Sustainable materials and processes for electronics, photonics and diagnostics

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Abstract

This paper discusses applicability of sustainable substrate alternatives for printed and other roll-to-roll (R2R) compatible electronics, photonics and diagnostics. Substrate candidates include bio-based plastics and cellulose based substrates, including paper, carton board and nano cellulose. This paper takes a case-specific approach for sustainability and besides changing the substrate also discusses other sustainability aspects for a temperature monitoring intelligent package solution. End-of-life processes, such as recycling, composting and biodegradability, will be paid a due attention. The role of life cycle assessment (LCA) as the main tool for quantifying environmental impact is discussed. The paper will summarize a set of selection criteria that sustainable devices have to fulfil in order to function as part of electronics, photonics and diagnostics products and at the same time be compatible with printing and other R2R compatible processes. Innovative component and device opportunities that increase electronics, photonics and diagnostics product sustainability are defined, and industrial expectations towards sustainability is summarized.

1 Background

Europe has a goal to become the world's first climate-neutral continent by 2050. In December 2019, the EU presented the European Green Deal, which is a roadmap for making European economy sustainable while also ensuring that the transition is competitive and inclusive for all of Europe [1]. This forces all industries, including electronics, photonics and diagnostics industry, to think how to find balance between economic growth, resource consumption and environmental issues.

One of the challenges in the electronics industry is that global electrical and electronic waste production is expected to increase from 47 to 72 million tons from 2017 to 2022 with 6.5 Compound Annual Growth Rate (CAGR%) as more electronic products are used [2]. In addition, the global consumption of material resources has increased fourteen-fold between 1900 and 2015, and is projected to more than double between 2015 and 2050 [3]. Just 20% of this waste is collected and recycled under appropriate conditions, with the remaining 80% posing environmental and health concerns [4]. This might result in some rare and valuable materials, also used in modern electronics, to run out. Furthermore, new types of components are merging that will at some point of their life-cycle end up in the biological environment. For example, sensors for precision agriculture, environmental monitoring or intelligent packaging as well as disposable diagnostic devices. These challenges call for actions to decrease the environmental footprint of electronics, photonics and diagnostics products.

There are different perspectives for environmental sustainability, and this paper focuses on these aspects [5]:

1. Use of materials originating from renewable resources, e.g. cellulose based materials or bio-polymer based plastics
2. Use of compostable or bio-degradable materials
3. Use of energy and material efficient manufacturing processes, e.g. R2R compatible printing and other methods
4. Effective reuse/recycle of materials, components and products i.e. circular economy
5. Design of products tailored for circular economy i.e. eco-design, circular design

At the moment, modern electronics are filled with circuit boards on which various metals (e.g. copper, indium, nickel) and composites (FR-4) or plastics (e.g.

polyimide, PET) are soldered together. Some of these materials are toxic (e.g. lead, cadmium) or break down into toxic substances. Electronics made of paper or of other sustainable substrate materials, such as cellulose based materials, bio-based plastics or bio-based composites can be viewed as a potentially cost-effective alternative in various applications. Use of these flexible and foldable substrate materials enables R2R high-throughput additive printing that is considered a more material-efficient process with less material waste during manufacturing than traditional electronics manufacturing methods. Flexible printed circuits offer several advantages compared to rigid circuits, including reduced package dimensions, reduced weight, and optimization of component available space [6]. Electronic Components and Systems Strategic Roadmap (ECS SRA) defines sustainable production as energy-efficient processes that use raw materials in an effective way, including minimized waste typical for R2R based processes [7]. It is estimated that additive manufacturing processes powered by electricity generated from renewable energy, use one tenth of the materials of traditional factory production, resulting in a dramatic reduction in CO_2 emissions and use of the Earth's resources [8]. The use of sustainable substrates also sets new demands for sustainability of ink and interconnect materials, and for their performance and compatibility. Printing ink sustainability can be improved by replacing metals with e.g. carbon based materials.

