				
Lower LCA score by 10%	CO_2 emission evaluated	Evaluation of impact lightweight geometry design to baseline Azurion Evaluate other environmental categories (most relevant to be defined)	Evaluation to be done for selected categories on all innovations in Pilot 1.1	Reduction of 22% and 40% compared to the baseline Azurion 3.0 (depending on benchmark scenario on energy, same utilization) Impact per patient: reduction of 40-62% compared to benchmark 1,

				reduction of 22-50% compared to benchmark 2, considering three utilization scenarios of 3, 4, or 5 patients treated per day.
Improve LCA/LCI processes and tooling	Data storage, LCA methodology compliant with CSRD Data model available within Windchill PLM BOM structure For lowest level of tree material weight and type available (proxy used for components for which composition is unknown). Data collection started, to be completed in Gen2	All materials and weights available for lowest level in BOM Recommendation for granularity of data in mixed components (e.g., PCBAs) Template and process for collection of sustainability data at suppliers established	LCA tooling works as a service for engineers to assess the impact of design choices on sustainability. LCA process fully automated for common evaluation criteria	LCA included in the VPC methodology to provide early insight on hotspots and possible benefits of the new proposition. Prototype tool for one-click LCA created. Collecting feedback.

4.1.2. Pilot#1.2 Sustainable system integration and product design of personals health products

Table 33: Sustainability Development Cycle Pilot 1.2

	Gen1 / M12 Implementation	Gen2 / M24 Implementation	Gen3 / M36 Plan	M36 Implementation Achievements
Sustainability Development Cycle				
Improve environmental impact assessment	New methods for assessing environmental impact explored.	Detailed PCBA LCA performed on simple PCBA.	Detailed PCBA LCA performed on Baseline and new Gen 3 PCBA.	Detailed PCBA LCA performed on Baseline and new Gen 3 PCBA. Methodology promoted for wider

	Final method selected.			adoption in Philips.
Reduce environmental impact	PCBA Hotspots identified.	Alternative technologies to reduce impact tested.	Final Gen 3 PCBA developed and assessed.	Final Gen 3 PCBA developed and assessed. The environmental KPI impact reduction Targets on PCBA Level are achieved. The KPI Target on Product Level was not achieved.

NOTE: *Due to confidentiality, details on the targets and technologies are not shown in this deliverable. All detailed results are presented in the sensitive deliverables.*

4.1.3. Pilot#1.3 Sustainable luminaire

Table 34: Sustainability Development Cycle Pilot 1.3

	Gen1 / M12 Implementation	**Gen2 / M24 Implementa-tion**	**Gen3 / M36 Plan**	**M36 Implementation Achievements**
Sustainability Development Cycle				
Slim lighting luminaires : reduction of thickness of all layers and reduction of weight	For all three options first samples made: a paper light source together with SCR and TER, a rigid light source together with TNO, and a flex light source together with VTT	Functional (small size) samples for all different options for printed electronics (SCR, TER, TNO, VTT)	Improved functional connectable/modular full-size samples for selected options for printed electronics (SCR, TER, TNO, VTT)	Full-scale, connectable/modular light sources using printed electronics for upward and downward lighting, installed in the demonstration models (SCR, TER, TNO, VTT)
Sustainable casing and diffusors	Housing: two different bio-based PLA filament materials from UPM tested and successfully housing samples printed; printing housing samples with PEF material from ARNP not successful yet Optics: foams from VTT tested and evaluated	Renewable, sustainable materials needed that can be 3D printed (housing); improved printability, absorption, reflection, transmission (UPM, ARNP, VTT)	Optimal renewable, sustainable material selected that can be 3D printed (housing); with good printability, absorption, reflection, transmission (UPM, ARNP, VTT)	Renewable, sustainable materials tested for 3D printability (housing), absorption, reflection, transmission (UPM, ARNP, VTT) Transparency of housing still an issue

Eco design and modularity	Modularity aspects and reversible connections included in Gen1 architecture	Designs enabling modularity, consisting of single material components and reversible connections	Designs enabling modularity, consisting of single material components and reversible connections	Modular design with reversible connection of the main components (housing, diffusor, light sources)
Sustainability Development Cycle				
Dismantling and separation to component level	Not included in Gen1	End of life: 40% recovery of materials (MIR)	End of life: 80% recovery of materials (MIR)	✓ Single material housing 82% of total ✓ Only 18 % heterogenous materials
Reduce material use	Samples made for all three options for printed electronics light module and for 3D printed housing	Additive manufacturing techniques, optimised low-weight design	Weight reduction light module by 25%	✓ Paper light source: 65% ✓ HUE light source: 83% ✓ Flex light source: 67% • Rigid light source: NA Includes reflector
Lowest possible LCA	Good results on LCA modelling of light module with FHG	Improved LCA modelling of light module, first modelling of housing and optics (FHG)	Full LCA model for light module, housing, and optics (FHG)	✓ Full LCA model available for light module, housing, and optics

