

D4.1 Demonstrator 1 Sustainable Smart Tag

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Executive Summary

The goal of this *D4.1 Demonstrator 1 Sustainable Smart Tag* document is to present an integrated view of the project's implementation and achievements for the sustainable smart tag, demonstrating the SUPERIOT node's capabilities in terms of dual mode communication, displaying information, as well as sensing and actuating the display or transmitters. This demonstrator aimed to showcase a sustainable smart tag in an actual demonstration scenario consisting of a number of functional tags communicating with a number of access points via a hybrid visible light and radio frequency communication protocol.

The demonstration was performed on a scaled-down version of an industrial material flow scenario, where the sustainable smart tag allows for optimization of the material flow within the electric motor manufacturing process. The demonstration was designed to highlight the advantages of bidirectional (downlink and uplink) dual (light and radio frequencies) communication modes under the constraints of the available power budget. The scenario successfully demonstrated multimode optical-radio communication between SUPERIOT network and node; featuring bidirectional (uplink and downlink) data exchange. It also showcased optical-radio reconfigurability; positioning capabilities via visible light communication; and environmental sensing of temperature, humidity, gas parameters and pressure. The system also enabled actuation of the E-paper display and optical-radio transmitters, and achieved energy autonomy through energy storage – including fully printed micro-supercapacitors in a hybrid node version– and energy harvesting as well. Thus, sustainability was ensured both by design and implementation.

In summary, Demonstrator 1 successfully validated and confirmed that the developed SUPERIOT system meets all the previously outlined features and functionalities required for industrial applications of the sustainable smart tag.

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Editions

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0.1	2025-10-27	Marcin Drzewiecki, MPICOSYS	Draft for internal review
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1.0	2025-10-31	Marcin Drzewiecki, MPICOSYS	Final version for submission
2.0	2026-05-22	Marcin Drzewiecki, MPICOSYS	Resubmission addressing the comments from the Project Officer and the Experts

1 Acronyms

6G	The sixth-generation mobile communication system
a-Si	amorphous Silicon
ALD	Atomic Layer Deposition
AP	Access Point
BBB	BeagleBone Black
BLE	Bluetooth Low Energy
CVD	Chemical Vapor Deposition
GUI	Graphical User Interface
EMI	Electromagnetic Interference
EPD	Electronic Paper Display
ICT	Information and Communication Technologies
IoT	Internet of Things
LED	Light Emitting Diode
MSC	Micro-supercapacitors
MQTT	Message Queuing Telemetry Transport
OPV	Organic Photovoltaic
PCB	Printed Circuit Board
PE	Printed Electronics
PIL	Python Imaging Library
RF	Radio-Frequency
RIoT	Reconfigurable IoT
RPi	Raspberry Pi
SLIPT	Simultaneous Light Information and Power Transfer
SWIPT	Simultaneous Wireless Information and Power Transfer
VLC	Visible Light Communication
WS	Workstation

2 Introduction

2.1 Motivation

The Internet of Things (IoT) is recognized as a key enabling technology for both industrial advancement and the improvement of the quality of life, in the context of current 5G and future 6G networks and beyond. The sustainable smart Tag - an IoT node that integrates optical and radio wireless technologies within a compact, reconfigurable design implemented using hybrid printed electronics (PE) and silicon-based technologies - has strong potential to become a cornerstone of this ongoing development.

Demonstrator 1 implemented the "Sustainable Smart Tag" within a practical industrial application scenario involving a number of functional tags in communication with a number of access points using the dual - visible light and radio frequency - communication protocol. The demonstration was structured to illustrate the advantages of this dual communication approach in enhancing both communication performance and energy efficiency.

The "Sustainable Smart Tag" applied in Demonstrator 1 was designed to communicate using visible light and radio frequencies, display information using electronic paper display (EPD), sense the environmental conditions and actuate the transmitters and the display. The features and functions integrated into the node were determined after the key applications were selected at the initial phase of the project. Such functions and functionalities became the list of the formulated requirements for Demonstrator 1. These requirements, which are detailed in the following chapter, were successively fulfilled by the system and node developed within the SUPERIOT project. The challenge for this demonstrator was to show how the dual communication modes: visible light communication and radio frequency communication, can be used to optimize the performance of the label (e.g., response speed in the industrial environment with heavy electromagnetic interference, localization speed) while staying within the available power budget. The smart tags operate over both radio and optical links. Optical links, offering inherent physical-layer security, are particularly suited for transferring critical information such as precise positioning data - achieving accuracy at the room, box, or shelf level - in industrial environments. Radio communication serves as a complementary mode, suitable for non-critical operations or in areas free from electromagnetic interference and regulatory constraints on radio usage. Additionally, the sustainable smart tags support fully bidirectional communication capabilities.

The general concept of Demonstrator 1 is presented in Figure 1.

Demonstrator 1

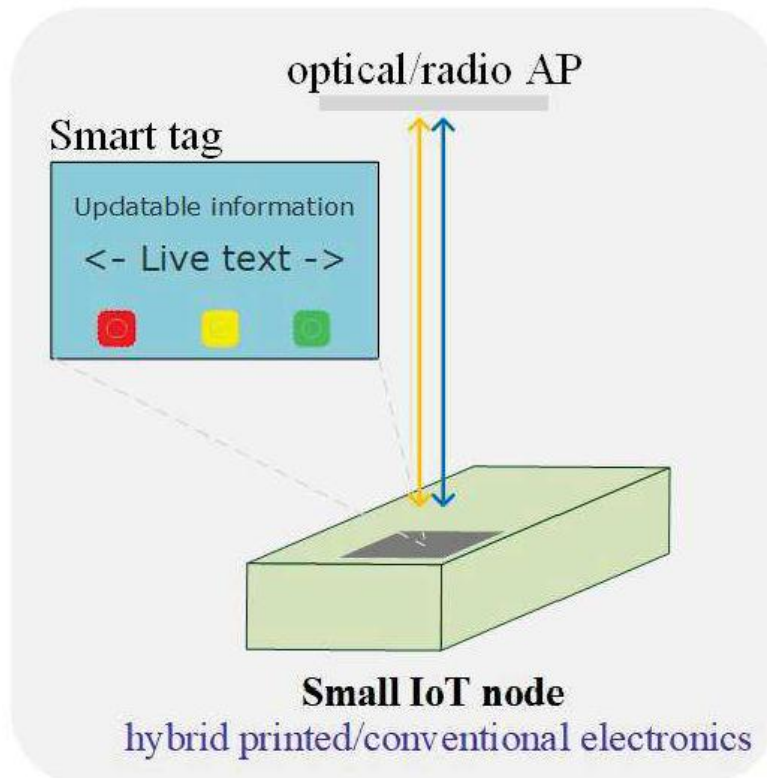


Figure 1. Demonstrator 1 of the SUPERIOT project – the general concept.

2.2 Summary

This deliverable presents the work carried out and the results achieved following the integration of Demonstrator 1. The main demonstration was performed in the Vitality Hub in Eindhoven, Netherlands at the SUPERIOT F2F meeting held on 23-25 September 2025 (see Figure 2 and Figure 3). An additional demonstration was conducted at the MPICOSYS laboratory in Gdynia, Poland on 23 October 2025 (see Figure 4). Both demonstrations were recorded and are included in the video provided in Appendix 1.



Figure 2. The main showcase demonstration of Demonstrator 1 performed in the Vitality Hub in Eindhoven, Netherlands at SUPERIOT F2F meeting on 23-25 September 2025 – view 1.

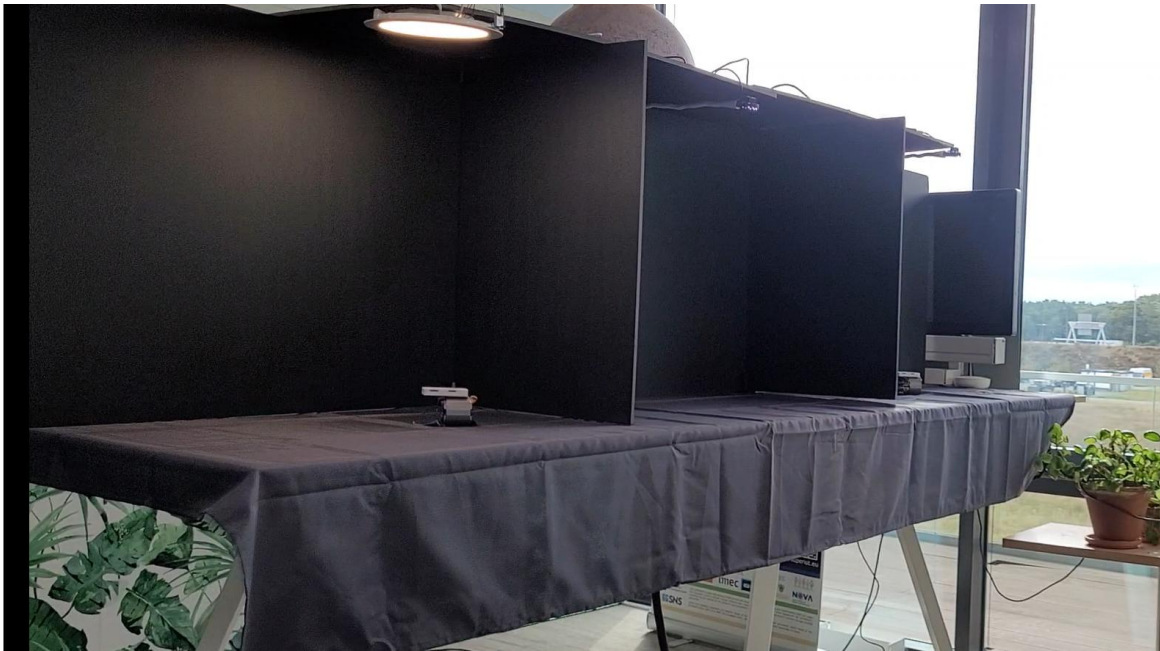


Figure 3. The main showcase demonstration of Demonstrator 1 performed in the Vitality Hub in Eindhoven, Netherlands at SUPERIOT F2F meeting on 23-25 September 2025 – view 2.

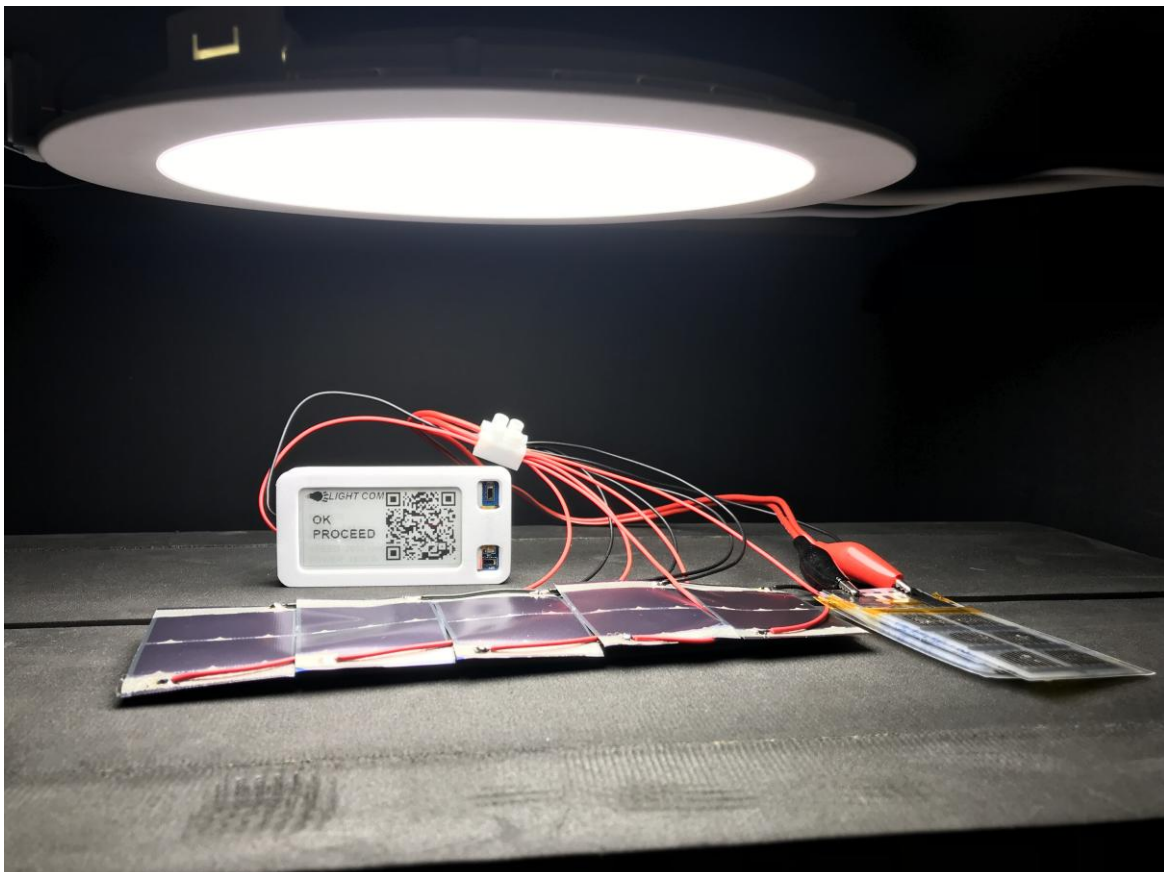


Figure 4. The additional showcase demonstration of Demonstrator 1 performed in MPICOSYS laboratory in Gdynia, Poland on 23rd October 2025.

Complementary showcase demonstrations, also intended for dissemination activities, were carried out at *EuCNC & 6G SUMMIT 2025* in Poznan, Poland, from 3 to 6 June 2025 (Figure 5

and Figure 6), and at *EWSN 2025-The 22nd International Conference on Embedded Wireless Systems And Networks* in Leuven, Belgium, on 22 September 2025 (Figure 7).



Figure 5. The showcase demonstration performed at EuCNC & 6G SUMMIT 2025 in Poznan, Poland, on 3-6 June 2025.



Figure 6. The showcase demonstration presenting the basic functionality of Demonstrator 1, carried out during *EuCNC & 6G Summit 2025* in Poznań, Poland, from 3 to 6 June 2025.



Figure 7. The showcase demonstration of Demonstrator 1 conducted during *EWSN 2025 – The 22nd International Conference on Embedded Wireless Systems and Networks* in Leuven, Belgium, on 22 September 2025.

Demonstrator 1, documented in the accompanying videos (Appendix 1) and described in this report, successfully validated that the developed SUPERIOT system and Sustainable Smart Tag (SUPERIOT node) meet all the required features and functionalities. The demonstrator showcased multimode optical-radio communication between the SUPERIOT network and node, bidirectional communication (uplink and downlink to the node), and optical-radio reconfigurability. Additional functionalities included positioning through visible light communication; environmental sensing of temperature, humidity, gas parameters and pressure; and actuation of the display and optical-radio transmitters. The node also demonstrated energy autonomy through the integrated energy storage – featuring printed electronics micro-supercapacitors (MSC) in the hybrid node version – and energy harvesting. Sustainability was achieved both through reconfigurability-oriented design and hybrid-node implementation.

The remaining features and functions envisioned for the SUPERIOT system – beyond those mentioned above – are successfully validated in the reports corresponding to Demonstrators 2, 3 and 4, namely Deliverables D4.2, D4.3 and D4.4, respectively.

2.3 Structure of the document

The rest of the document is organized as follows. Section 3 forms the core of the document, and it is titled *Demonstrator 1 Sustainable Smart Tag*. This section provides detailed information about the demonstrations performed. Section 3.1 outlines the general requirements for the demonstration. Section 3.2 gives an overview of the demonstrator. Section 3.3 presents the use case scenario. Section 3.4 describes how the defined use cases and goals were translated into the demonstrator scenario. Section 3.5 details the key integrations developed to enable the demonstration, and finally in Section 3.6, the execution and results of the demonstration are presented. Conclusions are presented in Section 4. Next, after Bibliography, List of figures, List of tables and List of contributors, there are also three appendices. Appendix 1 is the video of Demonstrator 1 Sustainable Smart Tag in the use-case of the industrial material flow. Appendix 2 presents demonstration scenario steps for the industrial material flow use case. Appendix 3 contains the EPD image codes applied according to the demonstration scenario industrial material flow.

3 Demonstrator 1 Sustainable Smart Tag

3.1 General requirements

Demonstrator 1 - Sustainable Smart Tag was designed to support dual-mode communication, information display, sensing and actuation functionalities. The main goal of this demonstrator was to show how the dual communication modalities – radio and optical links – can be used to optimize the performance of the label (e.g., in the industrial use case scenario providing the positioning information or material environmental information or enabling optimal control of material flow) while operating within the available power budget. Both radio and optical communication links were required to support bidirectional data/command exchange on the smart tags. The specific functions to be integrated into the node were determined following the selection of key applications areas identified during the initial phase of the project. This selection was guided by industry needs and the use case scenarios. Consequently, based on these considerations, the features and functionalities of Demonstrator 1 were formulated. The definition of the required and targeted features and functionalities was derived from the project proposal, grant agreement [1], subsequent amendments and Deliverable *D1.4 Description of selected scenarios, applications and their requirements*, where the use case scenarios of Demonstrator 1 are described [2]. These defined features and requirements were first compiled into a list and then formalized into project-level requirements. The complete set of general requirements Demonstrator 1, including their identifiers and descriptions, is presented in Table 1.

Table 1. Demonstrator 1 general requirements.

Label	Requirement	Description
Demo1-R-01	Multimode optical-radio communication	Demonstrator 1 shall provide multimode optical-radio communication between the SUPERIOT network and node.
Demo1-R-02	Bidirectional communications	Demonstrator 1 shall support the bidirectional communications. Multimode is not promised.
Demo1-R-03	Reconfigurability	Demonstrator 1 shall be optical-radio reconfigurable.
Demo1-R-04	Accurate positioning information	Demonstrator 1 shall provide accurate node positioning information. Accuracy at least to the room level or workstation / box level. Multimode was not mandatory in Demonstrator 1. Multimode positioning is presented in Demonstrator 2.
Demo1-R-05	Sensing	Demonstrator 1 shall provide the function for sensing temperature, air pressure, humidity, gas (air) parameters (electrical resistance).

Demo1-R-06	Actuating	Demonstrator 1 shall display the information and actuate the e-paper display refresh.
Demo1-R-07	Energy autonomy	Demonstrator 1 shall be energy autonomous by means of the energy harvesting and energy storage.
Demo1-R-08	Sustainability	Demonstrator 1 shall be sustainable at least by reconfigurability-enabling design and by the hybrid-node implementation.

