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ELECTRONICS FROM RENEWABLES: THE HYPELIGNUM PROJECT

Reshaping electronics, from materials to their end-of-life, is key to achieving a sustainable economy and society. HyPELignum, https://www.hypelignum.eu/, has the ambition to demonstrate a holistic approach to the manufacturing of electronics with net zero carbon emissions. To achieve this goal, the consortium is exploring the possibility of combining hybrid printed electronics, biogenic materials (e.g., wood and lignocellulosic polymers), and low-impact metals in manufacturing electronics and components.

Introduction

Electronics strongly affect our environment through, for example, the use of scarce and/or environmentally impacting resources, high energy and resource-demanding manufacturing processes, and large disposal rates. Therefore, *rethinking the existing electronics* paradigm is crucial for a more environmentally and economically sustainable economy. HyPELignum aims to demonstrate that manufacturing electronics with net zero carbon emissions is achievable by implementing a holistic approach centred on additive manufacturing (*e.g.* printing) and lignocellulosic materials, including wood. Since the introduction of the Green Deal, research activities focused on (i) the use of low environmental

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Fig. 1 - Prototype of lignin-based epoxy resin

impacting materials [1], (ii) optimisation in energy consumption, (iii) the use of biodegradable/biode-rived/recycled materials [2] and (iv) better utilisation of resources (e.g. additive vs subtractive manufacturing) [3] in electronics have fast grown. The HyPELignum aims to further strengthen this field by exploring and rethinking electronics around wood.
The main goals of the project are:
- the use of low-impacting materials (*e.g.* wood, lignocellulosic materials, transition metals, bio-derived synthetic molecules) in:
a) the formulation of inks, coating and fire retardants
b) the active material of energy storage
c) laminate for printed circuit boards (PCB);
- the exploitation of additive manufacturing in the production of:
a) standalone electronics (Hybrid printed electronics)
b) monolithically integrate functionalities within wood products (*e.g.* furniture, construction elements).

The final goal of the project is to demonstrate its vision through the realisation of 4 demonstrators:
1) electronics based on wooden materials based Eco-PCB and plywood,
2) implementation of sensors and actuators on large area wooden construction element,
3) sensorised interior element (*e.g.* furniture),
4) CAN modulated separation of electronics from substrates.

To achieve these results, a consortium based on 11 highly innovative partners was assembled:
- RISE Research Institutes of Sweden AB (**www.ri.se**) is the coordinator;
- PROFACTOR GmbH (**https://www.profactor.at/en/**);
- The National Institute of Chemistry (NIC, **https://www.ki.si/**);
- The Spanish National Research Council (CSIC) (**https://www.csic.es/**);
- ADLER-WERK Lackfabrik Johann Berghofer GmbH & Co KG (**https://www.adler-lacke.com/**);
- Nederlandse Organisatie voor Toeg epast Natuurwetenschappelijk Onderzoek (TNO) (**www.tno.nl**);
- Holzforschung Austria (HFA **www.holzforschung.at**);
- Infineon Technologies Austria AG (**https://www.infineon.com/**);
- The Danube Private University GMBH (**https://www.dp-uni.ac.at/en**);
- Swiss Federal Laboratories for Materials Science and Technology (**https://www.empa.ch/**);
- The Association of the Austrian Wood Industries (**https://www.holzindustrie.at/**).

Key project results

Lignin extraction and valorisation

Materials (*e.g.* PCB board) and components (*e.g.* packaging for μchip) in electronics mostly rely on fossil-based polymers; subsequently, electronic industries share the goal to reduce their dependency on fossil resources and move towards a more biobased economy. Lignin is a naturally occurring aromatic biopolymer present in wood and herbaceous biomass that can find application as a replacement for fossil-based polymers and as a raw material for producing biochemicals and building blocks. One challenge is efficiently extracting lignin with adequate purity and reactivity from the lignocellulosic biomass (beech wood, spruce wood and