4.2. Use Case #2 Sustainable manufacturing for electronics

4.2.1. Pilot#2.1 Embedded electronics for EEG monitoring

Table 35: Sustainability Development Cycle Pilot 2.1

	Gen1 / M12 Implementation	Gen2 / M24 Implementation	Gen3 / M36 Plan	M36 Implementation Achievements
Sustainability Development Cycle				
Sustainable sensor interface and electronics	First test pilot done	Development of a recycling electrode & printed electronics in the EEG sensor	Recycling paper based electrode pilot-ready & reusable EEG LDS sensor final prototype	Recycling paper based electrode achieved, EEG LDS sensor sample 3 is a functional

				prototype, final PoC design & development sensor ongoing
Reliability	Use of PLUX hub	Use of PLUX hub	Use of PLUX hub	Use of PLUX hub
Bluetooth streaming	Included in the Hub	Included in the Hub	Included in the Hub	Included in the Hub
Data logging	Use of PLUX hub	Use of PLUX hub	Use of PLUX hub	Use of PLUX hub
Signal acquisition & visualization	Use of PLUX EEG sensor and the BioSignals Studio software for data visualization	Use of PLUX EEG sensor and the BioSignals Studio software for data visualization	Use of EEG LDS sensor final prototype and Biosignals Studio Software for data visualization	Not achieved yet, waiting for the final prototype of the EEG LDS sensor
Sustainability Development Cycle				
Lower environmental footprint	No	No	Yes	Yes
Reusability	Yes, except the electrode	Yes, except the electrode	Yes, electrode recycling and a reusable EEG sensor	Yes, electrode recycling and a reusable EEG sensor

4.2.2. Pilot#2.2 Wearable health monitoring

Table 36: Sustainability Development Cycle Pilot 2.2

	Gen1 / M12 Implementation	**Gen2 / M24 Implementation**	**Gen3 / M36 Plan**	**M36 Implementation Achievements**
Sustainability Development Cycle				
Use more sustainable materials	Samples printed 12/2023 for testing.	Test prints to be made during summer 2024	Test prints to be made H2/2025	Successful printing made with sustainable material stack
Solution for multi-use electrode	Preliminary tests to be made	Test prints to be made during summer 2024	Test prints to be made H2/2025	Multi-use ECG electrodes made and tested. Based on test results the electrical contact between electrode and skin is easily

				unstable and requires tight integration of the electrode to the body.
Shelf lifetime	Not testing at Gen1	MOV makes tests for samples aged at climate chamber	MOV makes tests for samples aged at climate chamber	Climate chamber tests not made within project time due delays in part deliveries
ECG and bio-impedance signal quality	Tests to be made by MOV 02/2024 Tests benchmarking the performance to be made by EDI 04/2024	Tests to be made by MOV and EDI by end of 2024	Tests to be made by MOV and EDI by autumn 2025	Developed sustainable material stack worked for ECG and bio-impedance electrodes
Energy- and material-efficient wearable bioimpedance system on interconnect fabric	Stationary MFIA+PC acquisition baseline with Python processing on PC and commercial gold-polyimide electrodes; MCMT garment baseline with wiring embedded as a separate semi-manual step and sealed firmware	Compact wearable front-end and embedded respiratory-parameter algorithm benchmarked vs. MFIA baseline using Gen 2 sustainable electrodes; fabric with integrated wiring patterns simulated and manufacturing guidelines prepared; mapping/calibration /reprogramming methods lab-tested on benchtop nodes	Wearable node (target < 5 W) integrated with down-selected Gen 3 sustainable electrodes and embedded respiratory-parameter and signal-quality-index algorithm; garment-scale fabric with wiring embedded during fabric manufacture; post-deployment node re-mapping and re-flashing enabled	Wearable node operating with sustainable electrodes at reduced power and material footprint vs. Gen 1 baseline; single-process wiring embedding demonstrated at garment scale and post-deployment node re-mapping/re-flashing shown, reducing manufacturing waste and extending hardware lifespan
Sustainability Development Cycle				
LCA and functional comparison	To be made at VTT by 06/2024	To be made at VTT by 12/2024	To be made at VTT by 12/2025	Accomplished

Other				
Usability on patients	Preliminary tests to be made at MOV	Preliminary tests at MOV	Tests made at MOV and EDI	Works well for up to 24 hour wear time. Not suitable for sweating exercises and shower due paper substrate.
Price estimation	SCR will evaluate the samples also with the ink price	SCR provides price comparison for different Gen2 variants.	SCR provides price comparison between Gen3 and reference electrodes	Price around 20% cheaper than reference, less sustainable, medical electrodes

4.2.3. Pilot#2.3 Sustainable dashboard for automotive

Table 37: Sustainability Development Cycle Pilot 2.3

	Gen1 / M12 Implementation	Gen2 / M24 Implementation	Gen3 / M36 Plan	M36 Implementation Achievements
Sustainability Development Cycle				
Eco design and circular design to enable component disassembly and material recovery	Design of an HMI dashboard with thermoformed IME foil and deco foil to reach the specifications. Standard materials to be used in Gen1 as a reference	Reuse of Gen1 design	Reuse of Gen1 design	Reuse of Gen1 design
Bio-based substrate, inks and conductive adhesives for injection	NA, Gen1 done with standards materials	Evaluate bio-based substrates from partners: for functional and decorative films (printability - thermoformability) as well as pellets (injection)	Gen 2 substrate	Gen 2 substrate
Include functions:	Design and printing of all	Same as Gen1	Same as Gen1	Same as Gen1