The defined general requirements for Demonstrator 1 guided the implementation of the related tasks within WP4 and served as key design requirements to be fulfilled. The design results, that validate Demonstrator 1 and confirm that these requirements have been successively met, are presented and detailed in the following sections.

3.2 Demonstrator overview

Demonstrator 1 Sustainable Smart Tag successfully validated the SUPERIOT objective of developing and demonstrating a reconfigurable IoT (RIoT) node. It confirmed the strong potential of dual-mode optical and radio communication. The demonstrator development and integration provided the needed output in the form of the reconfigurable IoT node and access point design and implementation, energy subsystem and concept capabilities. It proved the feasibility of a novel, flexible and adaptable small-form-factor IoT node capable of supporting future networks based on both radio and optical communications. Moreover, it demonstrated that this concept holds significant potential for standardization and future adoption as a mainstream IoT technology.

3.2.1 Sustainable Smart Tag hardware components

The complete list of the hardware components of the SUPERIOT node applied to Demonstrator 1 Sustainable Smart Tag is presented in Table 2. The hardware components listed therein have been collectively analyzed in **D1.5 Deliverable: Methodologies for sustainability (2)**, where they were reported as *e-ink display module*, *node core module* and *LiPo battery*.

Table 2. The complete list of the hardware components of the SUPERIOT node applied to Demonstrator 1 Sustainable Smart Tag

Item No.	Name	Quantity	Manufacturer Part	Manufacturer	LCA analysis
1	Photodiode VEMD8080	2	VEMD8080	Vishay Intertech	node core module in D1.5
2	Infrared emitting diode XL-2012IRC-940	1	XL-2012IRC-940	XINGLIGHT	
3	Inductor 15nH	1	MLG1005S15NJT000	TDK	
4	Capacitor 1uF	10	CL05A105KA5NQNC	SAMSUNG	
5	Capacitor 4.7uF	2	1206B475K500NT	FH	
6	Capacitor 100nF	5	CL05B104KO5NNNC	SAMSUNG	
7	Capacitor 100nF	3	CC0603KRX7R9BB104	YAGEO	

8	Capacitor 220pF	1	CL10B221KB8NNNC	SAMSUNG
9	Capacitor 2.2nF	1	0603B222K500NT	FH
10	Inductor 6.8mH	1	FNR6045S682KT	cjiang
11	Capacitor 1uF	2	CL10A105KB8NNNC	SAMSUNG
12	Capacitor 47nF	1	CC0402KRX7R9BB473	YAGEO
13	Capacitor 15pF	4	CL05C150JB51PNC	SAMSUNG
14	Capacitor 100pF	1	0402CG101J500NT	FH
15	Capacitor 1pF	2	CL05C010CB5NNNC	SAMSUNG
16	Capacitor 1.5pF	1	CL05C1R5CB5NNNC	SAMSUNG
17	Capacitor 820pF	1	CC0402KRX7R9BB821	YAGEO
18	Capacitor 4.7uF	3	CL10A475KO8NNNC	SAMSUNG
19	Schottky Diode MBR0530T1G	3	MBR0530T1G	onsemi
20	Inductor 68uH	1	SMNR4030-680MT	SXN
21	Inductor 10uH	1	MLF1608E100KTD00	TDK
22	Inductor 4.7nH	1	LQG15HS4N7S02D	muRata
23	Inductor 2.2nH	1	LQG15HN2N2S02D	muRata
24	Connector FPC 0.5MM 24P Pull type H2.0mm Pick up	1	AFC07-S24ECC-00	JS
25	Transistor SI1308EDL-T1- GE3	1	SI1308EDL-T1-GE3	VISHAY
26	Transistor AO3401A	1	AO3401A	AOS
27	Transistor S8050_C2146	1	S8050 J3Y	CJ
28	Resistor 10kΩ	4	0603WAF1002T5E	UNI-ROYAL
29	Resistor 1Ω	1	0603WAF100KT5E	UNI-ROYAL
30	Resistor 2Ω	1	0603WAF200KT5E	UNI-ROYAL
31	Resistor 47kΩ	2	0603WAF4702T5E	UNI-ROYAL
32	Resistor 100kΩ	1	0603WAF1003T5E	UNI-ROYAL
33	Sensor BME688_C366447 8	1	BME688	Bosch
34	Wake-up receiver AS3933-BTST	1	AS3933-BTST	ams
35	Microcontroller nRF52833	1	nRF52833-QIAA-R	NORDIC
36	Crystal Oscillator 32MHz	1	Q22FA1280001800	EPSON
37	Crystal Oscillator 32.768kHz	1	SC- 20S,32.768kHz,20PPM,12.5 pF	Seiko
38	Capacitor 10uF	2	CL10A106KP8NNNC	SAMSUNG
39	Capacitor 100nF	1	CC0402KRX5R8BB104	YAGEO
40	Capacitor 220nF	1	TCC0402X5R224K160AT	CCTC

41	Schottky Diode B5819WS_C4884 05	1	B5819WS	Slkor	
42	LED diode BL- HJC36A-AV-TRB	1	BL-HJC36A-AV-TRB	BrtLed	
43	Transistor CJ2301 S1	1	CJ2301 S1	CJ	
44	Transistor BSS123	1	BSS123	CJ	
45	Resistor 2k Ω	2	0603WAF2001T5E	UNI-ROYAL	
46	Resistor 120k Ω	2	0603WAF1203T5E	UNI-ROYAL	
47	Resistor 5.1k Ω	2	0603WAF5101T5E	UNI-ROYAL	
48	Resistor 100 Ω	1	0402WGF1000TCE	UniOhm	
49	Voltage regulator ME6211C30M5G	1	ME6211C30M5G	MICRONE	
50	Battery management chip TP4054_C668215	1	TP4054	UMW	
51	Infrared receiver VSOP38338	1	VSOP38338	Vishay Intertech	
52	USB connector TYPE-C 3.1 MT 16P_C168688	1	918-418K2024S40000	JTJ	
53	e-ink display 2.13" 250x122 px	1	2.13inch e-Paper	WAVESHARE	e-ink module in D1.5
54	LiPo battery 110 mAh, 3.7 V	1	401030	Liter Energy Battery	LiPo battery in D.5

The complete list of printed electronics (PE) and Si-based hardware components of the SUPERIOT hybrid node applied to Demonstrator 1 Sustainable Smart Tag is presented in Table 3. The Si-based components listed therein have been collectively analyzed in **D1.5 Deliverable: Methodologies for sustainability (2)**, Section 6.4.1 Case 1 - Baseline microelectronic system, where they were reported as *e-ink display module*, *node core module* and *a-Si photovoltaic laminate*. The PE components (MSCs) have been analyzed in **D1.5 Deliverable: Methodologies for sustainability (2)**, Section 6.4.2 Case 2 - Hybrid system, where they were reported as *printed supercapacitors*.

Table 3. The complete list of printed electronics (PE) and Si-based hardware components of the SUPERIOT hybrid node applied to Demonstrator 1 Sustainable Smart Tag.

Ite m No.	Name	Quantit y	Manufacturer Part	Manufactur er	LCA analysis
1	Photodiode VEMD8080	2	VEMD8080	Vishay Intertech	node core module in D1.5
2	Infrared emitting diode XL- 2012IRC-940	1	XL-2012IRC-940	XINGLIGHT	
3	Inductor 15nH	1	MLG1005S15NJT000	TDK	
4	Capacitor 1uF	10	CL05A105KA5NQNC	SAMSUNG	
5	Capacitor 4.7uF	2	1206B475K500NT	FH	

6	Capacitor 100nF	5	CL05B104KO5NNNC	SAMSUNG
7	Capacitor 100nF	3	CC0603KRX7R9BB104	YAGEO
8	Capacitor 220pF	1	CL10B221KB8NNNC	SAMSUNG
9	Capacitor 2.2nF	1	0603B222K500NT	FH
10	Inductor 6.8mH	1	FNR6045S682KT	cjiang
11	Capacitor 1uF	2	CL10A105KB8NNNC	SAMSUNG
12	Capacitor 47nF	1	CC0402KRX7R9BB473	YAGEO
13	Capacitor 15pF	4	CL05C150JB51PNC	SAMSUNG
14	Capacitor 100pF	1	0402CG101J500NT	FH
15	Capacitor 1pF	2	CL05C010CB5NNNC	SAMSUNG
16	Capacitor 1.5pF	1	CL05C1R5CB5NNNC	SAMSUNG
17	Capacitor 820pF	1	CC0402KRX7R9BB821	YAGEO
18	Capacitor 4.7uF	3	CL10A475KO8NNNC	SAMSUNG
19	Schottky Diode MBR0530T1G	3	MBR0530T1G	onsemi
20	Inductor 68uH	1	SMNR4030-680MT	SXN
21	Inductor 10uH	1	MLF1608E100KTD00	TDK
22	Inductor 4.7nH	1	LQG15HS4N7S02D	muRata
23	Inductor 2.2nH	1	LQG15HN2N2S02D	muRata
24	Connector FPC 0.5MM 24P Pull type H2.0mm Pick up	1	AFC07-S24ECC-00	JS
25	Transistor SI1308EDL-T1- GE3	1	SI1308EDL-T1-GE3	VISHAY
26	Transistor AO3401A	1	AO3401A	AOS
27	Transistor S8050 C2146	1	S8050 J3Y	CJ
28	Resistor 10kΩ	4	0603WAF1002T5E	UNI-ROYAL
29	Resistor 1Ω	1	0603WAF100KT5E	UNI-ROYAL
30	Resistor 2Ω	1	0603WAF200KT5E	UNI-ROYAL
31	Resistor 47kΩ	2	0603WAF4702T5E	UNI-ROYAL
32	Resistor 100kΩ	1	0603WAF1003T5E	UNI-ROYAL
33	Sensor BME688_C36644 78	1	BME688	Bosch
34	Wake-up receiver AS3933- BTST	1	AS3933-BTST	ams
35	Microcontroller nRF52833	1	nRF52833-QIAA-R	NORDIC
36	Crystal Oscillator 32MHz	1	Q22FA1280001800	EPSON
37	Crystal Oscillator 32.768kHz	1	SC- 20S,32.768kHz,20PPM,12 .5pF	Seiko
38	Capacitor 10uF	2	CL10A106KP8NNNC	SAMSUNG

39	Capacitor 100nF	1	CC0402KRX5R8BB104	YAGEO	
40	Capacitor 220nF	1	TCC0402X5R224K160AT	CCTC	
41	Schottky Diode B5819WS_C488 405	1	B5819WS	Sikor	
42	LED diode BL- HJC36A-AV-TRB	1	BL-HJC36A-AV-TRB	BrLed	
43	Transistor CJ2301 S1	1	CJ2301 S1	CJ	
44	Transistor BSS123	1	BSS123	CJ	
45	Resistor 2k Ω	2	0603WAF2001T5E	UNI-ROYAL	
46	Resistor 120k Ω	2	0603WAF1203T5E	UNI-ROYAL	
47	Resistor 5.1k Ω	2	0603WAF5101T5E	UNI-ROYAL	
48	Resistor 100 Ω	1	0402WGF1000TCE	UniOhm	
49	Voltage regulator ME6211C30M5G	1	ME6211C30M5G	MICRONE	
50	Battery management chip TP4054_C66821 5	1	TP4054	UMW	
51	Infrared receiver VSOP38338	1	VSOP38338	Vishay Intertech	
52	USB connector TYPE-C 3.1 MT 16P_C168688	1	918-418K2024S40000	JTJ	
53	e-ink display 2.13" 250x122 px	1	2.13inch e-Paper	WAVESHARE	e-ink module in D1.5
54	Amorphous Solar Cell 449 μ W 3.7 V	5	LL200-2.4-37	PowerFilm Inc.	a-Si photovoltaic laminate in D.5
55	Printed MSC cells A ₁ +A ₂ +A ₃ +A ₄ module 38.4 mF	1	A ₁ +A ₂ +A ₃ +A ₄	NOVA.id.FCT	printed supercapacit or in D.5

3.2.2 Optimization techniques integrated in the demonstrator

Demonstrator 1 incorporates the optimization techniques identified and documented in D2.4, *Energy Subsystem for Node Integration*, and D3.4, *Energy Modeling and Optimization Algorithms*. The techniques selected for integration were those considered most appropriate for the industrial material-flow use case addressed by Demonstrator 1.

At node level, Demonstrator 1 makes use of the RIoT node energy models presented in D2.4, Section 3.4, together with the node-level energy prediction application described in D2.4, Section 3.5, and further enhanced in D3.4, Section 3.7. These outputs supported the identification of both suitable operational sequences and appropriate configuration parameters for the demonstrator, thereby ensuring an appropriate balance between system performance and energy efficiency. The selected setup was also guided by the detailed energy investigations reported in Chapter 3 of D2.4 and Chapter 3 of D3.4, including parameters such as transmission power levels, advertising and connection intervals, MTU size, PHY rate, and other related

communication parameters. Consequently, the final demonstrator configuration reflects optimization-informed analysis and design decisions rather than ad hoc choices.

The enhanced version of the node-level energy prediction application, which also incorporates energy-harvesting dynamics, was applied to the industrial material-flow scenario considered in Demonstrator 1 in order to assess energy feasibility and align the demonstration with the available energy budget, as further described in D4.1, Section 3.5.1.8. Demonstrator 1 also adopts the most energy-efficient hardware configuration identified in D2.4 Section 3.3.2 and Section 3.3.3, particularly with regard to minimizing deep-sleep current consumption.

A key optimization integrated into the SUPERIOT node was the enhanced software driving of the E-ink display, as detailed in D2.4, Section 3.3.1. This optimization reduced display energy consumption by approximately 83%, from 12.39 mJ to 2.13 mJ. Further optimization was achieved through hardware selection of the most energy-efficient E-ink display, including assessment of film type and ink type, as reported in D3.4, Section 6.1.1. Two alternative displays were evaluated, and the selected display exhibited 5.1 times lower energy consumption, with 0.417 $\mu\text{Wh}/\text{cm}^2$ compared to 2.132 $\mu\text{Wh}/\text{cm}^2$ for the alternative. Demonstrator 1 also incorporates the demo firmware optimization described in D3.4, Section 6.2.1.

At network level, Demonstrator 1 integrates the lightweight MQTT communication protocol, selected for its low power consumption, scalability, cost-effectiveness, and suitability for low-bandwidth network environments. This was complemented by the use of JSON as a lightweight data-interchange format that is straightforward to read, parse, and generate. The implementation of MQTT and JSON within the demonstrator is described in D3.4, Section 4.6.2.

Overall, Demonstrator 1 benefits from a coordinated set of node-level, firmware-level, hardware-level, and network-level optimization measures derived from D2.4 and D3.4 and tailored to the requirements of the industrial material-flow use case.

3.3 Use-case scenario(s)

The real-life application of the smart tags and labels has been considered in *D1.4 Description of the selected scenarios, applications, and their requirements*. For the purposes of providing the relevant input to **WP4 Test Bed/Demonstrators Development** and the **D4.1 Deliverable: Demonstrator 1: Sustainable Smart Tag**, we introduced the application, use case scenario, requirements, and SUPERIOT system components relevant to Demonstrator 1.

Considering the application of Demonstrator 1, we derived its use-case scenario. Then, based on this scenario, we derived the demonstrator requirements to shape the SUPERIOT demonstrator system blocks and their properties. These relationships and their connection with the real-life counterparts are shown in Figure 8 [2].

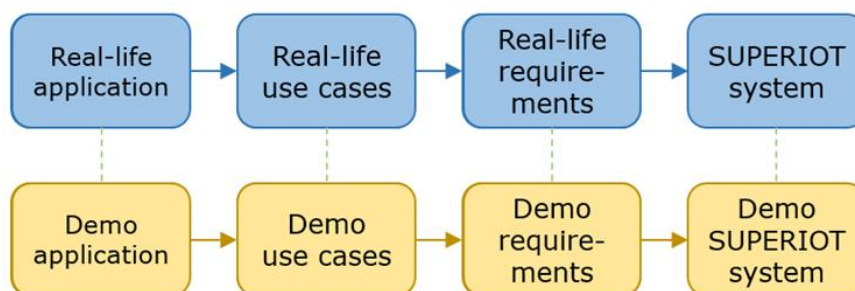


Figure 8. Applications, use cases and requirements and their relationships with the SUPERIOT system and demonstrators. [2]

It was necessary to demonstrate the real-life use case scenario which – according to the initial project assumptions, dissemination needs and portability requirements – was implemented as a demo-scale showcase.

3.4 Demonstrator scenario

The demonstration scenario consists of asset tracking and optimal flow control in an industrial scenario. We introduced this demonstration scenario based on the real-life scenario considered and detailed in Section 6.2.4.1 *Use case example 1: industrial material flow* in Deliverable 1.4.

3.4.1 Demonstration scenario: industrial material flow

Based on the demonstration scenario, we considered the application in the form of **smart tags and labels** for the industrial manufacturing of electric motors. From this, we derived the demonstrator use case scenario, which enabled the identification of the necessary tasks to be performed. Eventually, this facilitated the definition of the demonstrator requirements, as well as the SUPERIOT demonstrator system blocks and their properties, for the purposes of development and integration within WP4.

The key actors involved in the demonstration scenario are *Operator, Quality Engineer, Production Manager* and *Customer*, all represented by the *Presenters* or the *Recipients* of the demo presentation. The production process is reflected on a model scale. The product is a scaled model of an electric motor or a suitably small actuator motor. The times, distances and working stations' (WS1-WS6) dimensions are adjusted to match the demo scale, while preserving the full-scale capabilities of the system.

The demonstration scenario reflects the following electric motor production processes:

- attaching tags to units' frames (WS1);
- assemble the tagged frame with the stator (WS2);
- stator testing (WS5);
- machining the frame with the stator (WS3);
- soldering stator's electrical connectors (WS2);
- assembly of the frame and stator with the rotor and final motor assembly (WS2);
- motor running and performance tests (WS5);
- painting and curing of units on a painting station and curing machine (WS4);
- packing, storage and monitoring of products (WS6).

The direction and sequence of the material flow between these processes can be, to some extent, SUPERIOT-controlled in an agile manner, optimizing the utilization of the available resources at working stations WS2, WS3 and WS5. The demonstrator scenario assumes that the stator, rotor and frame are pre-fabricated at earlier stages, which are not covered in this demonstration. The demonstrator scenario was implemented in steps 1 to 4. Each activity could result in either success (OK) or failure (NOK). A successful outcome (OK) allowed the process to proceed to the next step, while a failure (NOK) status is handled and neutralized.

