Chapter

Establishing a Regional Industry 4.0 Electronics Hub: The GreenUpPCB Model

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Abstract

This chapter presents GreenUpPCB as a regional Industry 4.0 hub for electronics repair and retrofitting, based in Castelo Branco, Portugal. The initiative combines artificial intelligence, machine vision, 3D printing, and automation to extend the life cycle of obsolete printed circuit boards, particularly in renewable energy systems and railway rolling stock. By promoting circular economy practices and reducing electronic waste, GreenUpPCB supports sustainable and resilient industrial operations. The hub also strengthens regional development by linking academic research with industrial needs, offering training, innovation, and high-tech services to local small- and medium-sized enterprises. Its model enables smart manufacturing adoption in low-density territories without dependence on urban clusters. Aligned with the European Chips Act and national strategies for microelectronics, GreenUpPCB demonstrates how regional hubs can contribute to the green and digital transitions across multiple sectors, including energy and transport.

Keywords: Industry 4.0, circular economy, electronics retrofitting, artificial intelligence, regional innovation hub

1. Introduction

The rapid evolution of Industry 4.0 technologies is transforming the way industrial production and service provision are organised, placing automation, digitalisation, and sustainability at the core of innovation strategies. At the intersection of these trends lies GreenUpPCB, a regional laboratory based in Castelo Branco, Portugal, dedicated to extending the life cycle of electronic components through testing, retrofitting, and reverse engineering of printed circuit boards (PCBs). Its activities focus particularly on renewable energy systems – most notably wind and solar power – and railway infrastructure, two strategic sectors in which electronics play a critical role in ensuring operational reliability.

Portugal has emerged as one of Europe's leaders in renewable electricity generation. In 2023, renewable sources supplied 70.7% of the national electricity mix, with wind power accounting for 29.3% and solar photovoltaics 8.2%, the latter representing the fastest-growing segment [1]. The Central Region of Portugal, encompassing districts such as Castelo Branco, Coimbra, and Leiria, hosts a significant share of this capacity through large-scale onshore wind farms [2] and an expanding base of solar PV installations [3]. This rapid growth brings new challenges for the maintenance of electronic control systems, inverters, and monitoring devices, many of which are exposed to harsh operating conditions and face risks of obsolescence.

The country's railway sector, operated primarily by Comboios de Portugal (CP), also plays a pivotal role in the national mobility system and in supporting regional connectivity. Like many European operators, CP faces the dual challenge of accommodating increasing passenger demand while managing an ageing fleet. Maintenance, refurbishment, and modernisation of rolling stock are therefore essential to sustaining service quality until new units are fully procured and integrated into operations [4].

In this context, GreenUpPCB emerges as an initiative that directly addresses sectoral needs by providing advanced repair and retrofitting services for high-value electronics. By aligning circular economy principles with the technical requirements of both the renewable energy and railway industries, the laboratory contributes not only to extending equipment life cycles but also to advancing broader policy goals of sustainability and resilience. The following section outlines the context and motivation behind the establishment of this regional hub.

2. Context and motivation

Although wind farms, solar plants, and railway networks operate in different domains, they face similar challenges related to the reliability of complex electronic systems exposed to long service life cycles, high utilisation rates, and demanding environmental conditions. Delays in fleet or asset renewal place further emphasis on maintenance and refurbishment, making local technical capacity a crucial factor for sustaining both performance and safety standards.

In the central region of Portugal, wind and solar power represent the backbone of renewable generation. Extensive wind farms operate in areas such as Serra do Açor, Serra da Lousã, and Penamacor [2], feeding into a national grid that reached 79.3% renewable electricity in the first half of 2025 [1]. In parallel, solar PV capacity has expanded rapidly, supported by both large utility-scale projects and distributed generation on rooftops and industrial facilities. Lightsource BP is advancing a portfolio of five large solar farms totalling approximately 1.35 GW, which includes sites in Castelo Branco, among others [5]. Between late 2024 and mid-2025, solar installations grew by nearly 500 MW, with the central region playing a prominent role thanks to its high irradiation levels and availability of land [3]. This concentration of renewable assets creates a sustained demand for specialised maintenance of electronics, such as turbine controllers, pitch systems, inverter boards, and monitoring modules. In many cases, these devices rely on imported PCBs with limited local support, exposing operators to costly delays whenever faults occur.