Dynamic lighting, touch buttons, sliders	functions to achieve the IME functionalities and the constraints imposed by the automotive environment need to be respected			
Sustainability Development Cycle				
Evaluation of sustainability of IME technology for automotive	LCA performed by VTT, based on BOM data	Assessment of impact of using bio-based materials on LCA and comparison with LCA of Gen1 to propose recycling/reuse solutions (discussion with other partners)	Application of the guidelines defined by LCA on Gen2	Application of the guidelines defined by LCA on Gen2
Disassembly solutions (conductive and non-conductive adhesives)	NA, planned on Gen3	NA, planned on Gen3	Evaluate the implementation of dismantling solutions of foils and/or components from technical film using materials from partners or commercially available, while respecting automotive constraints	No commercial grade of adhesives on the market because of high T°C needed on thermoforming and injection steps
Other				
NA				

4.3. Use Case #3 (IFAG) Environmentally compatible single use electronics

4.3.1. Pilot#3.1a In Vitro Diagnostics

Table 38: Sustainability Development Cycle Pilot 3.1a

	Gen1 / M12 Implementation	Gen2 / M24 Implementation	Gen3 / M36 Plan	M36 Implementation Achievements

Sustainability Development Cycle				
Biodegradable substrate for printed electronics	First test-prints with test structures	Paper types modified (TER) to needs of sensor and test prints of full layout (TER)	Paper substrate (TER)	Paper substrate for printing
Biodegradable substrate for lateral flow microfluidics	Initial tests	Float barrier (VTT) and paper-based LFD investigated	Design and Manufacturing concept for fluidic in/on paper substrate (VTT, URV, CSEM, CBMED, SCR, CAN)	Nitrocellulose has been replaced with Analytical paper, proof-of-concept for integration of LFD in paper substrate (via float barrier) successful
Sensing two analytes in single system	Not yet	Sensor design, number of electrodes (overall, per sensor), description about mode of operation (CSEM, URV, CBMED)	Mode of operation to be specified by sensor developers, estimation of lifetime and statistic (CSEM, URV, CBMED)	C-peptide: mode of operation defined and tested Creatinine: proof-of-concept (optically) available (URV, MEDUG, CBMED)
Smartphone App	Basic operation APP (STS)	Custom App (STS)	Improved app (STS), usability, functions & features (save data, send data)	App tested with full prototype, user feedback evaluated and implemented, online dashboard available (STS)
Firmware	Basis demo for analog measurement at electrodes (IFAT)	Firmware to work with smartphone app (IFAT, STS), sensor specification of operation (URV, CBMED, CSEM)	Firmware to run full method flow of two sensors (charging, measurement, storing results internal, allow read out by authorised party) (IFAT)	Firmware available for full method flow – tested with fully integrated prototypes (IFAT, MEDUG, CBMED)
Electrodes	Test designs	Number of electrodes and material layers	Manufacturing flow plan	Successful manufacturing on PET and

		(Au, C) (URV, CBM, MEDUG, CSEM, ONA)	(URV; VTT; SCR; CAN)	paper using C instead of Au, electrochemical response tested (SCR, URV, CSEM, IFAT)
Functionalisation	Not yet	Layer manufacturing chain (SCR, VTT, CAN)	Manufacturing flow plan (URV; VTT; SCR; CAN)	Functionalization of electrode tested (CSEM)
Circuitry printing	Test prints with concept design	Printing to achieve necessary resolution for bare die flip chip (SCR) (CSEM for layout, full system: antenna & electrode)	Sustainable ink (copper) and bare die	Printing of fanout for bare die successful (CSEM, SCR), Multiple iterations of Cu-based printing with promising results
System Housing / Protection Layer	Credit card form factor housing to hold parts (IFAT)	3D design for cartridge (CSEM), pen like structure, dip on or pee onto, antenna redesign (CSEM, CSIC)	Reworked design (antenna) (IFAT, CSEM), decrease overall size	Full system housing available, multiple iterations done to improve performance (CSEM, URV, IFAT, MEDUG)
Super Cap	External	Cap suited for new form factor of Gen 2 (TAU)	Cap optimised to use case (TAU)	Sustainable supercap further optimized (TAU)
Sustainability Development Cycle				
LCA		LCA for individual components and materials. Concept of disposal: how to dismantle components for available waste categories in EU (Fraunhofer)	Information regarding disposability of components	LCA finalized for different prototype versions
Quality/ Extend shelf life		Visual humidity check printed by (VTT) maybe in the step of component	Investigate in sensors weak points / aging (URV, CSEM, CBMED, MEDUG)	Electronic parts tested for at least a shelf life of 4 months

		placement possible		
Biodegradability		Identify non-biodegradable components, and their options of circular waste management	Exchange of materials to biodegradable alternatives	3D printed housing using bio-plastics

