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Multilayer printed circuit boards made from paper – EU project CircEl-Paper demonstrates practical viability

The volume of electronic devices in the EU is growing faster than the recycling of the resulting electronic waste (e-waste). The key levers for better circularity are simplified recycling and the use of more sustainable materials. This approach was pursued by the EU-funded research project CircEl-Paper. It has demonstrated the practical feasibility of paper-based printed circuit boards (PCBs) for a more circular electronics industry and has manufactured demonstrators for three concrete use cases. Key product developments include improved paper substrates for PCBs made from both virgin and recycled fibers, along with printing inks for printed electronics based on recycled silver and bio-based binders.

According to official statistics, every citizen of the European Union generates around 12 kg of e-waste per year[1], with roughly 5.5 million metric tons collected in total in 2024. While the volume of devices placed on the market across the EU has risen by 82% since 2015 to more than 14 million metric tons, e-waste collection and recycling grew by only 72% over the same period. Recycling electronic printed circuit boards poses a particular challenge. These boards are typically made of composites such as FR4, a glass-fiber-reinforced epoxy laminate characterized by flame-retardant properties, high dielectric strength, and thermal stability. Multiple layers of conductive tracks and components are embedded in, assembled on, and interconnected within this composite material. As a result, such PCBs are difficult to separate into their constituent parts and to recycle due to the non-recyclable FR4 composite.

Taking this as its starting point, the CircEl-Paper project team developed the idea of replacing FR4 with paper composites and using it to build multilayer PCB substrates that can be easily broken down in an adapted paper recycling process using slightly modified aqueous process steps. The team also set out to find a more environmentally friendly substitute for the conductive tracks, together with a simple, economical manufacturing process, supported by a comprehensive life cycle assessment and an evaluation of ecotoxicity. Project coordinator Gerhard Domann of the Fraunhofer Institute for Silicate Research summarizes what was achieved over the four years of the project: "In CircEl-Paper, we successfully brought together two approaches. The first was to evaluate paper composites as substrates and their behavior in near-conventional PCB manufacturing. Since paper is in itself also suitable for high-throughput technologies, our second approach was to apply concepts from printed electronics to roll-to-roll processes on paper. Both approaches can be combined. This enabled us to produce multilayer paper PCBs with double-sided or even four-layer circuitry, plated-through VIAs, lamination, and hybrid integration of electronic components."

Circuit boards made from paper – is that even possible?

The good news first: yes, the CircEl-Paper team has shown that paper can be used as a substrate for electronic circuits, and that the printing resolution already attainable with screen-printing processes is sufficient to produce simple electronic devices. For the final phase of the project, the team chose three typical examples of disposable electronics as use cases: a roll-to-roll printed glucose sensor of the kind used by people with diabetes to measure their blood glucose levels, a four-layer temperature-time sensor for monitoring sensitive goods during transport and storage, and a foldable sound card for

[1] https://ec.europa.eu/eurostat/statistics-explained/SEPDF/cache/32212.pdf?v=1195816866224813

recording and playing back music or spoken messages in greeting cards. All three use cases were successfully implemented using the paper-based PCBs and the other materials developed in the CircEl-Paper project. Recyclability was also demonstrated. "But the road to get there was rocky," says Domann. "We faced major challenges, such as flame retardancy, moisture absorption, and surface roughness – all essential requirements for use as a PCB material. However, the better the technical properties of the paper composites became, the greater the impact this had on the standard paper recycling route." In the end, the team succeeded in producing paper PCBs with high resolution and reliability, designed for the requirements of the respective applications. For more demanding applications, the complexity of the circuits can be increased.

Environmentally friendly solutions for greater stability and flame retardancy

To be used as a PCB material, paper must be treated with flame-retardant substances in an impregnation process. To ensure that this does not come at the expense of recyclability and environmental compatibility, the project partners QSAR Lab and Joanneum Research evaluated the different material options in life cycle assessments and toxicity modeling. The roll-to-roll manufacturing and modification processes developed by the project partners Fedrigoni, RISE, and Joanneum Research were optimized for paper based on both virgin and recycled fibers and scaled up to larger volumes. Using this paper together with suitable adhesives and laminating processes, multilayer PCBs could be manufactured. The multilayer laminated papers exhibited the desired stability. While the recyclability requirements placed on the paper did cause some difficulties in the electroplating process, basic feasibility was demonstrated, and further paper development by project partner Fedrigoni reconciled functionality with recyclability.

Recycled silver for printed conductive tracks

In electronics, silver is – alongside copper – the metal of choice for manufacturing conductive tracks, thanks to its outstanding electrical conductivity and reduced tendency to oxidize. In life cycle assessment, however, silver as a primary raw material is rated as critical owing to the high environmental impact of mining and processing. The CircEl-Paper team therefore consistently relied on recycled silver. As part of the CircEl-Paper project, VFP Ink Technologies developed SECTR (Silver Electron Chemically and Thermally Resistant), an innovative silver conductive ink formulation incorporating recycled silver and bio-based binders. The ink formulation, commercialized as SECTR by VFP Ink Technologies, combines high electrical conductivity with strong chemical and thermal resistance. Developed for industrial screen-printing applications, SECTR demonstrates the potential of advanced functional inks to support both high-performance printed electronics and resource-conscious manufacturing processes. The ink formulation can be processed at low temperatures, starting from 50 °C, and has a long shelf life; it reduces the use of critical primary raw materials and is currently being prepared for commercialization. Further material formulations for active components were developed and tested by Fraunhofer ISC and Joanneum Research.