In those steps where VLC is available, the nodes' location can be determined using VLC. The stations were equipped with VLC lamps. A node located within the range of a particular lamp received a specific light signal. In this way, using the existing lighting (VLC) infrastructure, it was possible to determine where the node was located without the need to involve RF localization processes. The demonstration scenario steps, presented with procedural accuracy, are shown in tabular form in Appendix 2. The summary of the demonstration scenario steps is presented briefly below.

First, in **step 1**, operator attaches tags to units on WS1. Then, in **step 2**, the material (unit) is processed with flow direction and sequence between the WS2, WS5 and WS5, controlled in an agile manner using GUI. Next, in **step 3**, the units are painted and cured on WS4 with a painting station and curing machine. Finally, in **step 4**, on WS6 the product is packed, stored and monitored with the use of GUI. The industrial material flow between WSs is illustrated in Figure 9.

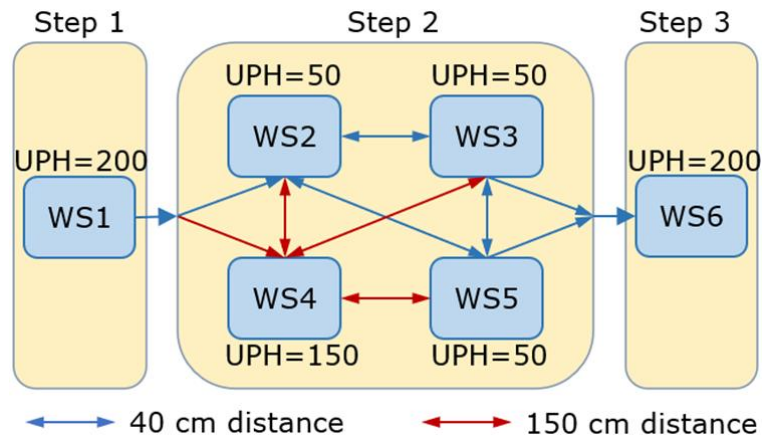


Figure 9. Illustration of distances and movement of item between workstations (WS) whose availability depends on their throughput specified in units per hour (UPH) – optimization of material and product flow.

The normal height of the working area is 100 cm in a real-life setup. For the scaled-down model, the height of the work area, i.e. the workstation countertop height, is 10 cm. Real-life production halls typically have a height of 5–6 meters to accommodate forklifts and machinery, while warehouses with overhead cranes are usually 7 meters or higher, with high-bay warehouses being even taller. This means that the height of the demonstrator's working station rooms is 70 cm on the model's scale. The factory hall lighting is usually mounted on the ceiling. The gateway and VLC lamp will be positioned centrally above the workstation countertop at a height of 70 cm from the floor. This means that the node located on the workstation countertop or transported on a work trolley between stations will be at a vertical distance of 60 cm from the gateway and VLC lamp.

The assumption of a linear scale of the model's dimensions carries certain implications. It should be noted that the radiation intensity (RF, VLC), defined as the power incident on a unit of area, decreases exponentially with distance from a point source. This should be taken into account when scaling the power of RF gateway and VLC lamp between the model and real-life setups. Moreover, the time scale must be handled carefully, as the relationship between energy harvesting time and the amount of energy harvested and stored e.g. in a MSC is not linear.

WS1 demonstrated the tags attachment and initialization workstation. This station has dimensions of 20 cm by 24 cm, with a free space of 9 cm around its edges. The station is located in a hall with a height of 70 cm. The gateway and VLC lamp (LEDVANCE DL SLIM 225MM 22W 4000K 2000 lm 150mA lamp was applied) were mounted at a height of 70 cm. At WS1, the SUPERIOT node utilized both VLC and BLE, enabling dual-mode communication. The activities performed at this workstation included attaching six tags to six units' frames.

WS2 demonstrated the preparation workstation. The station has dimensions of 20 cm by 24 cm, with 9 cm of free space around its edges. The station was located in a demo hall model 70 cm high. The gateway and VLC lamp were mounted at a height of 70 cm. At WS2, the SUPERIOT node used VLC instead of RF communication. BLE (2.4 GHz) was disabled to simulate conditions of ineffective RF communication, such as those caused by an electromagnetically polluted industrial environment. During the demonstration, the tags smoothly switched from RF to VLC communication to handle the RF communication problem. The following activities were performed at this station: assembling the tagged frame with the stator, soldering stator's electrical connectors, assembly of the frame and stator with the rotor and final motor assembly.

WS3 demonstrates the machining workstation. The station has dimensions of 20 cm by 24 cm, with 9 cm of free space around its edges. The station was located in a demo hall model 70 cm high. The gateway and VLC lamp were mounted at a height of 70 cm. At WS3, the SUPERIOT node uses VLC instead of RF communication. BLE (2.4 GHz) is periodically disabled to simulate conditions of ineffective RF communication, such as those caused by industrial environments near 3D computer numeric control (CNC) milling machines or lathes equipped with electric

drives, motors, and voltage/frequency converters. During the demonstration, the tags smoothly switch from RF to VLC communication to address RF issues. At this station, the machining of the frame with the stator is performed.

WS4 demonstrates the painting and curing workstation. It has a dimension of 60 cm by 24 cm, with 9 cm of free space around its edges. The painting section of the workstation has dimensions of 30 cm by 24 cm. The gateway and VLC lamp were mounted at a height of 40 cm. The curing section of the workstation has dimensions of 30 cm by 24 cm. At this station the painting and curing of the units are performed.

WS5 demonstrates the factory testing workstation. The station has dimensions of 20 cm by 24 cm. The free space around the edges of the station is 9 cm. The station was located in a model hall 70 cm high. The gateway and VLC lamp are mounted at a height of 70 cm. At WS5, the VLC offered by the SUPERIOT node is being partially used instead of RF communication. At WS5, the SUPERIOT node's VLC communication is used partially as an alternative to RF communication. This workstation simulates measurement operations, with cables arranged such that BLE RF signals could introduce interference in the measurement channels. During the demonstration, switching from RF to VLC communication eliminates these interferences, illustrating the seamless transition between RF and VLC modes. The following activities are performed at this station: stator testing, motor running and performance tests.

WS6 demonstrates the package and storage (warehouse) workstation. This station has dimensions of 100 cm by 50 cm. The station was located in a hall model, 70 cm high. The gateway and VLC lamp (LEDVANCE DL SLIM 225MM 22W 4000K 2000 lm 150mA lamp was applied) were mounted at a height of 70 cm. At this workstation, the SUPERIOT node's dual-mode communication – VLC and BLE (2.4 GHz) – is fully enabled. The following activities were performed at this station: packing, storage and monitoring of the product.

3.5 Demonstrator integration

In order to demonstrate the considered use case scenario of Demonstrator 1, specific development and integration tasks had to be carried out. The key development and integration tasks, completed during the project and WP4 period, are presented and detailed in this section. These tasks enabled the successful execution of the demonstration and ensured that the general requirements listed in Table 1 were fully met:

- Demo1-R-01: Multimode optical-radio communication
- Demo1-R-02: Bidirectional communications
- Demo1-R-03: Reconfigurability
- Demo1-R-04: Accurate positioning information
- Demo1-R-05: Sensing
- Demo1-R-06: Actuating
- Demo1-R-07: Energy autonomy
- Demo1-R-08: Sustainability

Demonstrator 1 integrates the inputs from work packages WP1, WP2 and WP3 and leverages the results detailed in their deliverables throughout the SUPERIOT project. To avoid redundancy, this deliverable focuses mainly on the work performed during the integration and preparation of the demonstrator.

3.5.1 Demonstration scenario industrial material flow integration

3.5.1.1 Light communication

The Demonstrator 1's sustainable dual mode RIoT node integrates BLE and VLC. It enables energy-efficient, reconfigurable and reliable communication with SUPERIOT network. The AP and

RIoT node operations are coordinated through state machines to manage data transfer, error handling, and communication over both optical and RF channels. Details on the AP state machine, network procedures and implementation are provided in D4.2 Demonstrator 2 Advanced Logistics in Medical ICT Scenario [3].

The view of Demonstrator 1's node and AP integrated into the SUPERIOT network is presented in Figure 10. There are two possible lamp variants: narrowband VLC mini lamp delivered in WP2 and LEDVANCE DL SLIM 225MM 22W 4000K 2000 lm 150mA commercial lamp integrated into SUPERIOT network in WP4.

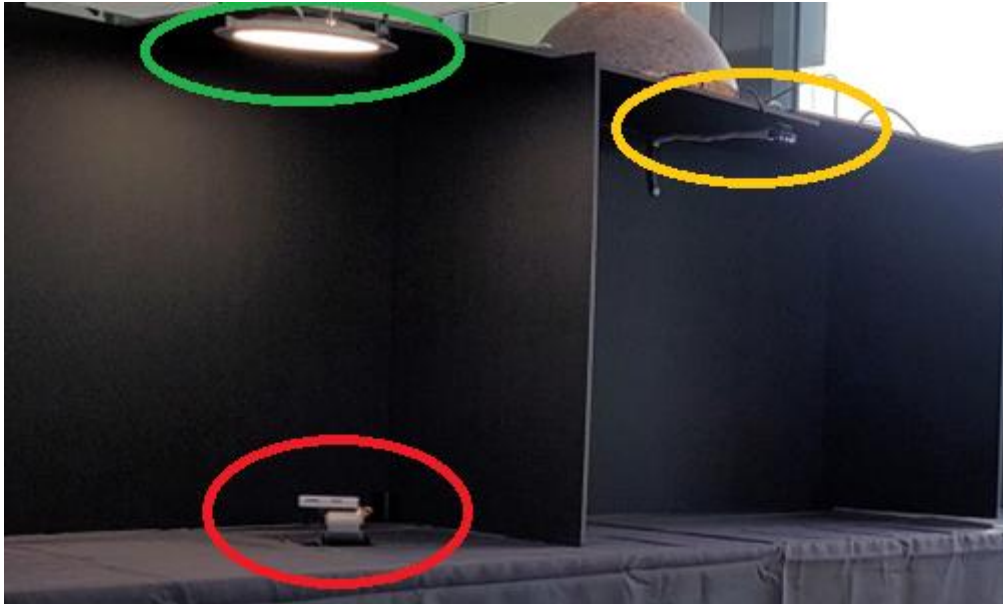


Figure 10. Demonstrator 1's RIoT node (red outline) and AP integrated into the SUPERIOT network – AP with LEDVANCE DL SLIM 225MM 22W 4000K 2000 lm 150mA on the left (green outline) and narrowband VLC mini lamp on the right (yellow outline).

In Demonstrator 1 application, RIoT nodes actively monitor wake-up signals via VLC, initiate communication procedures, and transmit sensor data over optical or radio channels enabling reconfigurability.

3.5.1.2 Radio communication

Within the RIoT network, Bluetooth Low Energy (BLE) communication plays a central role in enabling low-power, short-range connectivity between nodes and access points. Each node employs a state machine that continuously monitors BLE channels for discovery and data exchange procedures as needed. Once a BLE link is established, nodes transmit sensor readings, while the AP manages connection stability, data integrity, and collision avoidance.

The BLE protocol structure allows for efficient addressing and data encapsulation, with packets containing device identifiers, payload data, and error-checking. This facilitates reliable bidirectional communication even in dense network deployments, supporting periodic sensor updates, configuration commands, and acknowledgment messages.

Integration efforts also examine the coordination between BLE and system controllers, such as BeagleBone Black (BBB) units and Raspberry Pi (RPI) unit. Depending on deployment, a single BBB may manage one or multiple nodes, requiring tailored software routines to handle connection management and packet routing. These configurations directly influence network performance and scalability.

Overall, BLE communication represents a critical component for ensuring energy-efficient, reliable, and low-latency connectivity, complementing optical communication and forming the backbone of the smart hybrid environment network. Future work can continue to optimize

connection stability, reduce power consumption, and improve interoperability across heterogeneous node deployments.

3.5.1.3 Light localization

In the Demonstrator 1, node localization is based on a zone-oriented, light-based strategy, where each AP defines a coverage area and nodes are assigned to zones according to which AP successfully receives their transmissions. The zone-based localization uses uplink frame identification with the unique AP's MAC address and known position of the particular AP. Detailed explanations and figures are provided in D4.2 Demonstrator 2 Advanced Logistics in Medical ICT Scenario [3].

The view of Demonstrator 1's node and AP with known zone location integrated into the SUPERIOT network is presented in Figure 11.



Figure 11. Demonstrator 1's node (red outline) and AP (yellow outline) with known zone location integrated into the SUPERIOT network.

3.5.1.4 Actuation

In an industrial material flow scenario, the SUPERIOT nodes required actuation to update the electronic paper display with relevant information for factory personnel. The refresh was performed according to data received from the SUPERIOT network using visible light communication or radio frequency (BLE) communication.

For the execution of Demonstrator 1 and the applied use case scenario, MPICOSYS prepared the content for the Electronic Paper Display (EPD) and incorporated it into the firmware uploaded to the node. The EPD format of the content was prepared according to the images required for the demonstrated use case. The EPD format data were prepared with the use of the custom Python script developed for the 2.13" EPD display used in the node. The Python script used the Python Imaging Library (PIL). The images are shown in Figure 12 to Figure 19. The corresponding firmware codes for the images are presented in Listings L1-L8 (Appendix 3). The prepared data were implemented into the node firmware, stored in the node's flash memory, and called via the display update function. Thanks to the dual-mode communication capability of the SUPERIOT system, the appropriate icon was displayed depending on whether the downlink used radio or visible light communication.

This application enabled the node to actuate with up-to-date information related to industrial material flow, delivering relevant instructions to factory personnel, such as production operators or warehouse staff, in a manner fully controlled by the SUPERIOT network.



Figure 12. Information and data for controlling the industrial material flow: electric motor product nameplate – data received via VLC downlink.



Figure 13. Information and data for controlling the industrial material flow: OK PROCEED – data received via VLC downlink.



Figure 14. Information and data for controlling the industrial material flow: PASS TO NEXT WS – data received via VLC downlink.



Figure 15. Information and data for controlling the industrial material flow: WAIT FOR QUALITY ENGINEER – data received via VLC downlink.



Figure 16. Information and data for controlling the industrial material flow: electric motor product nameplate – data received via RF BLE downlink.



Figure 17. Information and data for controlling the industrial material flow: OK PROCEED – data received via RF BLE downlink.



Figure 18. Information and data for controlling the industrial material flow: PASS TO NEXT WS – data received via RF BLE downlink.



Figure 19. Information and data for controlling the industrial material flow: WAIT FOR QUALITY ENGINEER – data received via RF BLE downlink.

3.5.1.5 Software platform

For the demo execution, the SUPERIOT system was integrated with the Graphical User Interface (GUI) developed and maintained by MPICOSYS. The GUI serves as a dashboard for monitoring and controlling the industrial material flow. It is implemented as a web client application and can be accessed at https://superiot.mpicosys.com/demo/project_demonstrator1/browser/. It communicates with the SUPERIOT network, i.e., SUPERIOT server / broker superiot.mpicosys.com, using the Message Queuing Telemetry Transport (MQTT). In addition to its monitoring and control functions, the GUI served as a proof-of-concept demonstration of how an MQTT client can consume data from the SUPERIOT network. A view of the MQTT client web application is shown in Figure 20, Figure 21 and Figure 22.

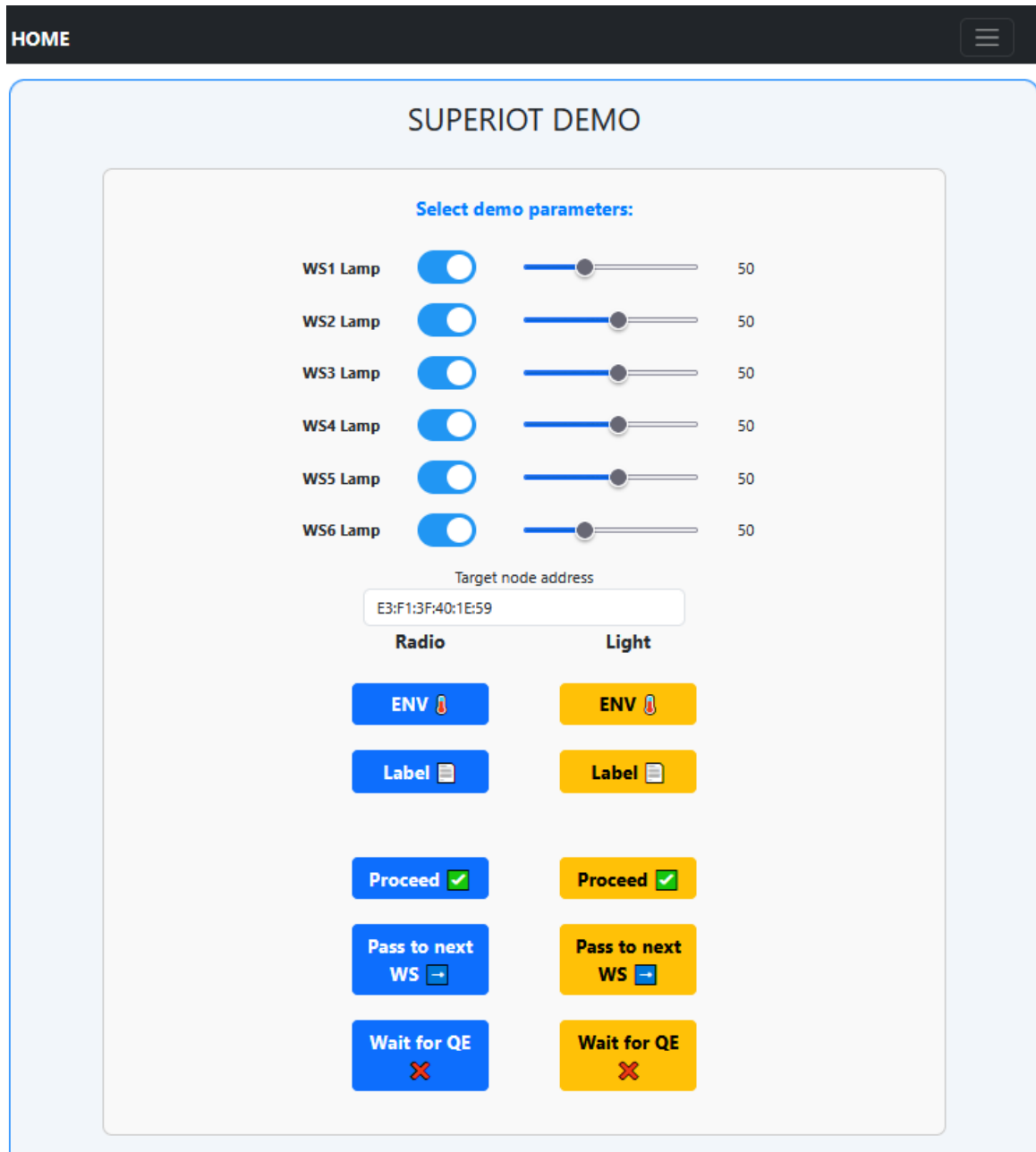


Figure 20. SUPERIOT Demonstrator 1 GUI dashboard – the MQTT client web application view 1: Selection of demo parameters: lamps power, target node, information sent over light and radio.