4.3.2. Pilot#3.1 b Smart Skin Patch

Table 39: Sustainability Development Cycle Pilot 3.1b

	Gen1 / M12 Implementation	**Gen2 / M24 Implementation**	**Gen3 / M36 Plan**	**M36 Implementation Achievements**
Sustainability Development Cycle				
Biosensors on the sensing cartridge: glucose	1st version fabricated (06/2024); in-vitro characterisation on synthetic sweat; salt inhibition identified (~50% signal loss vs expected).	Gen 2a: Cu/graphite inks validated; calibration R^2=0.82; agarose hydrogel mitigation implemented Gen 2b: optical sensor; in-vivo cohort (10 healthy + 1 T1D + 1 T2D); MARD=17.28%, CCC=0.711; CEG Zone A	Extend volunteer cohort; validate continuous monitoring at 1-min frequency; benchmark vs CGM for TIR and GMI	MARD=12.44%, MAE=17.58 mg/dL, r=0.86; continuous 1-min sampling; TIR 77% vs CGM 79%; GMI 7.19% vs 6.83%; CEG Zone A; ATTD 2026 (Barcelona
Printed Electrodes on the sensing cartridge made of renewable materials (Carbon base inks)	N/A — unsustainable Ag inks identified as dominant driver; LCA: electrodes = 60–90% of impact; patch GWP = 0.149 kg CO_2e (cradle-to-gate)	Cu and graphite inks validated as Ag/AgCl replacements; graphite showed comparable performance; GWP, ADPe, FAETP significantly reduced; LCA updated	Gen 3 optical design: eliminate all screen-printed electrodes from disposable patch entirely	Zero screen-printed electrodes in optical patch; −28 g CO_2e/patch vs Gen 2 electrode design; −80% mineral resource use; >3 kg CO_2e/month saved; cradle-

		(WP4/Fraunhofer IZM)		to-grave LCA (D4.6, EF3.1)
Layered collecting sweat substrates for sweat collection made of renewable materials	Salt-embedded layered substrate fabricated (09/2024); multi-layer collection characterised in bench tests; direct device connection requirement confirmed	Agarose-based hydrogel developed as passive sampler; in-vitro and in-vivo PoC validated with conductivity sensor; dilution effect noted proportional to initial hydrogel volume	Integrate sweat metering into optical patch architecture; eliminate need for electrode-based sensing layers in disposable	Optical patch: nylon rigid aligner, nonwoven polyester metering layers, double-sided adhesive tapes (skin + spacer), interrogation chamber, reflecting bed; no screen-printed electrodes; patch classified as MSW for EoL
High-quality data: A large amount of accurate and representative glucose profile data is essential to effectively train the predictive model. These data must be varied and correctly labelled to ensure accurate predictions	Relevant public datasets identified and analysed	First data sets analysis and synthetically generated to process sensor data; analysis of different models and selection of the model to be trained; n>1,831 real paired points collected	Train models with full real + synthetic + public dataset; validate with multimodal inputs	Models trained with real (n>1,831 paired), public and synthetic data; multimodal dataset (sweat glucose + clinical questionnaires + vitals); Random Forest best performer; external validity confirmed
Sustainability Development Cycle				
Redesign of the smart patch to achieve the lowest possible number of single-use items	NA	Cupper screen printed electrodes to substitute the silver based	Obsolete- Not carried forward	Obsolete- Not carried forward

4.3.3. Pilot#3.2 Smart hygiene

Table 40: Sustainability Development Cycle Pilot 3.2

	Gen1 / M12 Implementation	Gen2 / M24 Implementation	Gen3 / M36 Plan	M36 Implementation Achievements
Sustainability Development Cycle				
Sensors: Temperature, humidity, enzyme, pH	First versions of the printed temperature and humidity sensors included in the sensor label. Humidity sensors using biobased ink and temperature sensor using ink with reduced metal content. Enzyme and pH sensors developed as individual printed components.	Humidity and temperature sensors fully printed. Enzyme and pH sensors provided as components for assembly on the sensor label.	Mostly the same as in Gen 2. Temperature sensors with reduced metal content. Attempt to make sensor labels with fully printed sensors.	Improvements made compared to Gen 2. Temperature sensor including less metal than in Gen 2. Sensor labels made with all sensors printed directly on the label, replacing plastic sticker sensors.
Wireless readout	Wireless readout of sensor label not implemented. Wired connection to readout unit (transmitter).	Sensor label with design B implemented. Sensor label including ASIC as bare die and printed antenna coil for readout by NFC. Readout by NFC-enabled external reader, e.g. a smartphone	Same as Gen 2 but with further optimisation and added functionality for the use case	Design B: Readout of sensor labels with smartphone via NFC.
Wireless energy harvesting	Not implemented	NFC system as described above. Power to sensor label provided by NFC reader unit (e.g. smartphone)	Same as in Gen 2	Same as in Gen 2 for design B. The label is passive, so power is directly provided by NFC.