The railway sector illustrates a parallel challenge. CP operates with an ageing fleet that requires continuous refurbishment. Its Sustainability Report 2021–2023 highlights the importance of nationwide workshops located in Contumil, Guifões, Sernada do Vouga, Entroncamento, Figueira da Foz, Santa Apolónia, Campolide, Oeiras, Barreiro, and Vila Real de Santo António, which collectively sustain operations through repair, modernisation, and rehabilitation. In 2023, CP carried 172.6 million passengers (24 million more than the previous year), and this upward trend continued into 2024 and 2025 [4]. While new rolling stock is being procured from Alstom and Stadler companies, the procurement and homologation cycles mean that legacy trains will remain in service for several more years. Keeping these assets operational requires targeted electronic maintenance and retrofitting, often under tight schedules.

Beyond the technical dimension, the Portuguese central region faces socio-economic and infrastructural challenges that accentuate the need for a local electronics hub. Low population density and limited industrial infrastructure often oblige operators to send faulty boards to Lisbon, Porto, or abroad, increasing both costs and downtime [6–8]. Establishing a regional facility capable of delivering advanced diagnostic and repair services, therefore, represents not only an industrial necessity but also an opportunity to strengthen technological autonomy.

GreenUpPCB was envisioned in direct response to these challenges. By combining advanced diagnostic equipment, reverse engineering systems, and modular prototyping facilities, the laboratory provides the missing link between the rapid deployment of renewable assets, delayed fleet renewal in railways, and the pressing need for sustainable electronics management.

Its creation aligns with major strategic frameworks: at the European level, it aligns with the EU Chips Act [9] and the European Green Deal [10], both of which emphasise the importance of technological sovereignty and circular economy principles; at the national level, it aligns with the Portuguese National Energy and Climate Plan 2030 [11] and the National Strategy for Semiconductors [12]; and at the regional level, it aligns with the Agenda for Microelectronics e Semiconductors [13].

In addition, the Portuguese central region has consolidated collaborative platforms such as INOVC +, a strategic project bringing together 23 universities, polytechnics, technology centres, and municipalities to reinforce the regional innovation ecosystem. The initiative focuses on technology transfer, entrepreneurship, and knowledge valorisation across multiple domains, including digitalisation, Industry 4.0, and sustainability. While not dedicated solely to microelectronics, INOVC + provides the collaborative framework in which specialised initiatives such as GreenUpPCB can succeed, ensuring that regional innovation hubs are embedded in a wider ecosystem of research, education, and industrial partnerships [14].

2.1 Problem statement

The combined realities of rapid asset deployment in the renewable sector and delayed fleet renewal in the railway sector have created a critical operational gap: essential high-value electronics must remain functional far beyond their original design life. Both industries face mounting pressure to sustain service quality, meet environmental targets, and control costs, all while reducing downtime. Traditional approaches based on full equipment replacement are increasingly impractical due to long procurement cycles, supply chain constraints, and the environmental burden of manufacturing new components. In this context, GreenUpPCB emerges as a strategic solution, providing specialised local capacity to test, diagnose, repair, and retrofit electronic systems, thereby extending asset life cycles, reducing waste, and aligning with circular economy principles. By targeting two of Portugal's most strategically important sectors, the initiative addresses not only technical and economic challenges but also national and European policy priorities for sustainability, resilience, and technological sovereignty.

Addressing these sector-wide challenges requires more than incremental maintenance improvements; it demands a dedicated technological infrastructure capable of combining advanced diagnostics, precision repair, and rapid prototyping with the flexibility to serve multiple industries. The GreenUpPCB laboratory was conceived to fulfil this role, operating as both a technical service hub and a knowledge-transfer platform in the central region of Portugal. By integrating Industry 4.0 tools, such as computer-aided design and manufacturing (CAD/CAM), automated test systems, and data-driven fault analysis, the laboratory can diagnose and restore high-value electronic assemblies to operational standards that meet or exceed their original specifications. In the following section, the operational framework, technological resources, and collaborative strategies of GreenUpPCB are detailed, illustrating how the model supports both renewable energy and railway clients while remaining scalable to other industrial sectors.