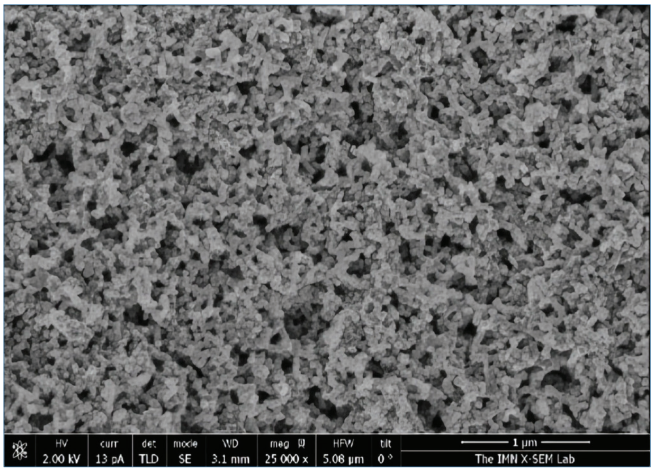

Fig. 2 - Scanning Electron Microscope image of Fe nanoparticles

wheat straw were chosen). A recently developed mild organosolv fractionation method (FABIOLA™) developed at TNO [4] is now applied in HyPELignum. The advantage of FABIOLA™ is that it can provide more reactive lignin factions than other technical lignins. Among the areas of applications targeted in the project for lignin, those of developing bio-derived reversible coating are of great relevance to achieve the project vision.

Recovery and recycling of raw materials (*e.g.* metals) and components are key to improving the sustainability of electronics. As part of HyPELignum, partner NIC is designing and developing bio-derived epoxy resins containing a covalent adaptable network (CAN) to enable the controlled degradation of the coating. In this development, the Organosolv Lignin from the TNO partner is modified to increase the carboxylic acid content and crosslink it with green-based epoxides. The first prototype of biomaterial with elastic behaviour was obtained (Fig. 1). The recyclability of both epoxy resins is under study.

Functional inks and dielectric materials

Functional inks are essential for the additive manufacturing of electronics. Conventional inks for printed electronics are based on fossil-derived polymers and, when high electrical conductivity is required, on Ag particles. In the HyPELignum project, partners RISE, NIC, CSIC and ADLER are working on improving the sustainability of inks by exploring the use of lignocellulosic polymers (*e.g.* binders and/or surfactants) in combination with carbon fillers or less impacting metallic filers (*e.g.* Zn, Fe and Ni) for both screen printable and inkjet printable functional inks. A significant challenge in formulating metallic conductive inks is the environmental stability and high control in the size and shape of the used fillers. To overcome this issue, CISIC is developing a fast one-step microwave-supported method for synthesising and stabilising metallic nanoparticles in solution. The use of microwaves ensures to reach higher temperatures in a faster (in the order of seconds) and more uniform way, allowing the synthesis of more homogenous particles with narrow size distributions (Fig. 2) [5]. Optimisation of reaction parameters such as microwave power, irradiation time, and solvent choice are key to maximise the advantages of the proposed synthetic process and