Sustainable materials for substrates and inks	Paper substrates and first versions of inks for humidity and temperature sensors	Biobased substrate (paper) and adhesives. Inks for printed sensors and conductors	Explore copper-based inks as replacement for silver	Copper ink performance was not good enough on paper. Future work.
Use of printing and other additive technologies ≥75% of sensor system	Initial processes for screen printing of the sensor label	Further developed processes for manufacturing of the sensor label including printing, lamination and assembly of components	Optimised processes for manufacturing of the sensor label Replace sensor sticker components with fully printed sensors.	Fully printed sensor labels made. Objective achieved for the sensor label.
Small in size	Sensor label dimensions: 299 x 37 mm	Design rules for printed circuitry and component sizes. Miniaturisation of components	Sensor label length and width maintained but more compact layout of sensor area.	Sensor label sizes: Gen 3A: 296 x 39 mm Gen 3B: 305 x 51 mm Transmitter electronics PCB miniaturised achieving a radius of 22 mm.
Sustainability Development Cycle				
LCA	Bill of materials and layout for sensor label	Extension of modelling to all life cycle phases Assess alternative design versions	Assess various EoL scenarios. Improve data quality on printed components. Extend indicators list	Design A: from 20 to 16 kgCO2e Design B: from ~32 to 22 kgCO2e Data quality improvement for the labels, transmitter and general use case.
Materials in sensor label ≥90% sustainable (by weight)	Paper substrate, biobased materials for humidity sensor, metal oxides for	No changes compared to Gen 1	Investigate possibility to replace silver with copper. Replace sensor sticker components	Slight reduction of material use compared to Gen 2. Sensor labels with fully printed sensors

	enzyme sensor and carbon electrodes used. Degree not yet quantified		with fully printed sensors.	reducing material use further. Sensor label dominated by cellulose substrate. Printed silver used since performance of copper printed on paper was not acceptable.
Other				
Minimal cost increase	Not assessed	Estimation of manufacturing costs	Estimation of manufacturing costs	Minimal addition in cost to the incontinence product has been achieved
Suitable for body/skin contact	Not assessed	Materials in sensor label selected accordingly	No changes compared to Gen 2	Materials selected accordingly

4.3.4. Pilot#3.3 Smart wound dressing

Table 41: Sustainability Development Cycle Pilot 3.3

	Gen1 / M12 Implementation	Gen2 / M24 Implementation	Gen3 / M36 implementation
Sustainability Development Cycle			
Environmentally friendly recycling with no added workload	Gen1 gives basis values and insight in recycling strategies	Recycling strategy options defined	End-of-life and recycling strategy defined
Sustainability results			
LCI system level		Include all components also early development stage ones and EoL	LCI of all components captured
LCA system level	Benchmark excluding EoL for hot spot identification;	Include EoL. Compare design options in more precise way	Evaluate impact of energy consumption during use phase and work on efficiency with precise

	comparison of 2 design options		analysis of use phase requirements. Include Handprint of developed system
LCA component level	Set benchmark for individual components with state-of-the-art technology	Comparison and improvement between flex PCBs; evaluate impact of energy consumption during use phase and work on efficiency Evaluate new technologies (printing and sustainable materials) for PCB at read out unit	Done
Digital product passport	Prepare NFC interface	Devine and collect required data (e.g. CO2 footprint, reuse periods) and prepare firmware	Include DPP at final system and make read out available via mobile phone

5. Social aspects

This section presents the social aspects considered in the design and deployment of each pilot. For every pilot, the relevant social are described individually, highlighting how social considerations have shaped the development of the prototypes and how they contribute to the overall acceptance and uptake of the pilot.

5.1. Use Case #1 Circular electronic devices

5.1.1. Pilot#1.1 Green and circular image guided therapy systems

Table 42: Social Aspects Pilot 1.1

Social aspect	Description
Community building	The modular geometry design and the envisioned (dis)advantages have been presented to 32 customers visiting our facilities, checking our view with their experiences in daily practice.
Communicating risks and benefits	Potential benefits in different application areas are shown in animations; triggering discussions with customers on their relevance / priorities. The lightweight system is ergonomical for a greater population of physicians.
Fairness	Light weight system may offer better access to care, e.g. in rural areas. Modular system improves the imaging capabilities of obese patients.
Adherence to social conventions and traditions	ESG (Environmental, Social, Governance) governance and business integrity are an integral part of the business processes, which are applied to all product innovations, including the ones in scope of Sustronics.
Monitoring	The modular geometry design and the envisioned (dis)advantages have been presented to 32 customers visiting our facilities, checking our view with their experiences in daily practice.

5.1.2. Pilot#1.2 Sustainable system integration and product design of personals health products

Table 43: Social Aspects Pilot 1.2

Social aspect	Description
Community building	Pilot #1.2 has been promoted on several occasions to key internal stakeholders. Inspired and supported by Sustronics, an internal Philips Sustainable PCBA community was initiated with as goal to address the environmental impact of PCBAs across Philips. For Sustronics specifically, the focus was to further spread the Sustronics knowledge across Philips, suggest focus areas and advocate for change. The community kicked off at the start of 2025. With Sustronics as key knowledge source, it delivered significant awareness increase on the topic of

	Sustainable PCBAs in the company, started collection of readily available knowledge, identified knowledge gaps and triggered several new internal activities beyond the Grooming and Beauty business. Externally, Philips and TNO Holst Centre hosted the keynote session of the Circular Design Forum 2025 - on the topic of Sustainable PCBAs; followed by a deep-dive with other CDF member-companies in a Breakout Session. Due to its success another session is planned for 2026.
Communicating risks and benefits	Communicating the results of this Pilot is beneficial to speed up innovation surrounding sustainable PCBAs and is done as much as possible. However, communication remains limited by IP sensitivity restrictions.
Fairness	Fairness is represented by the focus of Philips on Design for Repair.
Adherence to social conventions and traditions	The alternative technologies could be applied to a variety of Philips devices and therefore not exclusionary to any particular gender or ethnicity.
Monitoring	The integration of these new technologies into appliance architectures and platforms means these more sustainable solutions can be leveraged into Philips markets globally.