3. GreenUpPCB laboratory: Vision, scope, and technology

GreenUpPCB was established with the vision of becoming a regional reference in sustainable PCB reconditioning and reverse engineering. The laboratory's strategic objectives extend beyond technical repair, aiming to position itself as a knowledge centre for electronic circularity and to enable the local industry with diagnostic and retrofit solutions. By connecting education, research, and small- and medium-sized enterprises (SMEs), the initiative seeks to create a dynamic innovation ecosystem that promotes both technological and regional development.

The target sectors served by GreenUpPCB are diverse but strategically chosen. In the renewable energy field, the laboratory supports both wind and solar power operators, whose assets require continuous monitoring and refurbishment of electronic systems. In rail transportation, GreenUpPCB works closely with CP to extend the service life of essential train electronics, such as Eurocard circuit boards, which are often affected by component obsolescence. Beyond these two sectors, the laboratory also collaborates with companies in industrial automation, telecommunications, and the electronics repair market, providing a critical service base for both established SMEs and emerging technology start-ups.

To achieve these goals, GreenUpPCB integrates advanced technological resources into its operations. Diagnostic platforms from ABI Electronics [15] form the backbone of its testing and reverse-engineering activities, while artificial-intelligence-assisted fault detection enhances the precision of data logging and repair. Precision soldering is supported through JBC rework stations [16], enabling the handling of high-density components. The laboratory also employs rapid prototyping tools such as 3D printers and maintains digital repositories and modular component libraries that ensure long-term reproducibility of schematics and designs.

3.1 Artificial intelligence (AI) and machine vision in PCB diagnostics

The GreenUpPCB laboratory integrates AI and machine vision tools to enhance fault detection and accelerate repair processes. Traditional diagnostic methods, while reliable, are often time-consuming and highly dependent on operator expertise. AI-driven approaches enable faster, scalable, and more consistent analysis of PCB defects by leveraging large datasets of annotated images.

Several benchmark datasets have been used to train and validate machine learning algorithms for PCB diagnostics:

- The AI Challenger PCB Dataset contains thousands of labelled PCB images with annotated defects, supporting robust supervised learning methods [17].

- The DeepPCB Dataset provides 1,500 pairs of reference and tested PCB images with defect annotations, designed specifically for image alignment and defect detection tasks [18].

- The Kaggle PCB Dataset collections aggregate multiple community-contributed datasets, enabling the training of models for defect classification and object detection [19].

Machine vision systems, when coupled with these datasets, are capable of detecting shorts, opens, spurious copper, missing components, and misalignments with higher precision than manual inspection.

The integration of AI-assisted diagnosis with reverse engineering tools and precision rework systems [16] creates a hybrid repair process that reduces downtime, improves repair yield, and supports the scalability of circular electronics practices. At GreenUpPCB, such approaches are being developed to complement traditional ABI diagnostic platforms [15, 20], aiming to automate part of the diagnostic workflow. Furthermore, by embedding these techniques into training and micro-credential programmes, GreenUpPCB ensures that technicians acquire cutting-edge skills aligned with Industry 4.0 requirements.

4. Infrastructure and workflow

The GreenUpPCB laboratory (**Figure 1**) has been designed as a modular and expandable facility, capable of adapting to the evolving demands of electronics repair and innovation. The physical set-up initially occupies 25 square meters but is being scaled up to 150 square meters as projects and partnerships grow. This space is complemented by dedicated training laboratories that provide 20 workbenches equipped with oscilloscopes, signal generators, logic analysers, and ABI diagnostic systems [20]. Controlled rework environments ensure that sensitive PCB operations can be performed under safe and reliable conditions, while future expansion plans include the installation of cleanroom infrastructure to support high-precision prototyping and component handling.

The operational framework of GreenUpPCB is structured around three interlinked functions: technical services, collaboration with industry, and knowledge transfer. Technical services include PCB testing, retrofitting, and reverse engineering of obsolete electronic boards – activities that are central to extending the life cycle of equipment in the renewable energy and railway sectors. Collaboration with companies such as CP and HFA [21] ensures that the laboratory's services

Figure 1.
GreenUpPCB laboratory facilities.

a) b)

Figure 2.
Meeting with partners from (a) CP and (b) HFA.

respond directly to the needs of industrial stakeholders, while prototyping and iterative repair cycles are conducted under strict quality protocols.