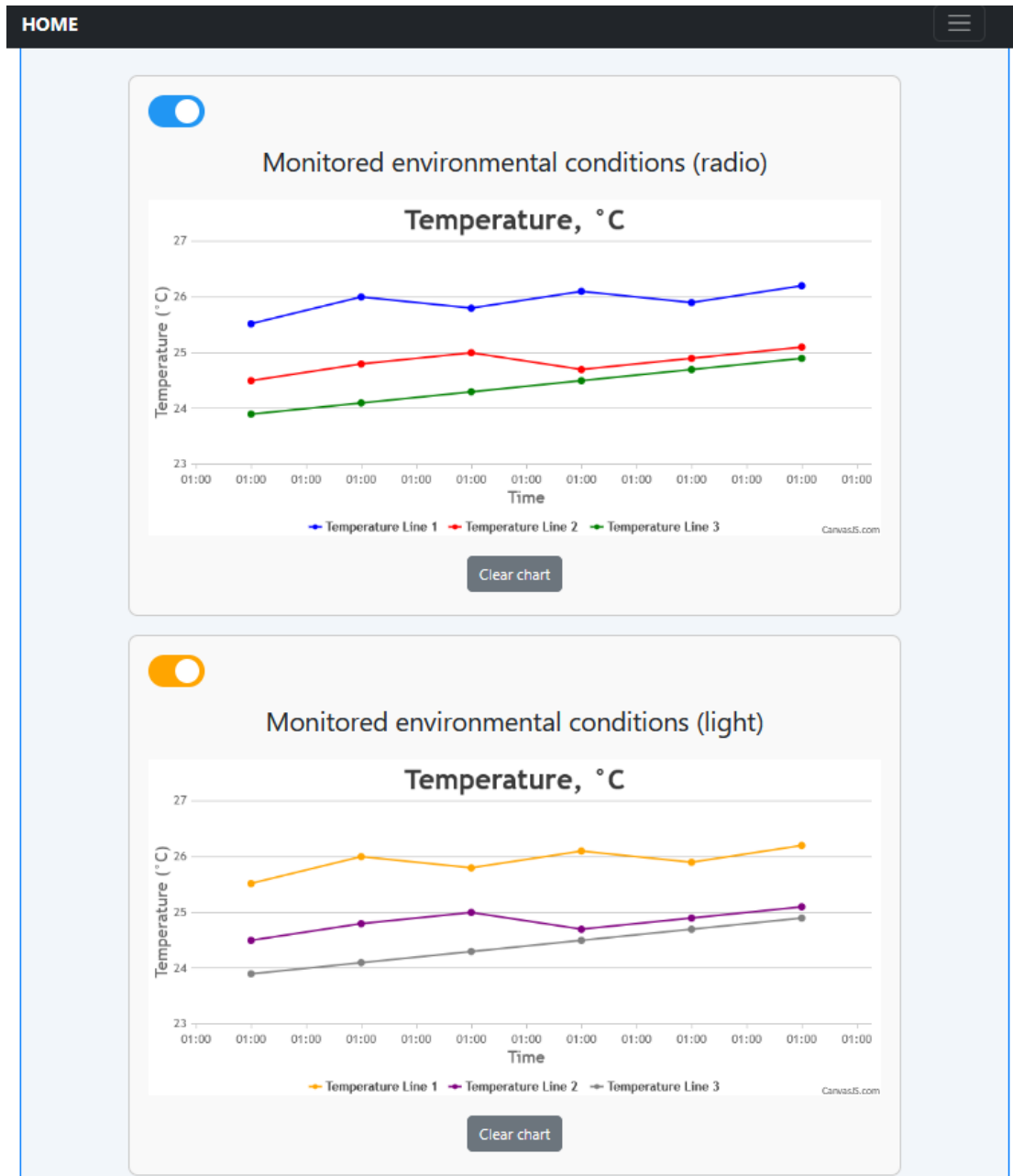


Figure 21. SUPERIOT Demonstrator 1 GUI dashboard – the MQTT client web application view 2: Monitoring environmental conditions over light and radio.

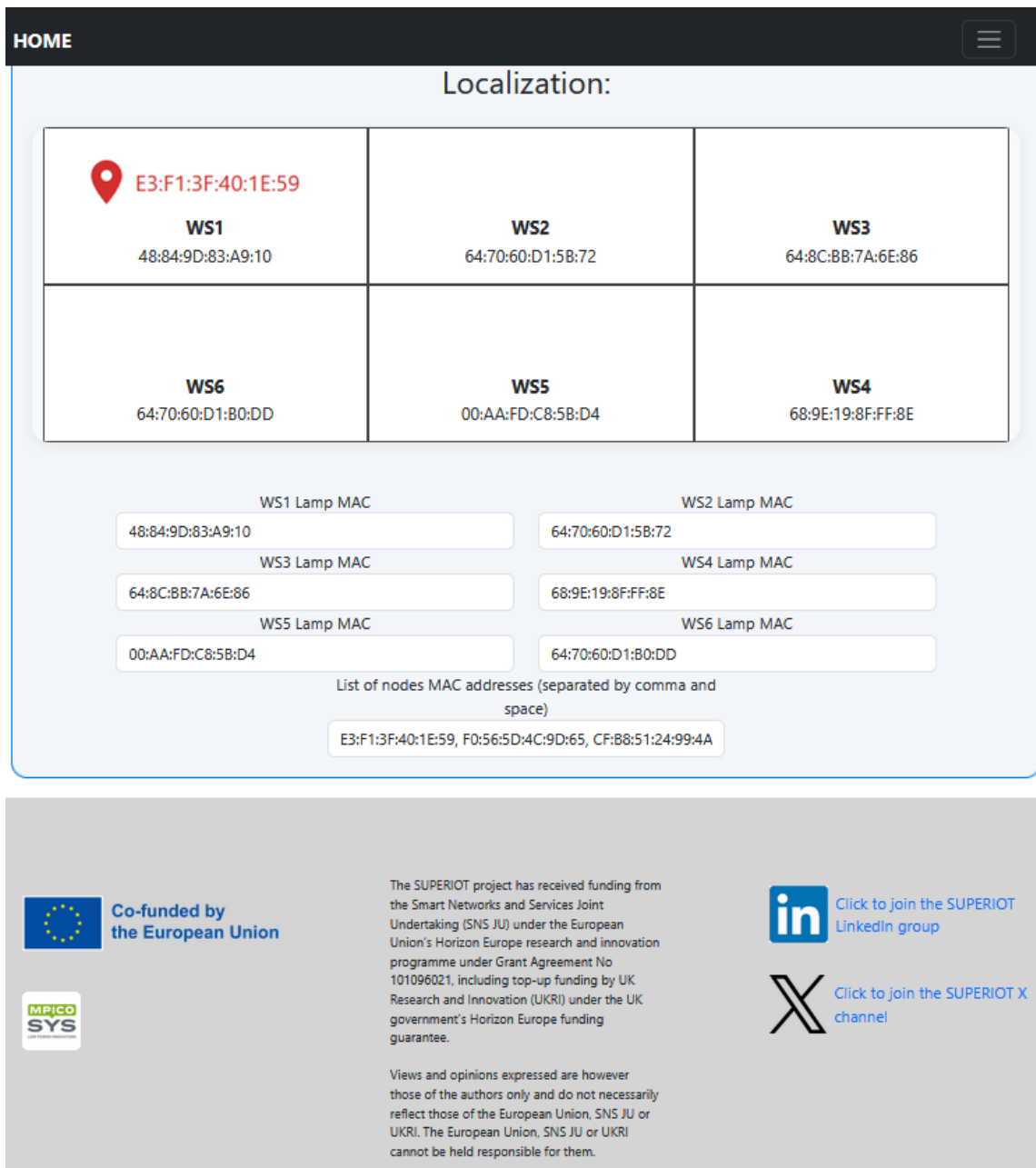


Figure 22. SUPERIOT Demonstrator 1 GUI dashboard – the MQTT client web application view 3: Localization tracking using visible light positioning and input of MAC addresses of SUPERIOT network devices.

The data can be transmitted and accessed via the cloud-based MQTT broker developed within the SUPERIOT project, using the JSON lightweight data-interchange format, as described in deliverable D3.4 *Energy Model and Optimization Algorithms* and implemented in the WP3 network software. This data structure can be readily received and processed by external applications, such as MQTT clients subscribing to the relevant MQTT topics.

3.5.1.6 Network

The SUPERIOT network, developed in WP3, was designed with the requirements of Demonstrator 1 in mind. The integration and development efforts for this demonstration focused on automating, parameterizing, and scripting the RPi master node and BBB access point (AP) devices. The RPi was configured to connect to the WiFi hotspot, share internet access with the BBBs connected to an Ethernet switch, and automatically execute the SUPERIOT network Python scripts developed in WP3 and further developed or integrated in WP4. Each BBB was set up to

verify the internet connection through the RPi before running its respective network scripts. These single-board computers – RPi and BBBs – were configured to operate in a plug-and-play manner. Remaining network-related preparations for Demonstrator 1 were limited to properly connecting the SUPERIOT network components according to the structure shown in Figure 23.

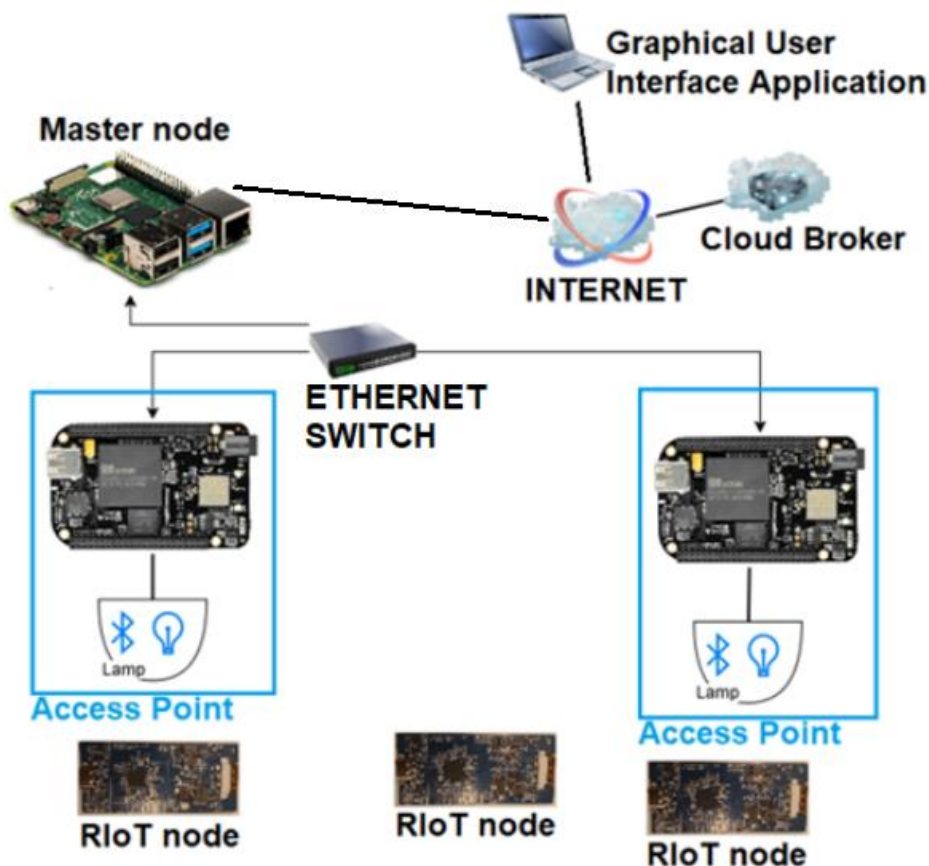


Figure 23. The SUPERIOT network structure: GUI, MQTT Broker (Cloud Broker), RPi (Master node) connected to the WiFi internet hotspot and sharing the internet access to BBBs, Access Point (BBB with VLC lamp and BLE communication module), RiOT node and Ethernet switch.

3.5.1.7 Energy storage MSCs

For the SUPERIOT project, the team at NOVA.id.FCT deposited MXene-based MSCs using the blade coating technique. The MXene ink was synthesized through a MILD (Minimally Intensive Layer Delamination) process, which avoids the use of highly corrosive reagents such as concentrated hydrofluoric acid (HF), instead employing less hazardous chemicals or milder reaction conditions. This approach improves safety and material quality while minimizing structural defects. Moreover, this method is also suitable for scalable synthesis and achieves a high yield of high-quality, single-layer MXene sheets with outstanding electrochemical properties [4]. The detailed ink synthesis protocol has been reported in [5]. For electrode deposition, the MXene ink was sonicated for 15 minutes to ensure uniform dispersion and was then deposited under ambient conditions using a K101 Control Coater at a speed of 1.5 meters per minute. Each layer (total of 10) was dried using a hairdryer and the final films were annealed at 80 °C for 15 minutes to improve uniformity and conductivity. To attain the desired voltage of ~3.6 V, a set of six MSCs in series was designed, as shown in Figure 24a. This configuration enables higher voltage operation within a compact device architecture. The six MSCs connected in series exhibited consistent electrochemical behavior, with total capacitances ranging from 7.4 to 10.6 mF at a scan rate of 5 mV s⁻¹ (Figure 24b).

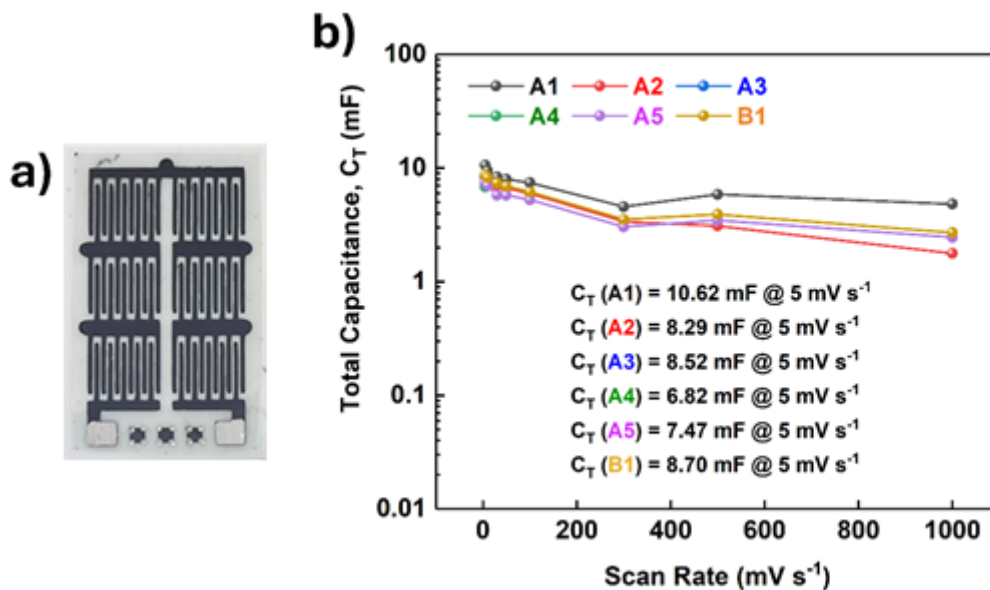


Figure 24. Examples of a) set of 6 MXene MSC in series (6 MSCs @ 3.6 V) and b) their total capacitance as a function of the applied scan rate.

To assemble the device, sets of 6 MXene MSC in series were coated with a PVA-H₂SO₄ gel electrolyte and drop-cast onto UV-treated electrodes with an active area of 0.768 cm². The electrodes were then left to dry overnight at room temperature. The devices were encapsulated using heat-sealed lamination pouches along the outer edges to protect them while avoiding thermal damage to the active region.

Subsequently, three of these 6-SC units were connected in parallel (Figure 25a and Figure 25b), resulting in an 18-SC configuration (3×6 SCs @ 3.6 V). This parallel integration significantly increased the overall energy storage capacity, as reflected by the higher total capacitance values ranging from 20.8 mF to of 27.6 mF at 5 mV s^{-1} (Figure 25c). This demonstrates the modularity and scalability of MXene-based MSCs, enabling them to be integrated into flexible energy storage modules with tunable voltage and capacitance outputs that are suitable for powering low-voltage electronic devices.

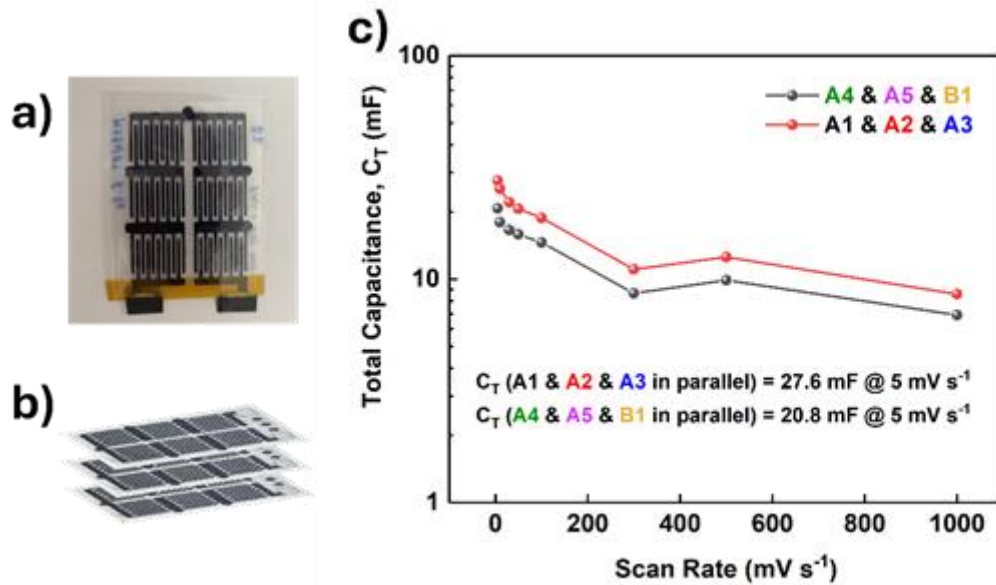


Figure 25. a) Example of the stacked 6-SC units in parallel (3×6 SCs @ 3.6 V); b) Schematic representation of the stacked MSC units and c) total capacitance as a function of the applied scan rate for two stacks units.