5.1.3. Pilot#1.3 Sustainable luminaire

Table 44: Social Aspects Pilot 1.3

Social aspect	Description
Community building	The project is presented at many locations, both internally and externally: • Presented at the LOPEC conference in Munich (Feb 2025) • Presented and discussed with several external lead customers during visits or online meetings • Showed during the Innovation Day with leading European customers • Showed during the Research Innovation Market • Internal meetings and discussions with the OEM business and with several businesses of the DDS division
Communicating risks and benefits	With the internal and external customers, the benefits like improved LCA, form freedom and faster time to market are mentioned. However, also the risks of new technology, cost level and supply chain are discussed.
Fairness	Everybody needs light, not only for seeing but also for biological reasons. An efficient, sustainable, and modular lighting system will lower the ecological footprint and improve broad useability.
Adherence to social conventions and traditions	The materials investigated will improve the sustainability of luminaire and the eco design will improve its performance on many R-strategies. This luminaire will not only be compliant with current legislation and society requirements but will be future proof due to the materials used and the design chosen.

Monitoring	The project is monitored on a regular base by the management. With the architects, key account managers and even with potential customers there are meetings to discuss the proposition.

5.2. Use case #2 Sustainable manufacturing

5.2.1. Pilot#2.1 Embedded electronics for EEG monitoring

Table 45: Social Aspects Pilot 2.1

Social aspect	Description
Health and Usability	• Improved **skin-compatible and flexible electrodes** • Enables **long-term and daily-life EEG monitoring**
Accessibility	• Supports **home-based and preventive healthcare** • Potential to reduce hospital dependency
Industrial and Societal Impact	• Shift toward **European/local manufacturing** • Reduced reliance on complex global PCB supply chains • Supports **advanced sustainable manufacturing skills**
Monitoring of social impact	• Gathering **feedback from test users** (comfort, usability, perceived eco-benefits) • Incorporating insights from **multiple partners** (PLUX, VTT, PIEP, SCR) to ensure broad stakeholder coverage • Continuous performance evaluation with **real EEG users** to validate both technical and social aspects of the solution

5.2.2. Pilot#2.2 Wearable health monitoring

Pilot Leader: SCR (Mikko Paakkolanvaara)

Table 46: Social Aspects Pilot 2.2

Social aspect	Description
Community building	There are currently no medical electrodes available at the markets which would be manufactured using more sustainable materials. Possibilities of more sustainable medical electrodes has been presented on international trade fairs, seminars, conferences, pitching competitions and demonstrator competitions.
Fairness	It is possible to get the price of more sustainable medical electrodes lower than the current medical electrodes. This increases the possibilities to have the medical service available wider in the world.
Adherence to social conventions and traditions	User experience of more sustainable medical electrodes is same or similar when compared to existing medical electrodes.
Monitoring	Results of the customers survey showed the interest for more sustainable medical electrodes among medical electrode product owners. Customer survey sent to 42 contacts.

5.2.3. Pilot#2.3 Sustainable dashboard for automotive

Table 47: Social Aspects Pilot 2.3

Social aspect	Description
Community building	Pilot 2.3 was presented multiple times internally and externally: • Presented at the LOPEC and TechBlick events at CEA's booth. CEA presented the project results to its printed electronics community. • Presented internally to the Surface Activation Innovation Team in FAU + to the whole community of the R&D Center of FAU in Méru (France) • Presented during SUSTRONICS General Assemblies (Munich, Oulu, Gothenburg, Guimarães and Barcelona) and in monthly reviews. These sessions helped engage consortium partners in co-developing the demonstrator. Regular exchanges also took place with technical partners to refine materials and processes
Communicating risks and benefits	Environmental benefits were clearly highlighted: we achieved 57% weight reduction of the dashboard, the energy consumption during manufacturing via IME is reduced compared to standard FR4 production, and we replaced 100% of standard fossil-based material by bio-based materials. Technical risks (e.g., plastic/metal separation during recycling, stability of bio-PC films) were discussed in monthly reviews and with partners (VTT, CEA, etc.) and integrated into LCA analysis.
Fairness	Pilot 2.3 aims to democratize access to sustainable automotive solutions by integrating recycled or bio-based materials and enabling easier disassembly for recycling. This reduces reliance on costly and critical virgin materials, promoting broader access to sustainable technologies, including in emerging or resource-constrained markets.
Adherence to social conventions and traditions	Pilot 2.3 aligns with European social and environmental norms, particularly upcoming regulations on end-of-life vehicles. It supports circularity, waste reduction, and material recovery — values that reflect current societal expectations for sustainability and environmental responsibility.
Monitoring	Social impact monitoring is embedded through environmental and technical KPIs (weight reduction, energy consumption, share of bio-based materials). The final LCA has been updated with 2 different scenarios for EOL: incineration vs. recycling.