A meeting with partners from CP and HFA is shown in **Figure 2**. The workflow is designed to be flexible, allowing the laboratory to address urgent repair requests while simultaneously engaging in long-term development projects.

Technology transfer is another key dimension of the laboratory's mission. By creating demonstrator projects and disseminating repair case studies, GreenUpPCB not only provides direct solutions to its partners but also contributes to broader knowledge sharing within the electronics repair ecosystem. The integration of advanced diagnostics, automated test systems, and CAD/CAM-based design tools further enables the laboratory to diagnose faults, reproduce obsolete schematics, and restore boards to a condition that often meets or exceeds their original specifications.

4.1 Case study: Reverse engineering Siemens Eurocard boards for CP trains

Reverse engineering of legacy boards represents one of the core applications of the GreenUpPCB laboratory. These boards, widely used in railway rolling stock and industrial automation systems, frequently suffer from component obsolescence and a lack of documentation. To address this challenge, the ABI BoardMaster/RevEng Schematic Learning System, shown in **Figure 3**, provides a structured method for recovering accurate schematics, ensuring that critical assets remain serviceable and aligned with circular economy principles.

The workflow for the reverse engineering of a PCB follows five main steps:

1. The manual workflow begins with the safe initialisation of both hardware and software. At this stage, the system is kept in disconnect mode until powered on, preventing short circuits or voltage mismatches. Once the hardware is switched on and the RevEng software is launched, the platform is ready for secure board connections. The next phase involves hardware and cable set-up, during which ribbon harnesses are connected to the channel ports of the RevEng unit. Specific cable assemblies are selected in the software. Clip connectors are then attached to integrated circuits, while the power rails are

Figure 3.
ABI reverse-engineering equipment in use.

configured. With these preparations complete, the system is fully prepared for scanning and accurate pin referencing.

2. Following this set-up, each component on the board is defined within the software to ensure correct identification during the scan. Components such as integrated circuits, resistors, capacitors, and diodes are registered with their reference designators, part numbers, packages, and values. When components are absent from the existing library, they can be replaced with similar devices of the same pin count or created manually, with subsequent corrections to the schematic symbols as required. To optimise the scanning process, some devices are included for mapping, while others, such as connectors or non-critical jumpers, are excluded. This careful preparation guarantees that the subsequent scanning phase captures the full connectivity of the relevant devices.

3. The scanning itself is conducted using hooks, clips, or probes, depending on the physical accessibility of the components, as shown in **Figure 4**. For example, resistors and diodes may be scanned using hook leads attached directly to their pins, whereas integrated circuits are often scanned with clips that contact all pins simultaneously. When components are too close together for hooks or clips, probes become the most reliable option, often used in combination with a footswitch for efficiency. Once the scanning command is executed, the RevEng system automatically detects all electrical connections, including power rails and signal nets, and stores the results in the netlist

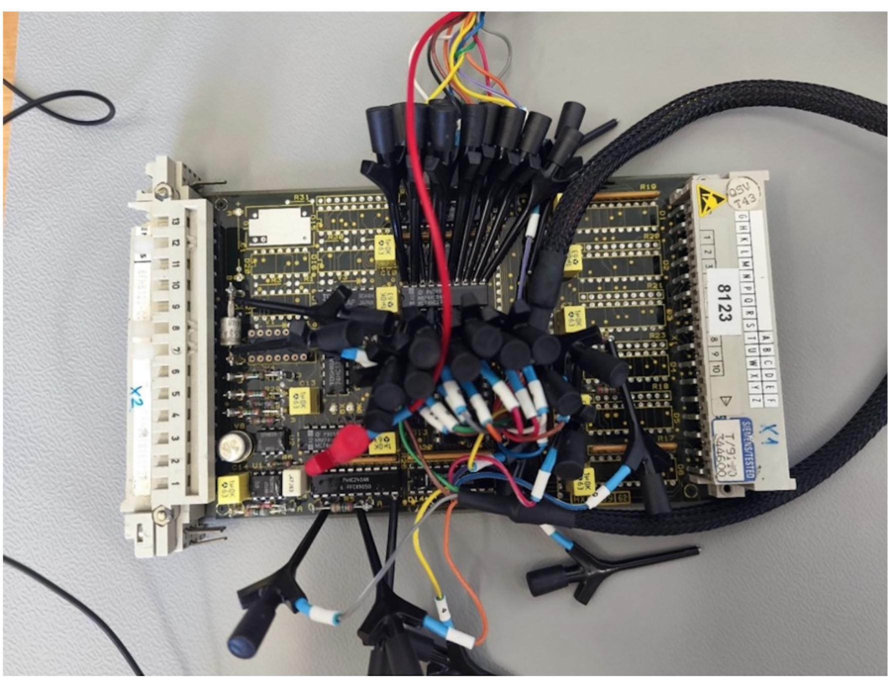

Figure 4.
ABI RevEng clips attached to a Eurocard board.

database. Coverage reaches 100% once every relevant connection has been identified and confirmed.