3.5.1.8 Node energy consumption prediction tool application software

For the SUPERIOT project, the team at University of Bristol developed and delivered a Windows OS-based Application for predicting the SUPERIOT node energy consumption accurately based on the energy models that were developed. The application allows users or network process designers to define the RIoT node operations for any desired scenario with states such as BLE, VLC, sensing, EPD, wake-up, idle, sleep, etc. It also supports saving and loading data, enabling users to preserve results at different steps. The application simulates energy harvesting dynamics – including RF energy harvesting, light energy harvesting, and MSC charge/discharge – based on the defined node operations. Users can work with predefined default parameters or adjust values to optimize configurations for their scenario. Additionally, the application allows optional creation of an IoT current profile dataset via the “Demo” tab. The application interface is shown in Figure 26.

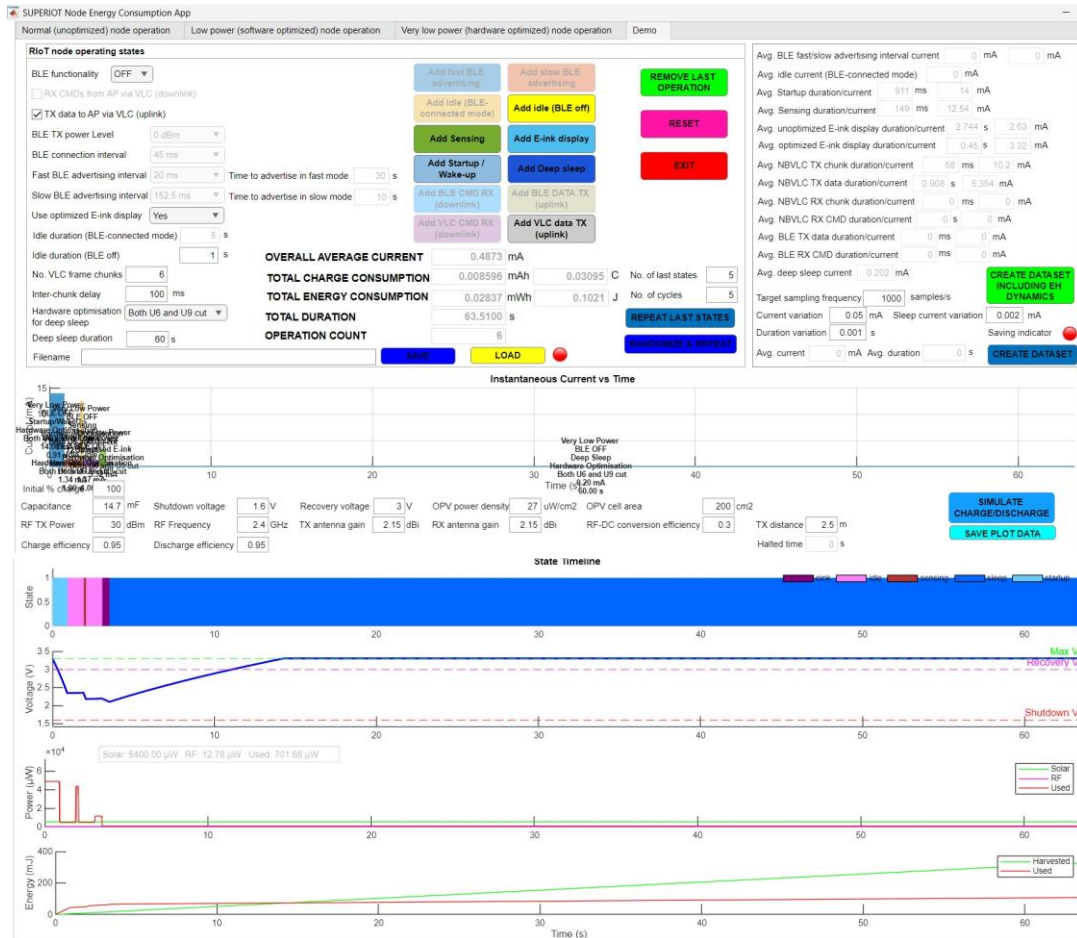


Figure 26. Node energy consumption prediction tool software application – the main window application view with “Demo” tab active.

The software application enabled the simulation of energy consumption for the considered use case scenario, allowing the demonstration to be adapted to the available energy budget. It also facilitated the sizing of the energy storage – MSC capacitance and the number of PV cells – to ensure stable operation of the hybrid node integrated into an energy-autonomous, batteryless application. The University of Bristol’s team also provided details for the node and network energy optimization in deliverables D2.4 [8] and D3.4 [9].

3.5.1.9 Hybrid version of node

The hybrid SUPERIOT node combines printed electronics (PE) and Si-based technologies. The printed MSC has been provided by NOVA.id.FCT. This printed MSC was needed for energy storage and stable operation under the variable power consumption, e.g. during the EPD refresh. Printed MSCs charge their capacity with energy harvested from the environment (light) and avoid power sags. Four MSCs: A₁, A₂, A₃ and A₄, connected in parallel were applied. The maximum capacitance of A₁+A₂+A₃ cells connected in parallel was 27.4 mF. The maximum capacitance of A₄ was 11 mF. Consequently, the total maximum capacitance of applied printed MSC was 38.4 mF. Deployed MSC cells A₁, A₂, A₃ are presented in Figure 27. Deployed MSC cell A₄ is presented in Figure 28. The details on the applied MSC were described in this chapter in 3.5.1.7.

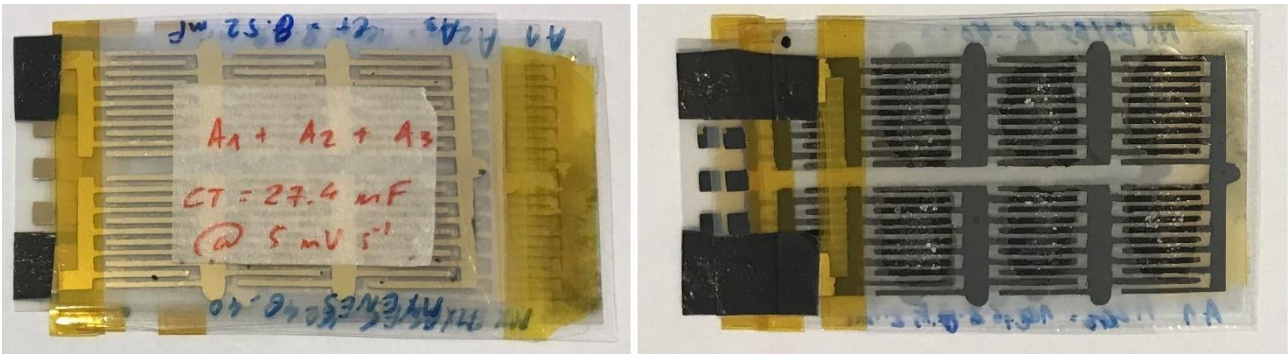


Figure 27. Printed MSC cells A_1 , A_2 , A_3 deployed in the Demonstrator 1's hybrid RIoT node – top view on the left and bottom view on the right.

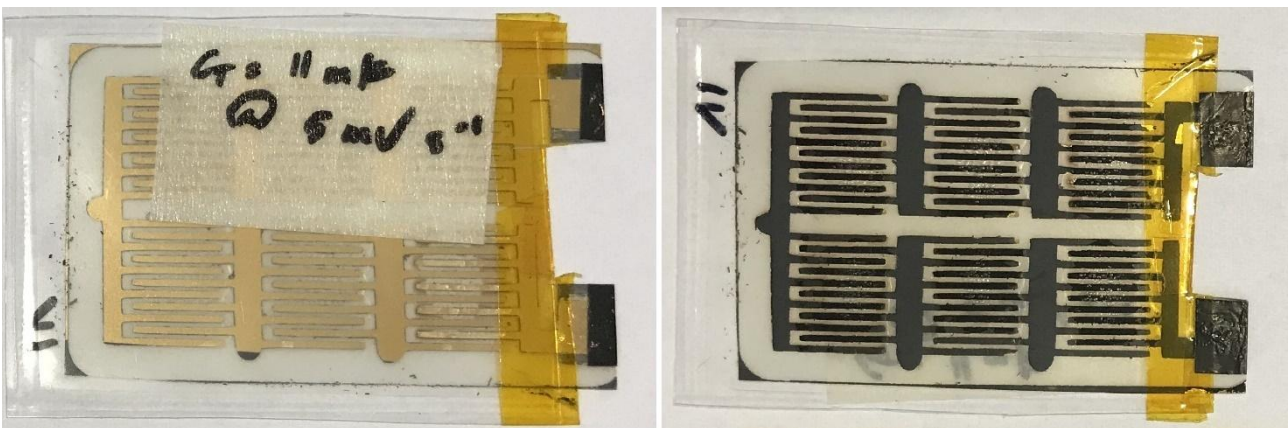


Figure 28. Printed MSC cells A_4 deployed in the Demonstrator 1's hybrid RIoT node – top view on the left and bottom view on the right.

The energy models, optimization techniques, and prediction application were developed by the University of Bristol. The industrial lamp with an integrated light communication module, developed by LIGHTBEE SL, supports both data communication and energy harvesting. Light energy harvesting is achieved using thin-film amorphous silicon flexible PV cells, laminated with standard PET and foil tape terminals. These commercially available PV cells, manufactured by Power Film Inc., are optimized for collecting artificial indoor lighting in environments such as warehouses, offices, and retail spaces. The maximum power of one PV cell is $449 \mu\text{W}$ (at 1000 lux). Five such PV cells connected in parallel were applied. This application yielded a total maximum power of 2.245 mW at 1000 lux. The PV cells were at the vertical distance of 15 cm from the lamp. This number of cells, dimensions, and distances were configured to obtain reduced charging times aligning them with the reduced timescale applied in the demonstration for charging, discharging, idle states between node's actions and data communication. The RIoT node core was provided by UOULU.

These components enabled MPICOSYS to integrate PE and Si-based technologies into a fully energy-autonomous system, applying the hybrid node in Demonstrator 1 as a batteryless solution. The operational hybrid node, communicating with the SUPERIOT network, refreshing its display, and reporting its location, is shown in Figure 29.



Figure 29. The hybrid SUPERIOT node combines printed electronics (PE) and Si-based technologies.

For such considered battery-less and hybrid node, the power consumption has been analyzed. The analysis covered the hybrid node operating scenario of 120 s in the demo-scale, presented in the video demonstration from 7:00 to 9:00 minute in Appendix 1. The particular steps of the analyzed battery-less and hybrid node demonstration scenario are presented in Table 4. The analysis was performed with the use of the node-level energy consumption prediction application described in 3.5.1.8 section of this document. The application’s simulation results are validated as consistent with the real physical hardware node and detailed in D3.4, Section 3.7. The results of the power consumption analysis are presented in Figure 30. For the scenario considered and according to the results presented in Figure 30, the energy consumption was 2400 mJ, that results in the average power consumption of 20 mW in a model scale for the operating period of 120 s. The real-life scenario, unlike the model-scale scenario, will have the extended idle states or deep sleep states between communication and actuation periods and thus significantly reduce the power consumption as the deep sleep mode before the wake-up of the node result in negligible (in the tens-of-microwatts range) power consumption. Consequently, for the real-life scenario where the node does not need to demonstrate the functions and only communicates and actuates once in a long time, it will be in deep sleep most of the time. Assuming the deep sleep state lasts more than twenty times longer than the active states, energy consumption will drop below 1 mW, for the real-life scenario of the industrial material flow where the material a large part of the time is stored and only monitored.

Table 4. The particular steps of the battery-less and hybrid node demonstration scenario analyzed for power consumption.

No.	State	Current [mA]	Duration [s]
1	Normal ; BLE Fast Advertising ; BLE TX Power 4 dBm ; BLE advertising interval 20.0 ms	6.95	1.00
2	Normal ; BLE Slow Advertising ; BLE TX Power 4 dBm ; BLE advertising interval 152.5 ms	5.66	12.00
3	Normal ; VLC CMD RX ; BLE TX Power 4 dBm ; BLE connection interval 45.0 ms	5.68	0.91
4	Normal ; Sensing ; BLE TX Power 4 dBm ; BLE connection interval 45.0 ms	12.28	0.52

5	Normal ; Optimised E-ink ; BLE TX Power 4 dBm ; BLE connection interval 45.0 ms	7.27	0.54
6	Normal ; BLE Slow Advertising ; BLE TX Power 4 dBm ; BLE advertising interval 152.5 ms	5.66	19.00
7	Normal ; VLC CMD RX ; BLE TX Power 4 dBm ; BLE connection interval 45.0 ms	5.68	0.91
8	Normal ; Optimised E-ink ; BLE TX Power 4 dBm ; BLE connection interval 45.0 ms	7.27	0.54
9	Normal ; BLE Slow Advertising ; BLE TX Power 4 dBm ; BLE advertising interval 152.5 ms	5.66	24.00
10	Normal ; VLC CMD RX ; BLE TX Power 4 dBm ; BLE connection interval 45.0 ms	5.68	0.91
11	Normal ; Optimised E-ink ; BLE TX Power 4 dBm ; BLE connection interval 45.0 ms	7.27	0.54
12	Normal ; BLE Slow Advertising ; BLE TX Power 4 dBm ; BLE advertising interval 152.5 ms	5.66	18.00
13	Normal ; BLE CMD RX ; BLE TX Power 4 dBm ; BLE connection interval 45.0 ms	7.55	0.00
14	Normal ; Optimised E-ink ; BLE TX Power 4 dBm ; BLE connection interval 45.0 ms	7.27	0.54
15	Normal ; BLE Slow Advertising ; BLE TX Power 4 dBm ; BLE advertising interval 152.5 ms	5.66	24.00
16	Normal ; BLE CMD RX ; BLE TX Power 4 dBm ; BLE connection interval 45.0 ms	7.55	0.00
17	Normal ; Optimised E-ink ; BLE TX Power 4 dBm ; BLE connection interval 45.0 ms	7.27	0.54
18	Normal ; BLE Slow Advertising ; BLE TX Power 4 dBm ; BLE advertising interval 152.5 ms	5.66	9.00
19	Normal ; VLC CMD RX ; BLE TX Power 4 dBm ; BLE connection interval 45.0 ms	5.68	0.91
20	Normal ; Optimised E-ink ; BLE TX Power 4 dBm ; BLE connection interval 45.0 ms	7.27	0.54
21	Normal ; BLE Slow Advertising ; BLE TX Power 4 dBm ; BLE advertising interval 152.5 ms	5.66	6.00

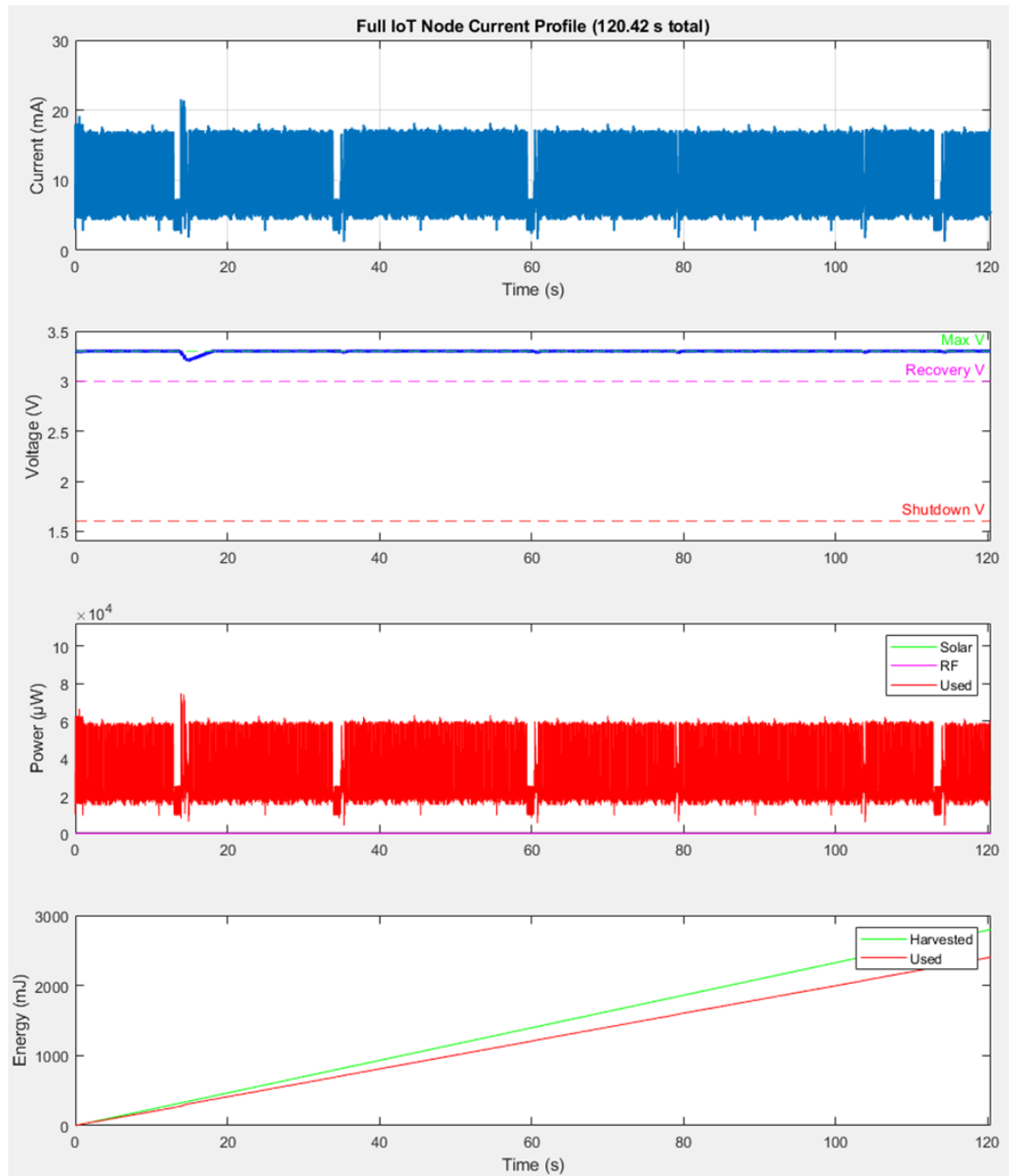


Figure 30. Results of the power consumption analysis: current, voltage, power and energy during the steps detailed in battery-less and hybrid node demonstration scenario.