5.3. Use case #3 Environmentally compatible single use electronics

5.3.1. Pilot#3.1a In Vitro Diagnostics

Table 48: Social Aspects Pilot 3.1a

Social aspect	Description

Community building	Presentation of background and intention at international and national congresses to reach a large community of users, e.g. medical doctors, but also health care professionals and – importantly – patients via patient organisations.
Communicating risks and benefits	Risks and benefits are clearly described at congresses to medical professionals. The user community is very large from persons with gestational diabetes, polycystic ovary syndrome or type 2 diabetes, including millions of obese people - this is a clear benefit, but also a risk in terms of communication. Risks and benefits will be communicated via the smartphone app.
Fairness	The UCPCR device is a non-invasive method for any user world-wide, not depending on high medical standards or clinical settings.
Adherence to social conventions and traditions	Many diagnostic tools like pregnancy tests are already based on urine detection. In addition, most of the people are used to lateral flow technologies as of the COVID detection period.
Monitoring	The stakeholder community is very frequently addressed via regular congresses and other medical events. Furthermore, patient organisations and health care professionals are incorporated in the monitoring of the social impact of the device development and use.

5.3.2. Pilot#3.1 b Smart Skin Patch

Table 49: Social Aspects Pilot 3.1b

Social aspect	Description
Community building	Throughout the project, publications, seminars and workshops are being carried out to publicize the research and results. Commitment to groups of diabetics to show them the device and generate a community of diabetics who can begin to use it experimentally. Workshop to raise awareness of the problem of diabetes in relation to environmental sustainability. Furthermore, given the non-invasive nature of the device, importance of glucose reading in everyone daily life is being explored and narrative of the need of it being built.
Communicating risks and benefits	We are developing the medical device according to ISO 13485, which involves risk analysis and post-market surveillance. In the future, recommendations generated and provided to patients through the use of AI will communicate the health and environmental benefits of wearing these devices.
Fairness	To generate equity, we have emphasised several key aspects in the design, production and distribution of the device: 1. Affordability. Designing the wristband with low-cost materials and scalable manufacturing processes.

	2. Availability in rural and marginalised areas. Ensure that the wristband is not dependent on constant internet connectivity or expensive smartphones. 3. Inclusion of diverse populations. Adapt the design to be comfortable and functional for different types of users, considering variations in sweat, patient age, environmental conditions, economic conditions, etc.
Adherence to social conventions and traditions	Our research proposes a non-invasive approach for the detection of diabetes using sweat which is a biological fluid routinely used in medical diagnostics across the world. These methods are widely accepted in clinical practice and do not challenge the social norms or traditions of the vast majority of cultures.
Monitoring	A market analysis is being carried out to consider the impact that the developed type II diabetes device could have on the diabetic population and their care environment. Project members are conducting real-life trials in a hospital, doing an experimental analysis with feedback from doctors and patients and nursing staff. Given the recent trends in wellness wearable devices, we conducted market research and analysis as well that suggested the potential of the developed device for healthy individuals to help them make conscious decision. We believe this might help reduce the risk of diabetes type 2 development.

5.3.3. Pilot#3.2 Smart hygiene

Pilot Leader: Essity Hygiene and Health AB (Shabira Abbas and Tilak Lakshmana)

Table 50: Social Aspects Pilot 3.2

Social aspect	Description
Community building	The SmartCare Change Indicator represents a significant step forward in delivering smart incontinence care that prioritises dignity and wellbeing. The system generates valuable data that can be used to optimise care routines and improve staff efficiency, ultimately supporting a more personalized, respectful, and dignified care experience. Throughout the project, key findings are being actively disseminated through targeted workshops and stakeholders. In parallel, an internal initiative is exploring the practical application of smart hygiene solutions through real-world user cases.
Communicating risks and benefits	An accessory to the medical device (incontinence product) is being developed in accordance with established standards, integrating thorough risk analysis focused on product safety. Moving forward, evolving recommendations communicated to caregivers and patients will emphasise the health and environmental benefits of using the device.
Fairness	We have focused on key principles throughout the device's design, production, and usability. Affordability remains a central priority; the change indicator is crafted from low-cost

	materials and built using scalable manufacturing methods to ensure it remains accessible to all.
Adherence to social conventions and traditions	Our innovation the Change Indicator marks a major advancement in smart incontinence care, with a strong focus on dignity and wellbeing. This discreet, sensor-enabled solution alerts caregivers through a mobile app when an absorbent product likely needs changing, reducing the need for manual checks. By limiting intrusive inspections, it safeguards residents' privacy and promotes greater comfort.
Monitoring	By reducing intrusive inspections, the system safeguards residents' privacy and enhances their overall comfort. Additionally, it generates valuable data that can be leveraged to streamline care routines and boost staff efficiency contributing to a more personalised, respectful, and dignified care experience.