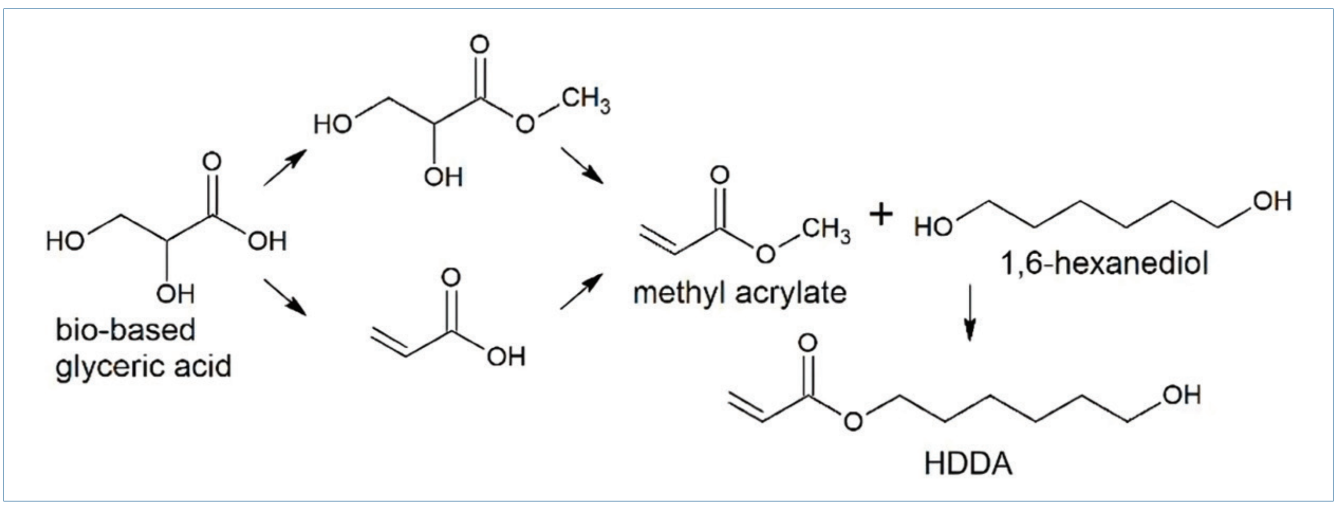

Fig. 3 - Synthesis of HDDA from renewable resources

to tune the nanoparticle's size and properties (*e.g.* colloidal and chemical stability). Moreover, taking advantage of the short reaction time and efficiency, the scaling up of the process could be achieved by using semi-automated larger batch reactors or a continuous in-flow microwave.

If biogenic materials have been implemented with different degrees of success in conductive inks, their implementation in dielectric materials is far more challenging. To increase the sustainability of dielectric inks and, more specifically, inkjet printable inks, the project aims to develop bio-based hexanediol diacrylate (HDDA) and demonstrate its applicability as a replacement for oil-based HDDA. To achieve the synthesis of bioderived HDDA, two steps will need to be accomplished:

i) the production of bio-based acrylate ester;

ii) the transesterification of this with hexanediol (Fig. 3). Currently, both processes are being optimised.

Demonstrators

The substrate is a key element in any kind of electronics, serving as its physical support. Conventionally used electronic substrates (PCBs) based on epoxy resins are estimated to account for approximately 50% of electronics' environmental impact.

EMPA in working on the development of eco-friendly Printed Circuit Board (ecoPCB) substrates under the HyPELignum project exploits the lignin-containing cellulose pulp (approx. 14% lignin) obtained as a byproduct of the Fabiola™ fractionation. The ecoPCBs were made by fibrillating the ligno-pulp into l-CNF (lignocellulose nanofibers) and applying pressure-temperature treatments. Lignin's thermoplastic effect and cellulose hornification created a rigid, mechanically robust, low roughness and low water vapour permeability substrate suitable for high-resolution printing and eco-electronics applications. Importantly, despite their enounced performances, the eco PCBs retain biodegradability, making them suitable for sustainable electronics. A demonstrator with an NFC antenna validated substrate usability, highlighting lignocellulose as a promising alternative to traditional PCB materials, is going to be produced by EMPA and PRO (Fig. 4). In addition to the ecoPCB in the HyPELignum project, plywood is also being explored as a replacement for conventional PCB laminates. Fig. 5 presents the first example of the additive manufacturing of an electronic device (a moisture - and temperature-sensing platform) on plywood by RISE, IFAT and HFA.

Fig. 4 - FC antenna demonstrator

Sustainability assessment and support to the community of industries/scientists

The HyPELignum project addresses some of the 10 «Rs» of a sustainable circular economy (refuse, reduce, rethink, reuse, repair, refurbish, remanufacture, repurpose, recycling, recover), especially 'rethink', which involves designing a product with circularity in mind; 'remanufacture', and creating a new product from secondary materials; and 'recycle', which requires processing products/materials back into raw materials.