Additionally, the power budget and energy consumption have been analyzed to give an estimation of how long the node is going to last without battery. To know the power budget, the analysis was performed including the MSCs as the energy storage in the conditions with no energy harvesting. The particular steps of the analyzed battery-less and hybrid node demonstration scenario are presented in Table 5. The listening for VLC commands was applied as disabled for saving the energy in the no-energy harvesting and battery-less configuration. The analysis results are presented in Figure 31. Using the applied MSC capacitance of 38.4 mF, the node achieves a battery-free operating lifetime of 26 seconds for the considered operating sequence. The duty cycle described in Table 5 was chosen to meet the demonstration requirements and consequently results in the observed 26-second node lifetime. However, in a real-world scenario, the power budget would not be exhausted because energy harvesting would supplement the system. Consequently, in the target operating conditions, the node lifetime will be not limited by the power budget.

Table 5. The particular steps of the battery-less and hybrid node demonstration scenario analyzed for power consumption.

No.	State	Current [mA]	Duration [s]
1	Low power ; BLE Slow Advertising ; BLE TX Power 4 dBm ; BLE advertising interval 152.5 ms	1.58	20.00
2	Low power ; BLE CMD RX ; BLE TX Power 4 dBm ; BLE connection interval 45.0 ms	4.40	0.00
3	Low power ; Sensing ; BLE TX Power 4 dBm ; BLE connection interval 45.0 ms	8.26	0.52
4	Low power ; Optimised E-ink ; BLE TX Power 4 dBm ; BLE connection interval 45.0 ms	3.65	0.54
5	Low power ; BLE DATA TX ; BLE TX Power 4 dBm ; BLE connection interval 45.0 ms	7.73	0.00
6	Low power ; BLE Slow Advertising ; BLE TX Power 4 dBm ; BLE advertising interval 152.5 ms	1.58	6.00

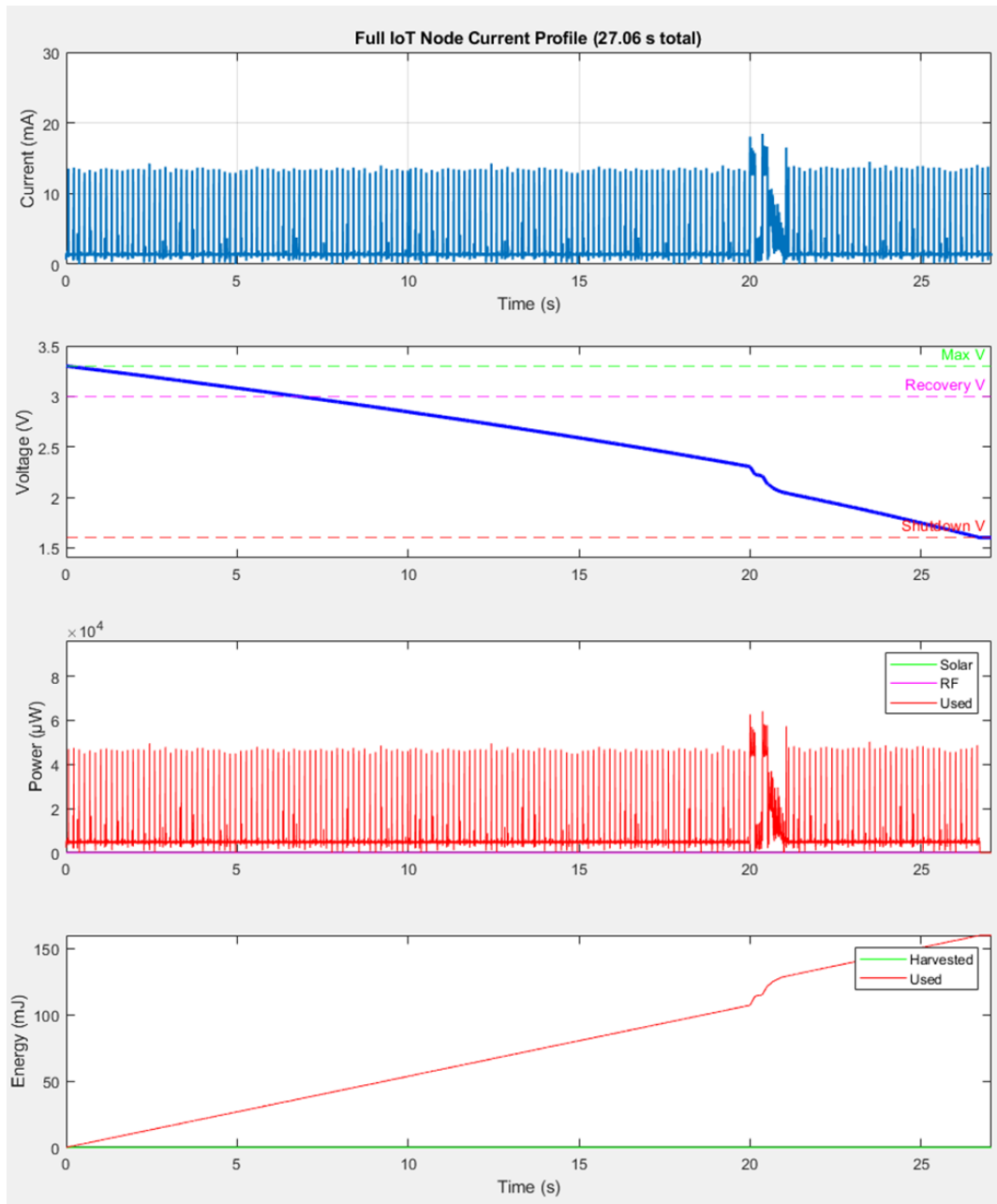


Figure 31. Results of the power budget analysis: current, voltage, power and energy during the steps detailed in battery-less and no-energy harvesting scenario.

This section provides also a brief overview of the printed components that were developed and that permit a more sustainable approach to achieving SUPERIOT goals. The main focus of their development was to create future replacements for the Demonstrator 1’s node components and for the 2nd scenario in deliverable D4.2 [3]. More detailed description of the printed components can be found also in deliverables D2.2 Sustainable ink formulation for the printed devices [6] and D2.3 Printed devices and sustainable materials for node integration [7].

Some of the PE components (Figure 32) were produced using thin film methodologies and patterned with photolithography on glass substrates. These components have small pads. To facilitate integration, printed circuit boards (PCBs) were developed to access the pads via conventional connectors.

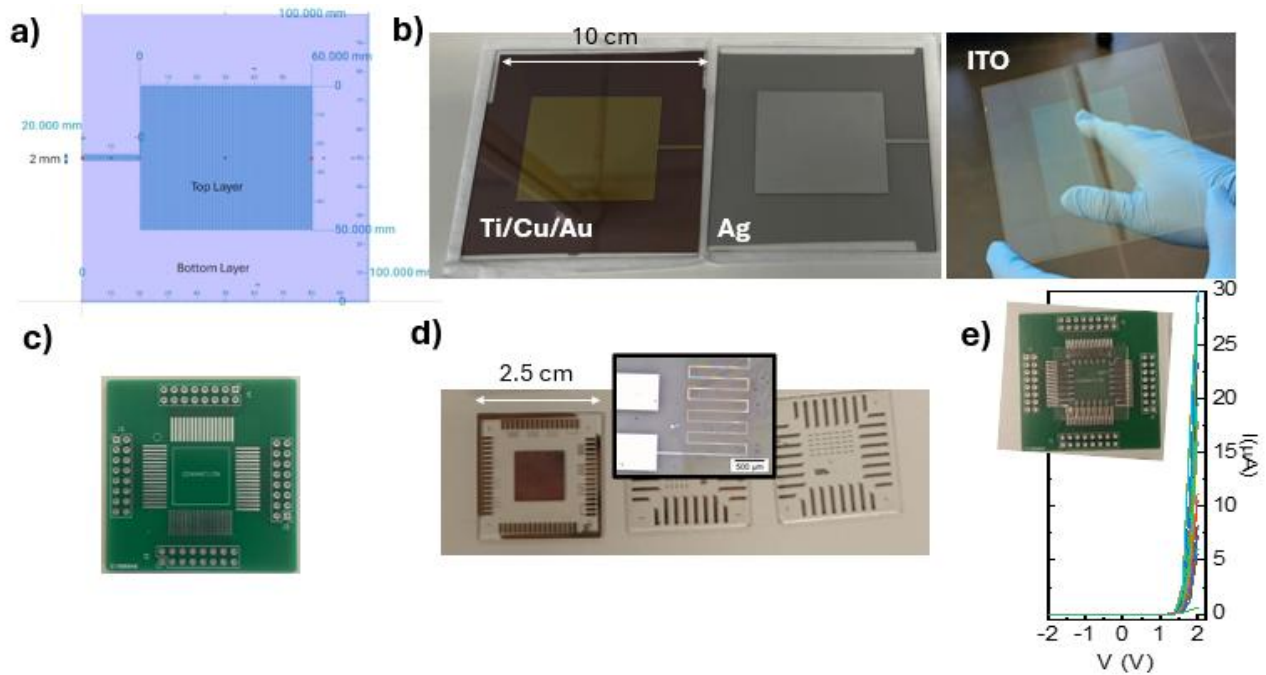


Figure 32. Printed components developed to replace conventional ones in demonstrator scenarios: a) backscattering antenna layout; b) printed antennas on Cu/Au, Ag ink, and ITO; c) developed PCB board for integration; d) resistors, capacitors, and photoresistors and e) diode characteristics.

3.5.1.9.1. Backscattering Antennas

In an attempt to produce a printed backscattering element, different layers were tested. Due to fabrication process constraints at NOVA.id.FCT, the selected substrate was 1.1 mm Corning glass, which is thinner and has different dielectric properties than the 1.57 mm Rogers board. A dielectric constant of 5.2 and a loss tangent < 0.003 at 100 kHz were determined for a capacitor of 250 pF. The antennas were produced by fabricating on both sides for the ground and front plane using different layers: i) Ti/Cu/Au by electron beam evaporation, ii) Ag ink by screen printing; iii) ITO (Indium-Tin-Oxide, a transparent and conductive film) by sputtering. Each deposition method has advantages and disadvantages, and the goal was to tune the overall resistance and backscattering properties of the antennas. The possibility of combining a transparent antenna (as in the case of ITO) was also considered and tests on fabricating metallic mesh antennas (etching the Cu/Au film or patterning the screen-printed Ag layer are also being considered).

3.5.1.9.2. Resistors

Substrates containing up to 16 different resistor values based on sputtered molybdenum (Mo) thin films were developed. Different resistance values can be attained by varying the width and length of the conductive tracks, which have a resistivity of $1.17 \times 10^{-4} \Omega \cdot \text{cm}$ and a thickness of 52 nm. Substrates with resistors ranging from 950 Ω to nearly 33 k Ω were produced.

3.5.1.9.3. Capacitors

The capacitors were produced using molybdenum (Mo) contacts and either 50-nm aluminium oxide (Al_2O_3) films produced by atomic layer deposition (ALD) or 220 nm Parylene-C layers produced by chemical vapor deposition (CVD). The capacitors' overlap area corresponds to $10^4 \mu\text{m}^2$, defining capacitors of approximately 15 pF (Al_2O_3) and 1.8 pF (Parylene-C). The characterization of the capacitors in frequency is being performed as well as the integration on the boards. The capacitance can be optimized according to the overlap area.

These substrates, which contain capacitors and resistors, can replace components in hybrid RF and light localization systems for SWIPT, SLIPT, and RF backscattering.

3.5.1.9.4. Photoresistors

As a proof of concept, photoresistors based on interdigitated electrodes and a perovskite layer were developed for use as light-responsive components in VLC. However, the frequency response was limited to a few kHz, so it was disregarded for scenario 2 of the demonstrator. Nevertheless, we are including this other PE component to supplement the list of devices that could be used in future light localization and communication systems.

3.5.1.9.5. Diodes

The development of the diodes was presented in the first report and deliverable 2.3. However, to integrate them into possible demonstrators, they were tuned to withstand higher operating voltages and were integrated into the PCB connector boards, as shown in Figure 32e.

3.6 Demonstration execution

The SUPERIOT consortium carried out the experiments for Demonstrator 1 at the Vitality Hub (2nd floor of High Tech Campus 85, Eindhoven, the Netherlands - Figure 33) during the project face to face meeting on 23–25 September 2025. The Vitality Hub is a collaborative test and exhibition space jointly operated by TU/e, Fontys, and IMEC NL, designed to host research pilots in health and vitality technologies.

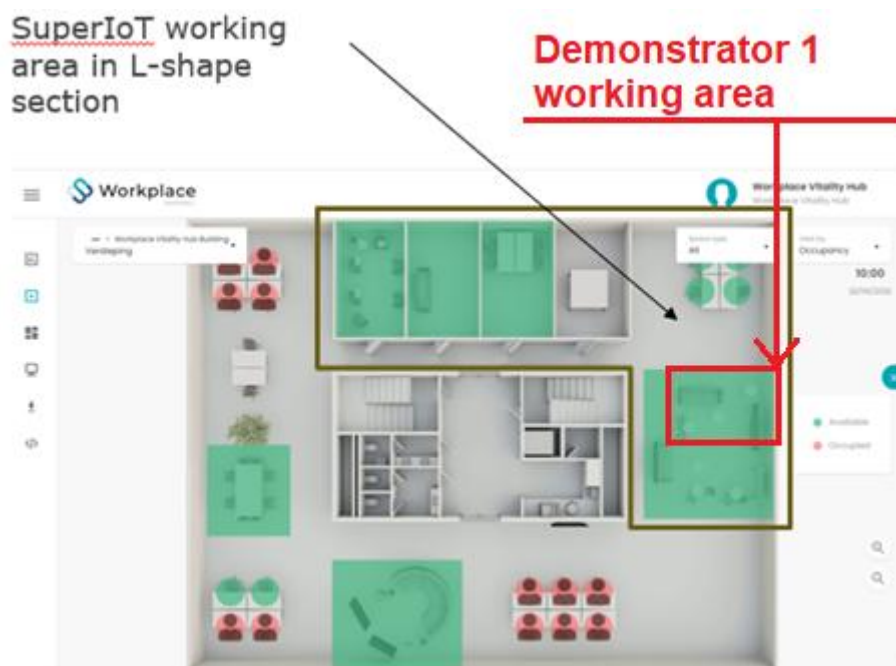


Figure 33. Layout of the 2nd floor of High Tech Campus 85: The Vitality Hub.

The setup is a modular office designed to accommodate the needs of Demonstrator 1's industrial material flow use case. It provides a controlled environment for realistic testing of indoor localization, wireless communication, and multi-sensor experiments. A dedicated SUPERIOT working area was designated in the rectangle along the L-shaped section, enabling deployment of access points (APs), light sources, and sensor nodes in the common area modelling industrial space on a demo scale.

The primary objective of the experiments was to evaluate the performance of the SUPERIOT system in terms of multimode optical-radio communication, bidirectional communications (uplink

and downlink), light-radio reconfigurability, positioning information, sensing, actuating, energy autonomy, and sustainability.

3.6.1 Demonstration scenario industrial material flow execution

was installed at the Vitality Hub. Figure 34 to Figure 36 illustrate the integrated setup, showcasing the use case conditions at a demonstrator-scale level.

- workstations WS1-WS6 in six separated zones
- access points installed under the ceiling of the factory hall zones
- the material – processed electric motors – with the Sustainable Smart Tags attached for monitoring and controlling the industrial material flow

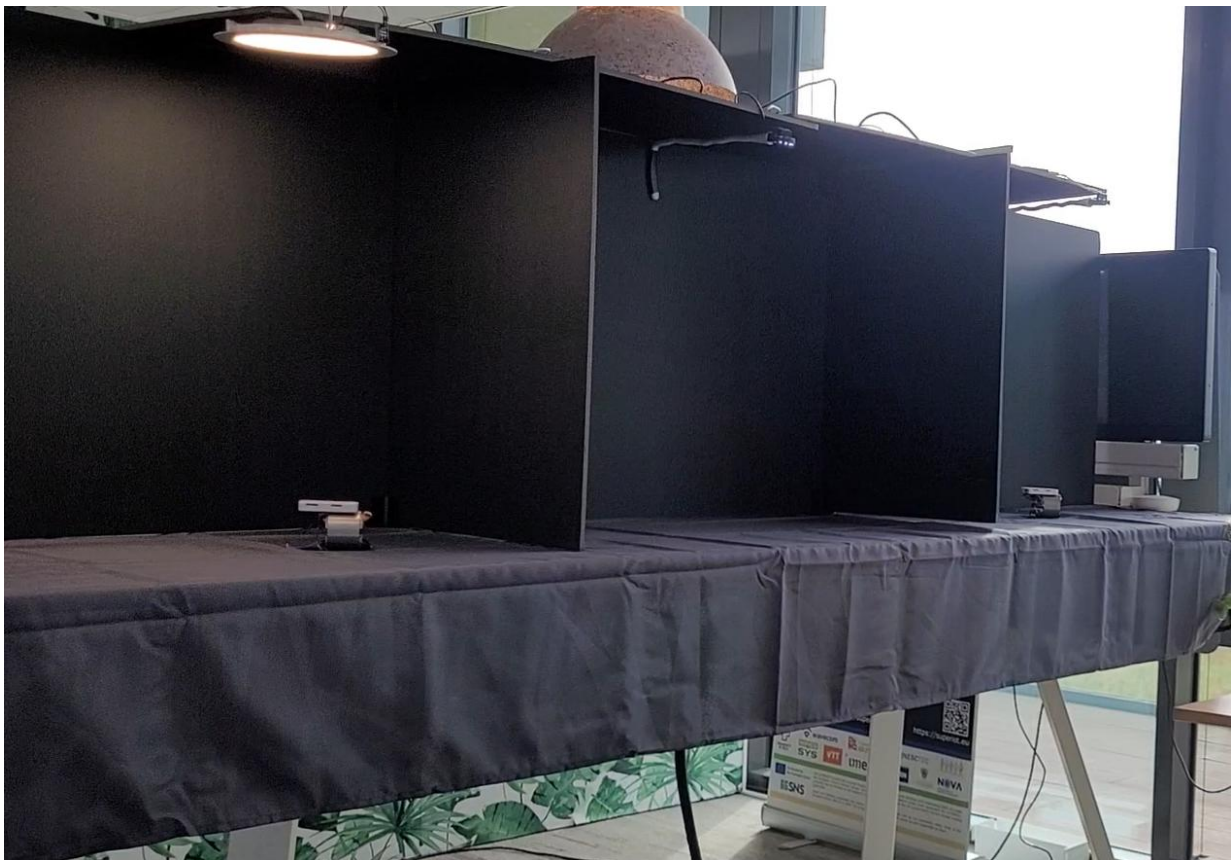


Figure 34. Demonstrator 1 integrated at Vitality Hub – view 1.