5.3.4. Pilot#3.3 Smart wound dressing

Table 51: Social Aspects Pilot 3.3

Social aspect	Description
Community building	Printing technologies were presented to a broad audience, e.g. at the LOPEC conference. The overall system architecture and LCA guided design was presented at 3 international conferences. (EGG, ICECS and REACT).
Communicating risks and benefits	Risks are assessed in the pilot in terms of health hazards. Benefits were communicated with the LCA results to practitioners from the field)
Fairness	Remote monitoring is specifically improving health care in less densely populated areas, because the wound is continuously monitored, while the dressing needs less frequent changing.
Adherence to social conventions and traditions	Chronic wounds can lead to shame of the patient. With the smart wound monitoring an easier remote support is enabled.
Monitoring	Partner is in the field of health care active. Market analysis was done and growing opportunities identified.

6. Conclusion

The deliverable D3.4 has detailed the development and results of Sustronics Gen 3pilots. The main achievements per pilot are listed below:

Pilot 1.1 (Green and circular image guided therapy systems). The first certification for one-time reuse of frames was realised in Gen 2. The energy saving mode has been implemented in a prototype, including AI-triggered activation and deactivation. The lightweight geometry has also been realised, including the option of having a modular end-effector. The prototype tool for LCA is available and linked to a live component database. Combined, the innovations are expected to exceed the targeted 10% reduction in LCA score.

Pilot 1.2 (Sustainable system integration and product design of personals health products). In Gen 1, the Learn Phase, a thorough LCA analysis was carried out to understand the environmental hotspots on a Baseline PCBA. For Gen 2, three more sustainable electronic innovations were selected and tested on a small PCBA. In Gen 3, these same technologies were applied to a more complex PCBA. This was then integrated into a device that was specially optimised to enable consumer disassembly and repair. The pilot successfully achieved impact reduction on PCBA Level KPI.

Pilot 1.3 (Sustainable luminaire). The different modules have been developed and characterised with more sustainable approach, such as bio-based materials. The LCA calculations support the approach selected for Sustronics project for decreasing the environmental impact.

Pilot 2.1 (Embedded electronics for EEG monitoring). Successfully developed, prototyped and validated sustainable EEG monitoring components combining paper-based printed electrodes and embedded electronics based on LDS technology. The best electrode variant (126W) demonstrated signal quality comparable to clinical reference electrodes and was validated for intended EEG monitoring applications. A functional embedded EEG sensor prototype (PIEP Sample 3) was also achieved, confirming the feasibility of alternative non-PCB electronics for biosignals acquisition. LCA results demonstrated significant sustainability improvements for the developed electrodes compared to conventional PET-based solutions, while also identifying clear improvement pathways for the embedded sensor towards industrial-scale sustainability optimisation.

Pilot 2.2, (Wearable health monitoring). More sustainable medical electrodes for ECG and bio-impedance measurement were developed, prototyped and tested. Best variants suited well for intended measurement use and were comparable against functionality of reference electrode. The LCA calculations supported prediction of developed electrodes to be more sustainable than reference ones.

Pilot 2.3 (Sustainable dashboard for automotive). LCA-driven design improvements and material substitutions have been made successfully. Optimised processing conditions for printing and thermoforming of bio-PC have been specified, and the bio-PC has been validated for both films and injection process. Switching to bio-PC has shown a clear decrease in environmental impact.

Pilot 3.1a (In Vitro Diagnostics). From Gen 2 to Gen 3, the prototype progressed from parallel “functional” and “sustainable” prototypes to a combined, more mature cartridge with stable NFC/app operation, a ~15-minute workflow, and markedly improved sustainability through material and integration changes, e.g. by using a bare die microchip, paper based substrates and Cu-ink for printing. In parallel, Gen 2 functional devices enabled clinical/lab testing at scale (65 fully integrated units), confirming electrochemical C-peptide discrimination in buffer and pooled T1D urine and establishing the basis for UCPCR-relevant measurements. Overall, Gen 3 consolidates performance and environmental gains (lower manufacturing impact and mineral use), while remaining limitations are assay/workflow complexity, integrated-strip reproducibility, and yield (mainly for Cu-ink printing on paper) that must be addressed for productization.

Pilot 3.1b (Smart Skin Patch). Gen 3 adopted the most sustainable and economically convenient solution for sweat glucose sensing. Optical detection through trans-reflectance spectroscopy. This was supported by LCA results. Gen 3 not only integrate a more sustainable hardware but as well software and AI prediction models that has been built with sustainable consideration in mind. The system has been tested with real volunteers, showing promising analytical accuracy and good clinical outcomes, with respect to MARD and end user acceptance.

Pilot 3.2 (Smart hygiene). Gen 3 is working with architecture Design A and B. Gen 2A has been tested end-to-end with the temperature and humidity sensor. The enzyme and pH have been verified outside the sensor label construction. LCA results show that the Design A is slightly superior to Design B as we are not discarding the microchip and the NFC antenna after every use. The Gen3A are manufactured both in laboratory scale and in industrial scale. Monolithic sensor label with all the sensors integrated is in the making.

Pilot 3.3 (Smart wound dressing). The Gen 3 has finalized the development of the individual functionalities. The generative AI framework and models have been improved for higher accuracy. The smart wound monitoring system was successfully tested under relevant conditions. A detailed LCA has been done with end-of-life components included.

In conclusion, all ten pilots have successfully completed the development and testing of their Gen3 prototypes, demonstrating the technical and operational feasibility of the proposed solutions.

Appendix A List of Tables and Figures

List of Tables

List of Figures