Assessment of recyclability and ecotoxicity

Recycling trials conducted by project partner Grenoble INP-UGA confirmed that printed and encapsulated paper PCBs can be processed in adapted paper recycling processes. Cellulose fibers are recovered, and silver and polymer fractions are separated out. High silver recovery yields were obtained with untreated papers (up to 83%) as well as with impregnated papers (up to 89%). The separated silver fraction was recovered and integrated into the formulation of new ink. The cellulose fibers recovered from impregnated paper still carry the impregnating agents. Tests need to be carried out in order to evaluate the potential of manufacturing new electronic devices from these fibers that still contain impregnating agents.

To assess ecotoxicity, the key components of the PCB paper and of the other materials used in the production of printed electronics were evaluated by project partner QSAR Lab using predictive models. The effects on various well-established model organisms were investigated. The analysis provided important insights into the toxicity profiles of these ingredients and made clear that careful substance selection is required to minimize potential risks to health and the environment. Overall, based on the available experimental data and computer-based toxicity assessment methods, most of the precursors and components of the material can be classified as relatively safe.

In parallel to the classical life cycle assessment carried out by project partner Joanneum Research, Fraunhofer ISC developed a knowledge and data platform (based on openLCA) for dynamic (time-dependent) and prospective (future-scenario-based) life cycle assessments, with the aim of supporting technology decisions at a very early stage of development through simplified LCA calculations. This building block allowed the project partners to specify their individual process flows in a standardized, machine-readable form. The process flows could then be imported directly into openLCA, with the definitions of the process chains preserved. Technically, this was implemented via a form-based user interface for process experts. By the end of the project, more than 150 materials, linked by more than 50 processes, were registered on the data platform. After the end of the project, the platform remains accessible as an archived dataset.

PCB paper also suitable for conventional manufacturing processes

Project partner ICAPE-MMAB played a central role in evaluating how the technologies and materials newly developed in CircEl-Paper perform in practice. ICAPE-MMAB tested and assessed the CircEl-Paper composites in its test production line under near-to-conventional PCB manufacturing conditions. However, the paper substrate is not compatible with conventional PCB processes since the chemistry used affects the paper stability. However, electroplating and etching can be conducted in modified “mild“ conditions. These processes have to be scaled up to be compatible with PCB manufacturing technologies. Conductive patterns were produced using near-to-standard PCB technologies, and conductive VIAs were created by electroplating. The structures achieved showed significantly higher conductivity than purely printed conductive tracks and enabled the production of multilayer demonstration samples. Also, based on printing technologies and lamination technologies, an alternative PCB technology can be set-up using printed structures as seed layer for galvanization. With these results, the CircEl-Paper project has opened the way for the further development of paper-based PCBs using more environmentally friendly materials – for a circular electronics industry.

Project information

Name: Circular Economy Applied To Electronic Printed Circuit Boards Based On Paper (CircEl-Paper)

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Partners:
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Grenoble INP-UGA, Grenoble, France

Joanneum Research, Graz, Austria
QSAR Lab, Gdańsk, Poland
RISE, Stockholm, Sweden
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Pictures



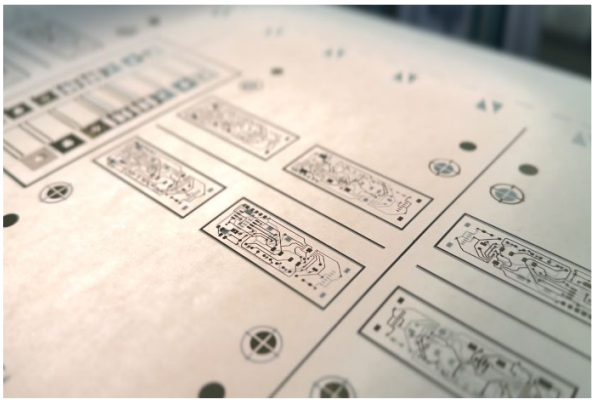
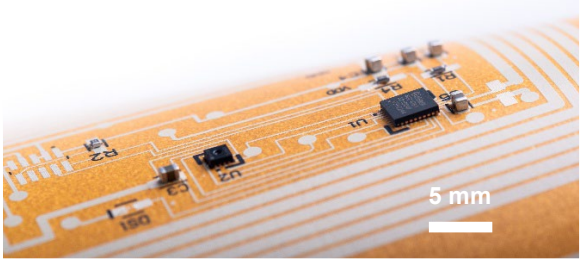


Fig. 1: New conductive ink formulation with recycled silver – even foldable! © CircEl-Paper

Fig. 2: Double-layer roll-to-roll printing process © CircEl-Paper



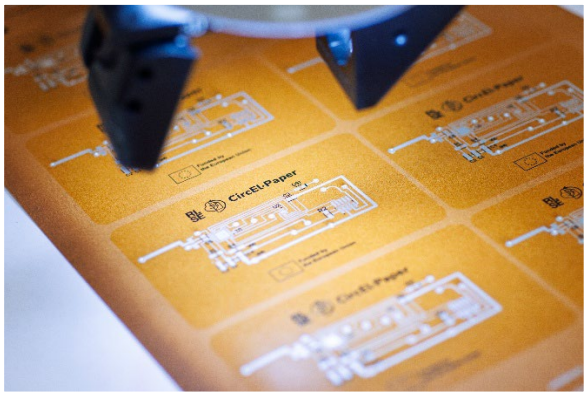


Fig. 3: High resolution for printed circuits (detail of the TTI-Sensor) © CircEl-Paper

Fig. 4: TTI sensor in credit card size with four-layer PCB with VIAs © CircEl-Paper

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CircEL-Paper - Circular Economy Applied To Electronic Printed Circuit Boards Based On Paper

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