Figure 35. Demonstrator 1 integrated at Vitality Hub – view 2.

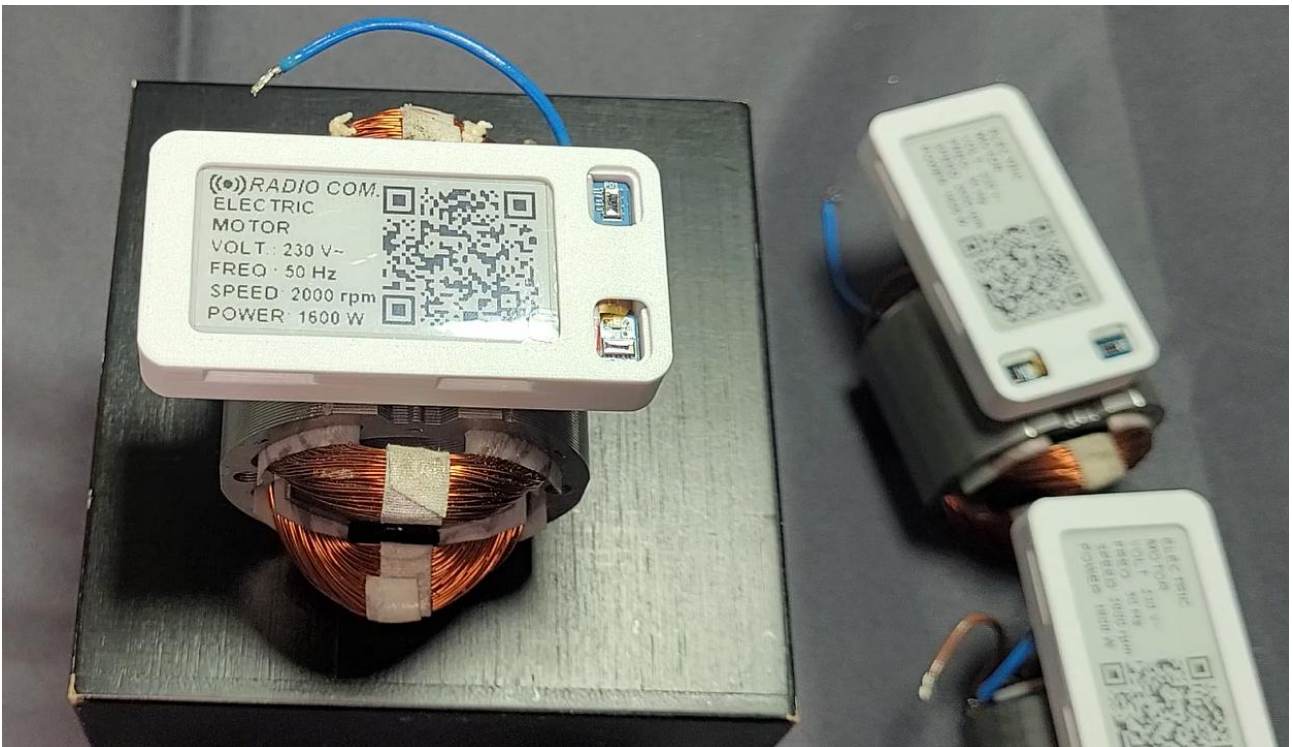


Figure 36. Demonstrator 1 integrated at Vitality Hub – view 3.

The demonstrator enabled the execution of the industrial material flow use case described in Section 3.4. Its integration, achieved through the works detailed in Section 3.5, allowed the material flow scenario to be realized as illustrated in Figure 37.

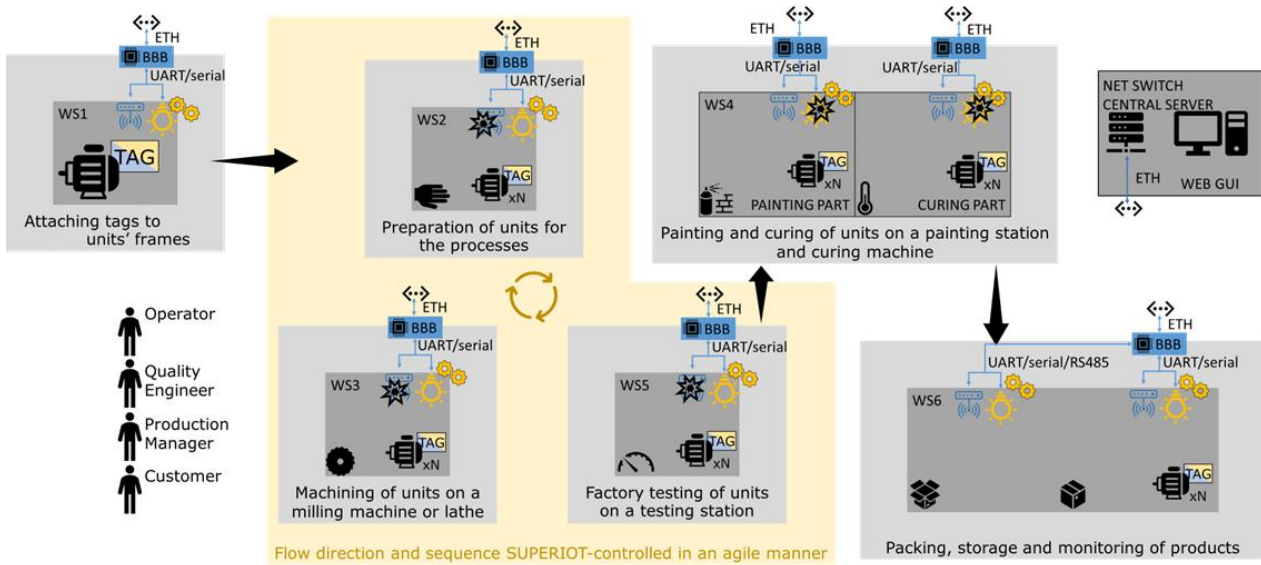


Figure 37. Illustration of the elements of the SUPERIOT system in the considered and executed demonstration scenario – the nodes (tags) with sensors and displays are attached to the flowing material and illustrated with yellow-blue rectangles.

The experiments addressed the following general requirements:

- Demo1-R-01: Multimode optical-radio communication
- Demo1-R-02: Bidirectional communications
- Demo1-R-03: Reconfigurability
- Demo1-R-04: Accurate positioning information
- Demo1-R-05: Sensing
- Demo1-R-06: Actuating
- Demo1-R-08: Sustainability by reconfigurability-enabling design

The next demonstration and experiment were conducted on 23rd October 2025 at the MPICOSYS laboratory in Gdynia, Poland, to further evaluate additional general requirements:

- Demo1-R-07: Energy autonomy
- Demo1-R-08: Sustainability by hybrid-node design

The demonstration in the MPICOSYS laboratory was carried out for the evaluation of Demo1-R-07 and Demo1-R-08 requirements due to a delay in the shipment of the MSC, which was necessary for hybrid node integration and served as the energy autonomy enabler (energy storage). Although the shipment was dispatched before the F2F meeting, it was delayed in transit and arrived at MPICOSYS in Gdynia, Poland after the F2F meeting held on 23–25 September 2025 at the Vitality Hub in Eindhoven, the Netherlands. Despite this, the second demonstration was successfully performed, and all general requirements were ultimately validated experimentally.

3.6.2 Video demonstration

To document the demonstration, video and audio recordings were produced collaboratively by VIVID and MPICOSYS. MPICOSYS presented the demonstrator, while VIVID captured the presentation and compiled the material into a finalized audio-video format. The recording highlights the key elements of the use case scenario and provides evidence for the validation of all general requirements formulated for Demonstrator 1.

The audio-video presentation of Demonstrator 1 Sustainable Smart Tag in the use-case of the industrial material flow is available online on the SUPERIOT project webpage - URL: <https://superiot.eu/results/demo-videos/demo-1> .

4 Conclusions

This deliverable detailed the architecture, integration, and execution of **Demonstrator 1 - Sustainable Smart Tag** for the SUPERIOT project. The main goal of demonstrating the Sustainable Smart Tag in the considered use case was successfully achieved.

The demonstration was carried out at a demo scale, following the industrial material flow scenario in which a sustainable smart tag enables optimization of material handling throughout the electric motor production process. The experiment was designed to emphasize the benefits of bidirectional (uplink and downlink) and dual-mode (optical and radio frequency) communication, demonstrating efficient label performance within the system's available power constraints.

The implemented scenario successfully showcased and proved:

- Demo1-R-01: Multimode optical-radio communication - Demonstrator 1 provides the multimode optical-radio communication between the SUPERIOT network and node.
- Demo1-R-02: Bidirectional communications - Demonstrator 1 supports bidirectional communications.
- Demo1-R-03: Reconfigurability - Demonstrator 1 is optical-radio reconfigurable.
- Demo1-R-04: Accurate positioning information - Demonstrator 1 provides accurate node positioning information, at least to the room level or workstation / box level.
- Demo1-R-05: Sensing - Demonstrator 1 is capable of sensing environmental parameters, including temperature, air pressure, humidity, and gas concentration (via electrical resistance measurement).
- Demo1-R-06: Actuating - Demonstrator 1 displays the information and actuates the e-paper display refresh.
- Demo1-R-07: Energy autonomy - Demonstrator 1 is energy autonomous by means of the energy harvesting and energy storage.
- Demo1-R-08: Sustainability - Demonstrator 1 is sustainable at least by reconfigurability-enabling design and by the hybrid-node implementation.

In conclusion, Demonstrator 1 successfully verified that the developed SUPERIOT system fulfills the functional and performance requirements for industrial deployment of Sustainable Smart Tag solutions.

The main hardware constraint of Demonstrator 1 stems from the integration of printed electronics with conventional electronic components. While printed technologies offer significant sustainability benefits, they currently exhibit lower electrical efficiency and reliability compared to established silicon-based solutions. In addition, the battery-less IoT node operates under a very limited power budget, making it highly dependent on energy harvesting from RF or light sources. This dependency inherently restricts the range of feasible use cases, as both RF and optical access must be available in the deployment environment.

The stringent energy constraints impose important trade-offs across system performance, including reduced transmission range, limited communication frequency, constrained sensing capabilities, and restricted continuous operation time. Furthermore, the hybrid communication architecture introduces additional complexity. Optical communication requires line-of-sight conditions and is sensitive to ambient light variations as well as obstructions, whereas RF communication is susceptible to interference and can experience spectrum congestion in dense environments. Other hardware limitations include challenges in PCB and antenna miniaturization, as well as the limited thermal and mechanical stability and durability of printed components and e-Ink displays.

From a software perspective, a key challenge lies in efficiently managing the coexistence of communication interfaces. The firmware must dynamically coordinate RF and optical

communication channels while ensuring low latency and ultra-low power consumption. At the same time, the resource-constrained embedded platform limits the complexity of network protocols, security mechanisms, and data processing algorithms that can be implemented.

Interoperability represents another important challenge. Although the current implementation successfully demonstrates the concept and supports scalable prototyping, further standardization is required to enable large-scale deployment and seamless integration with external IoT ecosystems.

Looking ahead, future development should focus on improving the maturity, robustness, and integration of printed electronic components, particularly antennas, sensors, and hybrid interfaces with conventional electronics. Advances in energy harvesting and ultra-low-power design will be critical for enhancing operational autonomy. On the software side, priority areas include adaptive communication management between optical and RF channels, lightweight yet effective security solutions, AI-assisted power optimization, and integration with standardized IoT frameworks and cloud platforms.

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9 Appendix 1

Video of Demonstrator 1 Sustainable Smart Tag in the use-case of the industrial material flow

Available online on the SUPERIOT project webpage - URL:

<https://superiot.eu/results/demo-videos/demo-1>

10 Appendix 2

Demonstration scenario steps for the industrial material flow use case
(presented with procedural accuracy)

Step 1: Attach tag to unit

Substep	Action description	Output
-	Operator played by presenter (P) or recipient (R) attaches tags to the models of units' frames. Each model has dimensions that fit within the outline 10x10x10 centimeters. The tag has a form that is easy for the actor to handle and of a size that does not impact the demonstration. This step is performed at station WS1. The operator (P or R) verifies the operation of attaching the tags to the units.	<p>The displayable operations are as follows:</p> <p>OK PROCEED: [OK] Operator (P or R) proceeds with the step for particular unit with tag.</p> <p>WAIT FOR QUALITY ENGINEER: [NOK] Operator (P or R) waits for the Quality Engineer to identify and solve the detected problem.</p> <p>PASS TO NEXT WORKSTATION: [OK] Operator (P or R) passes the item to the next workstation if the status OK PROCEED is displayed e.g. when tag is detected in the workstation that is ready to proceed.</p> <p>Routing information shown on the tags' displays:</p> <p>[OK] "PASS TO NEXT WORKSTATION" [Operator (P or R) proceeds with the step].</p>

Step 2: Process the unit with flow direction and sequence controlled in an agile manner

Substep	Action description	Output
2.1	Operator (P or R) routes the units to workstation WS2 based on the information displayed on the smart tag. The layout of the station's blocks and their relative distances are shown in Figure 9. Particular workstations are described in detail in the paragraphs following this figure. After assembling the frame with the stator, the exceeding temperature is recorded on one of the smart tags.	<p>One minute after delivery to the workstations, the following information is displayed on the tag that exceeds the temperature threshold:</p> <p>[NOK] "WAIT FOR QUALITY ENGINEER" Operator (P or R) does not route the item as exceeding temperature was recorded, and Operator must wait for action by the Quality Engineer before proceeding.</p> <p>At the same time the following information is displayed on the rest of the tags:</p> <p>[OK] "PASS TO NEXT WORKSTATION" [Operator (P or R) proceeds with the step].</p>

2.2	Quality Engineer (P or R) performs an inspection, finds no damage or problem after inspection and enters a report into the system with the use of a GUI. Quality Engineer clears the temperature-exceeding alarm for Tag 2 via the GUI.	The following information is displayed on all tags: [OK] "PASS TO NEXT WORKSTATION" [Operator (P or R) proceeds with the step].
2.3	Operator (P or R) routes the tags to the free workstations.	The following information is displayed on the tags: [OK] "OK PROCEED" [Operator (P or R) proceeds with the step for particular unit with tag].
2.4	Operator (P or R) routes one tag to another WS by mistake.	The following information is displayed on the tag: [OK] "PASS TO NEXT WORKSTATION": Operator (P or R) passes the item to WS5 to complete the stator testing. [Operator (P or R) proceeds with the step].
2.5	Operator (P or R) routes the missing tag to WS5.	The following information is displayed on the tags: [OK] "OK PROCEED" [Operator (P or R) proceeds with the step for particular unit with tag]. Next, after a minute and completing the processes, the following information is displayed on all tags: [OK] "PASS TO NEXT WORKSTATION" [Operator (P or R) proceeds with the step].
2.6	Operator (P or R) routes the tags to the next free WS.	The following information is displayed on the tags: [OK] "OK PROCEED" [Operator (P or R) proceeds with the step for particular unit with tag]. Then, after a minute of demonstration processing time, the following information is displayed on the tags: [OK] "PASS TO NEXT WORKSTATION" [Operator (P or R) proceeds with the step].
2.7	Operator (P or R) routes the tags to the next free workstations.	After a minute, the following information is displayed on the tags: [OK] "PASS TO NEXT WORKSTATION" [Operator (P or R) proceeds with the step].
2.8	Operator (P or R) routes the tags for assembly of the frame and stator with the rotor and final motor assembly.	After a minute, the following information is displayed on the tags:

		[OK] "PASS TO NEXT WORKSTATION" [Operator (P or R) proceeds with the step].
2.9	Operator (P or R) routes tags to WS5 for motor running and performance tests.	The following information is displayed on the tags: [OK] "OK PROCEED" [Operator (P or R) proceeds with the step for particular unit with tag]. Then, after a minute of demonstration processing time and PASSED performance tests, the following information is displayed on the tags: [OK] "PASS TO NEXT WORKSTATION" [Operator (P or R) proceeds with the step].

Step 3: Painting and curing of units on a painting station and curing machine

Substep	Action description	Output
3.1	Operator (P or R) routes tags to WS4 painting station to paint the units.	After a minute, the following information is displayed on the tags: [OK] "PASS TO NEXT WORKSTATION" [Operator (P or R) proceeds with the step].
3.2	Operator (P or R) routes tags to WS4 curing machine to cure the units.	The following information is displayed on the tags when the curing is in progress: [OK] "OK PROCEED" [Operator (P or R) proceeds with the step for particular unit with tag].
3.3	Operator (P or R) routes one tag to WS6 by mistake. Moreover, operator (P or R) puts another tag at a temperature that is too low.	The following information is displayed on these two tags: [NOK] "WAIT FOR QUALITY ENGINEER" [Operator (P or R) waits for the Quality Engineer to identify and solve the detected problem].
3.4	Quality Engineer (P or R) performs an inspection, finds no damage and enters a report into the system with the use of GUI. Quality Engineer clears the alarm related to curing disturbance for tags via GUI. Both tags are re-routed to WS4 curing machine to finish curing the unit.	The following information is displayed on the tags: [OK] "OK PROCEED" [Operator (P or R) proceeds with the step for particular unit with tag]. Then, after two minutes of demonstration processing time, the items are ready for packing and storage. The following information is displayed on the tags: [OK] "PASS TO NEXT WORKSTATION" [Operator (P or R) proceeds with the step].