4. The next stage of the workflow is netlist generation. At this point, all detected connections are exported as a digital file, commonly in *.wrl or *.txt format. The structure of this file is divided into three main sections: components, values, and nodes. The components section lists all devices with their references, part numbers, and packages, while the values section defines the electrical values of resistors and capacitors. The nodes section contains the electrical connections, with pre-defined nets such as VCC and GND, as well as automatically generated labels for other signal paths. This netlist provides a comprehensive digital map of the board, bridging the gap between physical hardware and schematic representation.

5. Once exported, the netlist is imported into an EDA/CAD program to generate a complete schematic diagram. The user configures the page size and component clearance to match the board complexity, and then allows the software to automatically place all components in logical groups around a central reference device. This ensures that interconnections are displayed meaningfully. Autoconnect functions are then applied to wire the nodes, producing a complete schematic with all components placed and interconnected according to the imported data. The process results in a functional diagram that accurately represents the original Eurocard board and can be used for repair, redesign, or documentation purposes.

To provide a clearer overview of the methodology, **Figure 5** illustrates the full workflow adopted in the case study on reverse engineering Siemens Eurocard boards. The process begins with careful preparation and non-destructive netlist extraction, followed by logic function analysis, schematic reconstruction, validation, and testing. The workflow concludes with the renewal of obsolete components, documentation of the schematics, and reintegration of the reconditioned boards into the railway fleet.

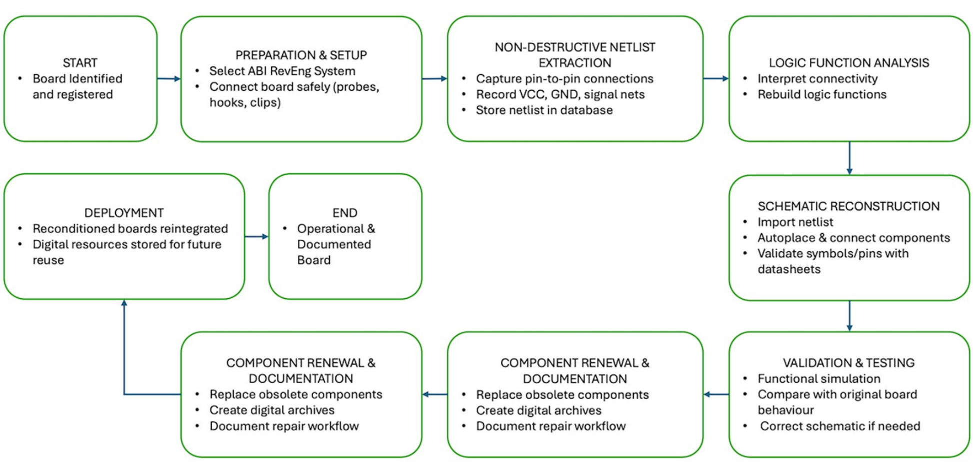

Figure 5.
Workflow for reverse engineering electronic boards using the ABI RevEng system, as applied in the CP case study.

Nonetheless, several practical considerations have emerged during the application of this workflow. Clearance values on the PCB must be adapted to the density of components for optimal readability. Selecting a central component with multiple interconnections is essential to achieve a logical arrangement of the schematic. Furthermore, library definitions must always be verified against official datasheets to ensure correct pin numbering, since inconsistencies may occur between systems. Ultimately, the reverse engineering process combines automated learning with manual oversight, producing schematics that are both technically accurate and practically usable.