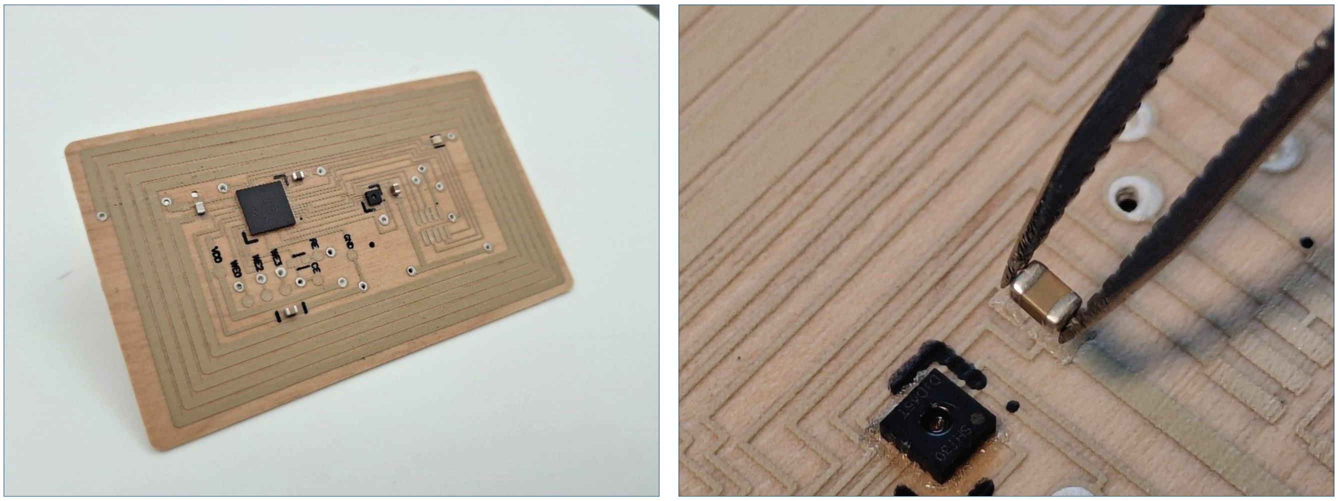

Fig. 5 - Screen-printed moisture sensing demonstrator on plywood. Left: front of the demonstrator; Right: RLH and Temperature sensor

HyPELignum, along with other EU founder projects (BAMBAM, ECOTRON, SusFE, SUINK, UNICORN, REFORM, EECONE, SUSTRONICS, CIRCUITS, Sustain-a-Print, CircEL-paper, Treasure) have united under the common aim of promoting greener and more sustainable electronics in Europe by forming the EU Green Electronics Working Group. This joint initiative extends the visibility of each project's research, fortifies the relationships between the different projects, will support the harmonisation and dissemination of "green electronics", is expected to catalyse the development of a more inventive and sustainable future in electronics and will provide a roadmap to support the broader community of researchers and industries interested in creating greener electronics.

Conclusions

The HyPELignum started in October 2022 and is expected to end in September 2026. In its first two years of activities, the project has generated materials (*e.g.* lignin fraction, nano-particles), processes (*e.g.* synthetic pats for bio-derived functional molecules and polymers), and knowledge that has led to the formulation of inks, coating, new resins (lignin-based epoxy resins) that could lead to new opportunities in green electronics. Furthermore, to showcase the vision of the project, the first series of prototypes of wooded electronics, such as Screen-printed moisture sensing and NFC antenna demonstrators, were obtained.

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Elettronica da fonti rinnovabili: il progetto HyPELignum

Rimodellare l'elettronica, dai materiali alla fine del ciclo di vita, è fondamentale per realizzare un'economia e una società sostenibili. HyPELignum, **https://www.hypelignum.eu/**, ha l'ambizione di dimostrare un approccio olistico per la produzione di elettronica a zero emissioni di carbonio. Per raggiungere questo obiettivo, il consorzio sta esplorando la possibilità di combinare elettronica stampata ibrida e materiali biogenici (ad esempio legno e polimeri lignocellulosici), metalli a basso impatto nella produzione di elettronica e componenti.