Step 4: Packing, storage and monitoring of the product

Substep	Action description	Output
-	<p>Operator routes the unit at a distance of 150 cm from WS4 to WS6. The packing area has dimensions of 24 cm by 30 cm. The storage area has dimensions of 60 cm by 50 cm.</p>	<p>Properties information shared with the Quality Engineer (P or R), Production Manager (P or R) and Customer (P or R) on the tags and in the GUI monitor panel and web application(s) – e.g.:</p> <p>[OK] "OK PROCEED" [Operator (P or R) proceeds with the step for particular unit with tag].</p> <p>In a case of parameters exceedance – e.g., temperature or location – the following information will be displayed:</p> <p>[NOK] "WAIT FOR QUALITY ENGINEER" [Operator (P or R) waits for the Quality Engineer to identify and solve the detected problem].</p> <p>The history of localization, acceleration and temperature is displayed on the GUI monitor panel and associated web application(s). The Operator (P or R) moves the units and presents the corresponding temperature, and localization history charts to the Quality Engineer (P or R), Production Manager (P or R), and Customer (P or R).</p>

11 Appendix 3

The EPD image codes applied according to the demonstration scenario industrial material flow

Listing L1. The EPD format data PRODUCT NAMEPLATE (VLC) corresponding to Figure 12:

```
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0x03,0xc0,0xff,0xe0,0x3c,0x07,0xf1,0xff,0xfe,0x00,0x7f,0xfe,
0x1f,0xc0,0x7f,0xff,0x00,0x3f,0xff,0x9f,0xe0,0x38,0x0f,0xff,
0xfe,0x00,0x7f,0xff,0x1f,0xc0,0x7f,0xff,0x00,0x3f,0xff,0x1f,
0xe0,0x78,0x0f,0xff,0xfe,0x00,0x7f,0xff,0x1f,0xc0,0x7f,0xff,
0x00,0x3f,0xff,0x1f,0xe0,0x78,0x0f,0xff,0xfe,0x00,0x7f,0xff,
0x1f,0xc0,0x7f,0xfe,0x00,0x3f,0xff,0x1f,0xe0,0x78,0x1f,0xff,
0xf0,0x3f,0xc0,0x1f,0xfe,0x03,0xff,0xf0,0x1f,0xc7,0x8f,0x1e,
0x3c,0x07,0xff,0xff,0xf0,0x3f,0xc0,0x0f,0xfe,0x03,0xff,0xf0,
0x3f,0xc7,0x8f,0x1e,0x3c,0x07,0xff,0xff,0xf0,0x3f,0xc0,0x0f,
0xfe,0x07,0xff,0xf0,0x3f,0xc7,0x8f,0x1e,0x3c,0x07,0xff,0xff,
0xf0,0x3e,0x78,0x0f,0x80,0x3f,0xff,0x80,0x3e,0x7c,0x0f,0x03,
0xfc,0x07,0x83,0xff,0xf0,0x3c,0x78,0x0f,0x00,0x3f,0xff,0x00,
0x3c,0x3c,0x0f,0x01,0xfc,0x07,0x81,0xff,0xf0,0x3c,0x78,0x0f,
0x00,0x3f,0xff,0x00,0x3c,0x3c,0x0f,0x01,0xfc,0x07,0x81,0xff,
0xf0,0x3c,0x7c,0x0f,0x80,0x7f,0xff,0x00,0x3c,0x3c,0x0f,0x03,
0xfe,0x0f,0x03,0xff,0xf0,0x3c,0x7f,0x8f,0xe1,0xfc,0x07,0x01,
0xfc,0x3f,0x8f,0x1e,0x3f,0xf8,0x0f,0xff,0xf0,0x3c,0x7f,0x8f,
0xe1,0xfc,0x07,0x01,0xfc,0x3f,0x8f,0x1e,0x3f,0xf8,0x0f,0xff,
0xf0,0x3c,0x7f,0x8f,0xe1,0xfc,0x07,0x01,0xfc,0x3f,0x8f,0x1e,
0x3f,0xf8,0x0f,0xff,0xf0,0x3c,0x7f,0xf8,0x1f,0x7f,0x80,0x01,
0xff,0xfc,0x01,0xf3,0xff,0xef,0xfb,0xff,0xf0,0x3c,0x7f,0xf0,
0x1e,0x3f,0x80,0x01,0xff,0xfc,0x00,0xe1,0xff,0xc7,0xf1,0xff,
0xf0,0x3c,0x7f,0xf0,0x1e,0x3f,0x80,0x01,0xff,0xfc,0x00,0xf1,
0xff,0xc7,0xf1,0xff,0xf0,0x3c,0x3f,0xf0,0x1e,0x3f,0xc0,0x01,
0xff,0xf8,0x01,0xf1,0xff,0x87,0xf1,0xff,0xf0,0x3c,0x00,0x00,
0x00,0x00,0x7f,0xf0,0x3f,0xc0,0x0f,0xfe,0x3c,0x07,0x8f,0xff,
0xf0,0x3c,0x00,0x00,0x00,0x00,0x7f,0xf0,0x3f,0xc0,0x0f,0xfe,
0x3c,0x07,0x8f,0xff,0xf0,0x3c,0x00,0x00,0x00,0x00,0x7f,0xf0,
0x1f,0xc0,0x0f,0xfe,0x3c,0x07,0x9f,0xff,0xfe,0x0f,0x87,0xfe,
0x01,0xc3,0xff,0xfe,0x0f,0xff,0x83,0xff,0xff,0xff,0xff,0xff,

Listing L7. The EPD format data PASS TO NEXT WS (RF BLE) corresponding to Figure 18:

```

{0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,
0xff,0xfe,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,
0xff,0xff,0xff,0xff,0xff,0xc0,0x0f,0xff,0xff,0xff,0xff,0xff,
0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0x80,0x03,0xff,
0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,
0xfe,0x0f,0xc1,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,
0xff,0xff,0xff,0xff,0xfc,0x3f,0xf0,0xff,0xff,0xff,0xff,0xff,
0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xfc,0x78,0x78,0xff,
0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,
0xfc,0xe0,0x0c,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,
0xff,0xff,0xff,0xff,0xff,0x81,0x07,0xff,0xff,0xff,0xff,0xff,
0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0x8f,0xc3,0xff,
0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,
0xff,0x9f,0xe3,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,
0xff,0xff,0xff,0xff,0xff,0xfe,0xff,0xff,0xff,0xff,0xff,0xff,
0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xf0,0x3f,0xff,
0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,
0xff,0xf0,0x1f,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,
0xff,0xff,0xff,0xff,0xff,0xe0,0x1f,0xff,0xff,0xff,0xff,0xff,
0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xe0,0x1f,0xff,
0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,
0xff,0xe0,0x1f,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,
0xff,0xff,0xff,0xff,0xff,0xf0,0x3f,0xff,0xff,0xff,0xff,0xff,
0xff,0x00,0x01,0xff,0x00,0x01,0xff,0xff,0xff,0xf8,0x7f,0xff,
0xff,0xff,0xff,0xff,0xff,0x00,0x01,0xff,0x00,0x01,0xff,0xff,
0xff,0xbf,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0x03,0xff,
0xfc,0x71,0xff,0xff,0xff,0x9f,0xe7,0xff,0xff,0xff,0xff,0xff,
0xff,0xff,0x0f,0xff,0xfc,0x71,0xff,0xff,0xff,0x87,0xc7,0xff,
0xff,0xff,0xff,0xff,0xff,0xfc,0x1f,0xff,0xfc,0x71,0xff,0xff,
0xff,0xc0,0x0f,0xff,0xff,0xff,0xff,0xff,0xff,0xf0,0xff,0xff,
0xfc,0x71,0xff,0xff,0xfc,0xe0,0x1c,0xff,0xff,0xff,0xff,0xff,
0xff,0xc1,0xff,0xff,0xfc,0x71,0xff,0xff,0xfc,0x7f,0xf8,0xff,
0xff,0xff,0xff,0xff,0xff,0x81,0xff,0xff,0xfe,0x71,0xff,0xff,
0xfe,0x1f,0xe1,0xff,0xff,0xff,0xff,0xff,0xff,0x00,0x01,0xff,
0xfe,0x03,0xff,0xff,0xff,0x07,0x83,0xff,0xff,0xff,0xff,0xff,
0xff,0x00,0x01,0xff,0xfe,0x03,0xff,0xff,0xff,0x80,0x07,0xff,
0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0x8f,0xff,0xff,
0xff,0xe0,0x1f,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,
0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,
0xff,0xff,0xff,0xff,0xff,0xff,0xff,0x1f,0xff,0xff,0xff,
0xff,0xdf,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0x00,0x01,0xff,

```


0xff,0xf0,0x07,0xff,0xff,0xff,0xff,0xff,0xff,0x00,0x01,0xff,
0x1c,0x71,0xff,0xff,0xff,0xfc,0x0f,0xff,0xff,0xff,0xff,
0xff,0x80,0x01,0xff,0x1c,0x71,0xff,0xff,0xff,0xff,0xff,
0xff,0xff,0xff,0xff,0xff,0xff,0xf1,0xff,0x1c,0xf1,0xff,0xff,
0xff,0xdf,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xf1,0xff,
0x9c,0xe3,0xff,0xff,0xff,0xc1,0xff,0xff,0xff,0xff,0xff,
0xff,0xff,0xf1,0xff,0x80,0xc7,0xff,0xff,0xff,0xe0,0x1f,0xff,
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0xff,0xfe,0x03,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,
0xe3,0xff,0xff,0xff,0xff,0xff,0xe3,0xff,0xff,0xff,0xff,
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0xff,0xf0,0x3f,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,
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0xff,0xcf,0xe7,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,
0xff,0xff,0xff,0xff,0xff,0xcf,0xf3,0xff,0xff,0xff,0xff,
0xff,0xff,0xc1,0xff,0xff,0xff,0xff,0xff,0xff,0xcf,0xf3,0xff,
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0xff,0xff,0xff,0xff,0xff,0xe3,0xe3,0xff,0xff,0xff,0xff,
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0xff,0xfc,0x0f,0xff,0xff,0xff,0xff,0xff,0xff,0x01,0xff,0xff,
0xff,0xf1,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,0xff,
0xff,0x80,0x3f,0xff,0xff,0xf1,0xff,0xff,0xff,0xff,0xff,
0xff,0xff,0xff,0xff,0xff,0xf8,0x03,0xff,0x00,0x01,0xff,0xff,
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0xff,0xf1,0xff,0xff,0xff,0xf8,0x3f,0xff,0xff,0xff,0xff,
0xff,0x80,0x3f,0xff,0xff,0xf1,0xff,0xff,0xff,0xe0,0x0f,0xff,
0xff,0xff,0xff,0xff,0xff,0x01,0xff,0xff,0xff,0xf1,0xff,0xff,
0xff,0xe7,0xc7,0xff,0xff,0xff,0xff,0xff,0xff,0x03,0xff,0xff,
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0xff,0x00,0x7f,0xff,0xf8,0x3f,0xff,0xff,0xcf,0xf3,0xff,
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0xff,0xcf,0xf3,0xff,0xff,0xff,0xff,0xff,0xff,0xfe,0x01,0xff,
0xc0,0x07,0xff,0xff,0xff,0xcf,0xf3,0xff,0xff,0xff,0xff,
0xff,0xff,0xe1,0xff,0x8f,0xe3,0xff,0xff,0xff,0xe7,0xf3,0xff,

0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0x8f, 0xf3, 0xff, 0xff,
0xff, 0xf3, 0xc7, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff,
0x1f, 0xf1, 0xff, 0xff, 0xff, 0xff, 0xcf, 0xff, 0xff, 0xff, 0xff,
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0xc0, 0x07, 0xff, 0xff, 0xff, 0xcf, 0xe7, 0xff, 0xff, 0xff, 0xff, 0xff,
0xff, 0x1c, 0x71, 0xff, 0xe0, 0x0f, 0xff, 0xff, 0xff, 0xcf, 0xf3, 0xff,
0xff, 0xff, 0xff, 0xff, 0xff, 0x1c, 0xf1, 0xff, 0xf8, 0x3f, 0xff, 0xff,
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0xff, 0xff, 0xff, 0xff, 0xff, 0xc1, 0xcf, 0xff, 0xff, 0xff, 0xff, 0xff,
0xff, 0xf0, 0x07, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xf7, 0xff, 0xff,
0xff, 0xff, 0xff, 0xff, 0xff, 0xfc, 0x0f, 0xff, 0xff, 0xff, 0xff, 0xff,
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0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff,
0xff, 0xff, 0xff, 0xff, 0xff, 0xc1, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff,
0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xf8, 0x0f, 0xff,
0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff,
0xff, 0xff, 0xe3, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff,
0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xc0, 0x03, 0xff,
0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff,
0xff, 0xc3, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff,
0xff, 0xff, 0xff, 0xff, 0xff, 0xf1, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff,
0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xfc, 0x7f, 0xff,
0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff,
0xff, 0xff, 0x1f, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff,
0xff, 0xff, 0xff, 0xff, 0xff, 0xc3, 0xc7, 0xff, 0xff, 0xff, 0xff, 0xff,
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0xff, 0xff, 0x03, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff,
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0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xcf, 0xff, 0xff,
0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff,
0xff, 0xcf, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff,
0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff, 0xff,

0xfc,0x00,0x00,0x1e,0x00,0x78,0xff,0xff,0xff,0x3f,0xc7,0xf1,
0xff,0xc7,0x87,0x01,0xfc,0x00,0x00,0x1e,0x00,0x78,0xff,0xff,
0xff,0xe7,0x01,0xff,0x3f,0x3f,0x82,0x0f,0xf3,0xf8,0x70,0x1f,
0xff,0xcf,0x99,0xff,0xff,0xe0,0x00,0x0f,0x00,0x3f,0x80,0x0f,
0xe3,0xfc,0x70,0x1f,0xff,0xc7,0x81,0xff,0xff,0xe0,0x00,0x0f,
0x00,0x3f,0x80,0x0f,0xe3,0xfc,0x70,0x1f,0xff,0xc7,0x81,0xff,
0xff,0xe1,0xf8,0x7e,0x0c,0x3f,0x80,0x0f,0xff,0xff,0xf0,0x7f,
0xff,0xff,0xff,0xff,0xf1,0xe3,0xf8,0x70,0x1e,0x3c,0x00,0x0f,
0xfc,0x7f,0x80,0xfe,0x07,0xf8,0xff,0xff,0xf1,0xe3,0xf8,0xf0,
0x1e,0x3c,0x00,0x0f,0xfc,0x3f,0x80,0xfe,0x03,0xf8,0xff,0xff,
0xf1,0xe3,0xf8,0x70,0x1e,0x3c,0x00,0x0f,0xfe,0x7f,0x80,0xfe,
0x03,0xf8,0xff,0xff,0xff,0x3c,0x78,0x1f,0xff,0xff,0xf8,0x03,
0xff,0xff,0x8f,0xff,0xfc,0x07,0xff,0xff,0xfe,0x3c,0x78,0x0f,
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0xfe,0x3c,0x78,0x0f,0xff,0xff,0xf8,0x01,0xff,0xff,0x8f,0xff,
0xfc,0x07,0xff,0xff,0xff,0x3c,0x78,0x1f,0xff,0xff,0xf8,0x01,
0xff,0xff,0x8f,0xff,0xfe,0x1f,0xff,0xff,0xf1,0xe0,0x78,0xf1,
0xfe,0x3f,0x80,0x01,0xe0,0x7c,0x00,0xf0,0x03,0xf8,0x0f,0xff,
0xf1,0xe0,0x78,0xf1,0xfe,0x3f,0x80,0x01,0xe0,0x3c,0x00,0xe0,
0x03,0xf8,0x0f,0xff,0xf1,0xe0,0x7c,0xf1,0xfe,0x3f,0xc0,0x01,
0xe0,0x7c,0x00,0xf0,0x03,0xf8,0x1f,0xff,0xff,0xfc,0x7f,0xf1,
0xf8,0x0f,0xff,0xf1,0xe3,0xfc,0x00,0xff,0xc3,0xe0,0x7f,0xff,
0xfe,0x3c,0x7f,0xf1,0xe0,0x07,0xff,0xf1,0xe3,0xfc,0x00,0xff,
0xe3,0xc0,0xff,0xff,0xfe,0x3c,0x7f,0xf1,0xe0,0x07,0xff,0xf1,
0xe3,0xfc,0x00,0xff,0xe3,0xc0,0xff,0xff,0xff,0x7e,0xff,0xf1,
0xe0,0x0f,0xff,0xf1,0xc3,0xfc,0x01,0xff,0xc3,0xc0,0x7f,0xff,
0xff,0xff,0xff,0xf1,0xe1,0xff,0xf8,0x00,0x03,0xfc,0x0f,0x00,
0x00,0x78,0x1f,0xff,0xff,0xff,0xff,0xf1,0xe1,0xff,0xf8,0x00,
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0x01,0xe7,0xc1,0xfe,0x00,0x7f,0xc0,0x3f,0xff,0xff,0xff,0xff,
0xf0,0x00,0x07,0x9f,0x01,0xfc,0x7f,0xf0,0x03,0xc7,0xff,0xfe,
0x00,0x00,0x01,0xff,0xf0,0x00,0x07,0x8f,0x01,0xfc,0x7f,0xf0,
0x03,0xc7,0xff,0xfe,0x00,0x00,0x01,0xff,0xf0,0x00,0x07,0x9f,
0x03,0xfc,0x7f,0xf0,0x03,0xc7,0xff,0xfe,0x00,0x00,0x01,0xff,
0xff,0xc0,0x07,0xff,0x1f,0xff,0xff,0xff,0xff,0xff,0xff,0xfe,
0x1f,0xff,0xf1,0xff,0xff,0xe0,0x07,0xff,0x1f,0xff,0x80,0xff,
0xfc,0x3f,0xff,0x1e,0x3f,0xff,0xf1,0xff,0xff,0xe0,0x07,0xff,
0x1f,0xff,0x80,0xff,0xfc,0x3f,0xff,0x1e,0x3f,0xff,0xf1,0xff,
0xff,0xe0,0x07,0xff,0x1f,0xff,0xc1,0xff,0xfe,0x7f,0xff,0x1e,
0x3f,0xff,0xf1,0xff,0xff,0xe0,0x00,0x00,0x1e,0x7c,0x7f,0xf1,
0xff,0xc7,0xff,0x1e,0x3e,0x00,0xf1,0xff,0xff,0xe0,0x00,0x00,