In all repair and reverse engineering activities, GreenUpPCB applies strict safety and quality protocols aligned with the requirements of critical sectors such as rail transport and renewable energy. Electrostatic discharge control is ensured through the use of grounded workstations, antistatic equipment, and controlled environments. Every board undergoes functional testing after repair, retrofitting, or reverse engineering, guaranteeing that performance meets or exceeds original specifications. Full traceability is maintained by documenting diagnostic steps, replacement components, and test results, while attention to component provenance ensures that only certified and reliable parts are used.

5. Human capital and ecosystem development

A central pillar of GreenUpPCB is the development of human capital, which is essential for sustaining innovation and ensuring the long-term viability of circular electronics practices. The laboratory has adopted a multi-layered training strategy that combines micro-credentials, international exchanges, and open training initiatives. Within three years, the aim is to provide micro-credential courses that will certify at least 20 technicians with specialised skills in PCB diagnostics, rework, and reverse engineering. Erasmus + internships have already been established, welcoming students from institutions such as Üsküdar University [22], thereby fostering an international learning environment. In parallel, junior researcher placements are supported under national programmes [23], and training activities are opened to regional technicians, enabling them to upgrade their competencies and access advanced methodologies.

Beyond education, the laboratory plays a vital role in strengthening the local innovation ecosystem. Partnerships with regional companies ensure that SMEs benefit from diagnostic services and retrofitting expertise that would otherwise be difficult to access in low-density territories. GreenUpPCB collaborates with its partners not only by offering services but also by codeveloping research and development projects. In doing so, the laboratory acts as a bridge between academic research and industrial application, mentoring new ventures in the electronics sector and supporting the creation of start-ups that focus on repair, retrofitting, and reverse engineering.

This role is reinforced by the Polytechnic Institute of Castelo Branco's StartUp.CB initiative, which provides infrastructure, access to mentors, specialised training, and sustained guidance for start-up projects arising from or linked to the Polytechnic's research units [24]. Meanwhile, the Centro de Empresas Inovadoras (CEI, Castelo Branco) [25] expands this ecosystem by hosting FabLab CB [26], prototyping laboratories, and coworking spaces, and offering incubation and pre-incubation services. These facilities enable new electronics spin-offs and start-ups to rapidly move from concept to prototype and allow GreenUpPCB's repair and reverse engineering case studies to be tested, showcased, and scaled locally.

The laboratory also places significant emphasis on communication, awareness, and education directed at the wider community. Workshops are regularly organised in schools across the region. In May 2025, GreenUpPCB coorganised a thematic workshop in collaboration with Inova-Ria – Rede de Inovação em Aveiro, under the initiative Microelectronics for a Better Future [27]. The session focused on circularity in electronics, with discussions on eco-design, recovery, and materials recycling strategies. A photograph of the session is presented in **Figure 6**, illustrating the collaborative spirit of the initiative.

Participation in regional innovation fairs provides opportunities to showcase demonstrator projects, while online dissemination ensures that case studies and repair methodologies are shared with a broader audience. These outreach activities not only raise awareness of the importance of circularity in electronics but also inspire new generations of students to engage with science, technology, engineering, and mathematics (STEM) fields. Through this comprehensive approach to human capital development, GreenUpPCB cultivates a skilled workforce, empowers SMEs, and contributes to building a culture of technological resilience and sustainability. By linking training, research, and industrial practice, the laboratory demonstrates how capacity-building initiatives can transform regional ecosystems and support the wider European agenda for digital and green transitions.

Figure 6.
GreenUpPCB and Inova-Ria workshop on circularity, eco-design, and recycling (Castelo Branco, 2025).

6. The GreenUpPCB model: A framework for regional innovation hub on electronics

The GreenUpPCB hybrid model (**Figure 7**) synthesises the experience of the laboratory into a framework that can guide the creation of regional circular innovation hubs for electronics. Rather than viewing its activities as isolated technical services, the model integrates six mutually reinforcing dimensions: mission and objectives, infrastructure and technology, operational workflows, human capital development, ecosystem integration, and policy alignment. Together, these dimensions form a holistic and replicable blueprint for establishing electronics repair and retrofitting capacity in low-density regions.

6.1 Mission and objectives

At its core, the GreenUpPCB model seeks to extend the life cycle of electronic systems, reduce waste, and strengthen technological sovereignty. It does so by providing advanced diagnostic, repair, and reverse engineering services to sectors where electronics are critical – particularly renewable energy and rail transport. The mission is not only to solve immediate technical problems but also to anchor knowledge, skills, and infrastructure in regions that are typically underserved by high-tech innovation.

6.2 Infrastructure and technology

The model is built upon modular infrastructure and Industry 4.0 technologies. Diagnostic platforms, AI-assisted defect detection, CAD/CAM design tools, and precision rework stations enable the recovery and renewal of obsolete systems. Importantly, these technologies are scalable and portable, allowing the model to adapt to other regional contexts.

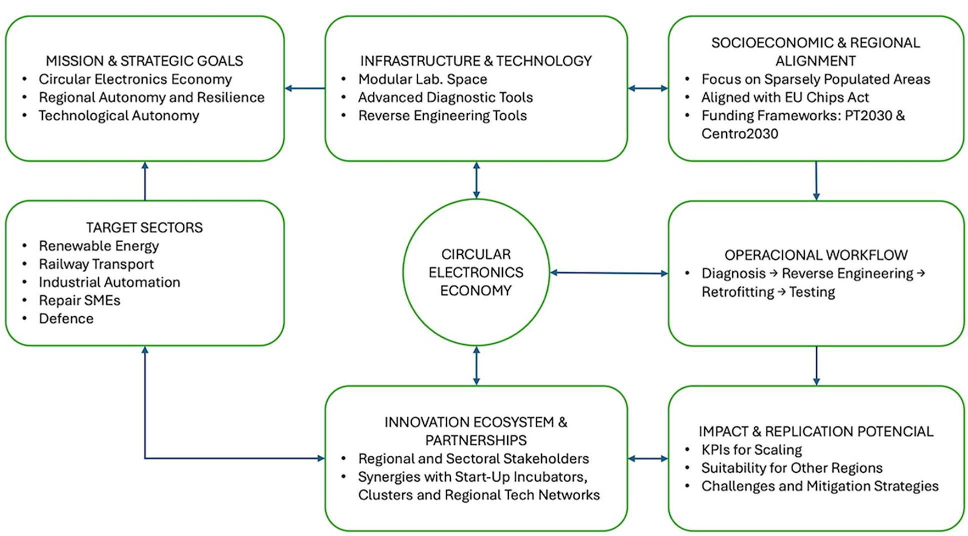

Figure 7.
Conceptual and logic-based model of the GreenUpPCB circular innovation hub.

6.3 Socio-economic and regional alignment

The model is designed to operate within, and contribute to, strategic policy agendas. At the regional level, it supports the Agenda for Microelectronics and Semiconductors [12]; at the national level, it complements the PNEC 2030 [11]; and at the European level, it aligns with the EU Chips Act [9] and the Green Deal [10]. This multi-level coherence ensures that local initiatives have visibility and support within broader transitions. A distinctive pillar of the model is its strong human-centred approach. Micro-credentials, Erasmus + exchanges, researcher placements, and open training opportunities create a skilled workforce embedded in the region. Training is not treated as an ancillary activity but as a driver of sustainability, ensuring that specialised knowledge is retained locally.

6.4 Operational workflows

Technical services follow structured processes that combine traditional repair with reverse engineering and rapid prototyping. By documenting and disseminating workflows, such as the reverse engineering of Siemens Eurocard boards for CP [4], GreenUpPCB ensures that tacit knowledge becomes transferable, strengthening both regional resilience and international learning.

6.5 Impact and replication potential

One important dimension of the GreenUpPCB model is its emphasis on measurable impact and replicability. From the outset, the hub has been designed not only as a service provider but also as a catalyst for systemic change in low-density regions. Impact is assessed across multiple dimensions, ranging from technical (eg, number of boards repaired, downtime reduced), educational (students and technicians trained), economic (SMEs supported, start-ups incubated), and environmental (waste avoided, equipment life cycles extended). By documenting case studies and disseminating open training resources, the model creates a knowledge base that can be transferred to other territories. Its modular infrastructure and portable methodologies make it adaptable to diverse regional contexts, while its alignment with European and national policy ensures institutional support. GreenUpPCB demonstrates a dual capacity: delivering immediate local benefits while offering a scalable framework for replication in other low-density regions facing similar challenges in renewable energy, transport, and industrial automation.

To make the impact of GreenUpPCB more tangible and to facilitate replication in other regions, a compact set of key performance indicators (KPIs) has been defined. These indicators capture not only the technical and operational efficiency of repair and retrofitting processes but also their educational, economic, and environmental contributions. **Table 1** summarises eight core KPIs that provide measurable benchmarks for assessing performance over a three-year horizon. They reflect industry-standard metrics such as repair yield and mean time-to-diagnosis, as well as broader sustainability goals, including waste and CO_2e avoided, technicians trained, and SMEs supported.

6.6 Innovation ecosystem and partnerships

The GreenUpPCB model demonstrates that a hub's impact depends on strong local and regional partnerships. At Castelo Branco, collaboration with CP [4], HFA

Domain	**Indicator**	**Target**
Technical quality	Repair yield (% of boards successfully restored)	≥ 85%
Technical efficiency	Mean time-to-diagnosis (average hours per PCB)	≤ 4 h
Operational impact	Downtime avoided (days of equipment unavailability saved in rail/energy)	150 + days
Life cycle extension	Average lifetime extension per PCB (years)	+5 years
Environmental impact	Electronic waste avoided (kg of PCBs not discarded)	500 kg
Environmental impact	CO_2e avoided (through reduced manufacturing of replacement boards)	20–30 t CO_2e
Human capital	Technicians trained/certified (micro-credentials, internships)	20
SME support	Regional SMEs supported (through services or joint R&D)	10
Ecosystem	Start-ups/spin-offs created	1
Knowledge transfer	Schools and awareness activities (STEM workshops)	10 schools

Table 1.
KPIs for the GreenUpPCB hub, designed to measure technical, economic, educational, and environmental impacts over a three-year horizon.

[21], StartUp.CB [24], CEI [25], and FabLab CB [26] has created an ecosystem where SMEs and start-ups can access advanced services while experimenting with new ideas. Workshops with networks such as Inova-Ria reinforce this collaborative dimension, embedding the hub within wider innovation systems.

7. Conclusion

GreenUpPCB exemplifies how a regional initiative can operationalise the principles of Industry 4.0 and the circular economy to create a sustainable and replicable model for electronics repair and retrofitting. By combining advanced diagnostic technologies, reverse engineering methods, and modular infrastructure, the laboratory has successfully addressed two pressing challenges: equipment obsolescence and resource scarcity in sectors that are strategically vital for Portugal, particularly renewable energy and rail transportation.

The experience of GreenUpPCB demonstrates that low-density territories can do more than passively benefit from innovation – they can actively lead it. By linking academic research with industrial needs, the hub provides concrete solutions to local companies while simultaneously offering training and capacity-building for technicians, students, and entrepreneurs. This dual role ensures that the laboratory's impact extends well beyond immediate technical services, fostering workforce development and strengthening the regional innovation ecosystem.

The journey, however, has not been without constraints. Recruiting highly specialised staff remains a challenge in a labour market where talent is often drawn to larger urban centres. Dependence on external suppliers for advanced diagnostic equipment can cause delays, while the continuity of funding is a recurring concern in research and development environments. Yet, these challenges have spurred adaptive strategies, such as modular infrastructure planning, the diversification of funding sources, and the establishment of strategic alliances with universities, SMEs, and regional innovation agencies. Together, these measures enhance the sustainability and resilience of the hub.

Equally important is the initiative's alignment with national and European policy frameworks. At the Portuguese level, it advances the Agenda for Microelectronics and Semiconductors [12] and the National Plan for Energy and Climate 2030 [11]; at the European level, it aligns with the EU Chips Act [9] and the Green Deal [10]. GreenUpPCB illustrates how ambitious policy strategies can be translated into practice through targeted interventions that create locally embedded hubs of expertise.

Ultimately, the case of GreenUpPCB demonstrates that electronics repair and retrofitting are not merely technical necessities but also drivers of socio-economic resilience. By extending the life cycle of PCBs, the laboratory reduces electronic waste, lowers costs, and ensures continuity in critical infrastructures. Just as importantly, it shows that innovation does not need to be confined to metropolitan centres: with the right vision and collaborative framework, smaller regions can become active participants in Europe's green and digital transitions.

In sum, the GreenUpPCB model provides a framework for sustainable smart manufacturing that is inclusive, regionally anchored, and policy-aligned. Its success offers a practical pathway towards greater technological sovereignty in Europe, while promoting a greener, more circular, and more resilient industrial future.

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