International Electronics Manufacturing Initiative (iNEMI) defines the main gaps for sustainable electronics as: access to LCA data, eco-design knowledge, materials substitution and availability, and value recovery and consistent metrics [9]. In the following sections we discuss these aspects under the framework of the on-going ECOtronics research and ecosystem project [10]

2 New product innovations based on sustainable materials and processes

New business opportunities for companies operating with sustainability targets have been defined by ECOtronics project:

- Sustainable materials: Materials are required that are environmentally friendly, societal and financially sustainable, and based on renewable resources.
- Eco-design and circular design: Invention of product designs and existing products (re-designs) that increase product life-cycle and lifetime, increase energy and material efficiency, and close the materials loops. Ability to disassemble materials and components results in reuse of materials, and easy separation of materials for recovery. For example, currently 1.5 billion smartphones are sold annually, representing a potential $150 billion of value entering the market. At the end of the product lifetime, much of this value does not return to the material circulation due to inefficient recycling. If materials and components could be reused effectively, much of this value would remain in the system without polluting the environment [4].
- New products with sustainability as competitive edge: Companies developing and integrating electronic devices can use sustainability as their competitive advantage. This will help them differentiate from the competitors, by offering products with similar performance and price, but with sustainable aspects in materials, supply chain, manufacturing processes and end-of-life management.
- Targeting to zero waste concepts: When electronics industry adopts circular economy principles, new processes and facilities are required for efficient material reuse, recycling and renewable material composting.

Environmentally sustainable devices are required for product sectors, such as, intelligent packaging, environmental sensors and disposable diagnostics. Environmental sensors are such devices that end up in the environment at some point of their life cycle. Some of them are left in the environment after use, which calls for biodegradable solutions. Disposable diagnostics are single-use devices that are used in large quantities, thus representing a waste management issue. Intelligent packaging solutions are electronic components integrated into transport or item packages. These components cannot interfere with the existing packaging recycling schemes.

The product case in this paper is a temperature monitoring intelligent packaging solution [11] (Figure 1) that is used as a demonstrator case for ECOtronics. By focusing on a product concept instead of a single component, multiple aspects affecting environmental impact and sustainability are taken into account. The product concept is based on small surface mount device (SMD) components including a thin near field communication (NFC) temperature monitoring integrated circuit (IC) (thickness 40µm) for logging and communication, and light emitting diodes (LEDs) (thickness <200µm) for indication of logging and threshold temperature. The circuit is R2R printed, and the energy module for powering up the device is based on a printed supercapacitor with organic photovoltaics (OPV) as the energy harvesting method [12] implemented with sustainable and non-toxic materials.

Printed diodes and transistors can be integrated for implementing the supercapacitor (SC) loading and conversions circuits. This energy module, having the size of a credit card, is designed for indoor operation conditions to provide 2.3V supply voltage. This solution provides potentially environmentally friendly alternative to batteries.

Figure 1. Rough design for temperature monitoring package.

The following sections will discuss different environmental sustainability aspects for this product case collected during ECOtronics: material selection, manufacturing processes and environmental impact quantification.

3 Material requirements

The requirements for the substrate material come not only from the application specific requirements, but also from the printing process requirements and inks. For a R2R based printing process the typical substrate thickness is between 35-375 µm to enable smooth running of the process. The material should be dimensionally stable even in elevated temperature, which can be up to 140°C during curing and sintering process of the ink and even higher for some inks, but only for a short time. Some inks require UV-curing (e.g. 200 W/cm at 365 nm), which states stability requirements against UV-light exposure. The attachment of the ink and deposition of coating layer may need plasma treatment to activate the substrate surface for better ink and coating wetting or adhesion, so there is tolerance needed for the plasma treatment. Even though plasma treatment can activate the substrate surface, at least for a short time, the substrate should be non-conductive as such to ensure electron transfer only along the printed areas.

From the ink perspective, the substrate should be chemically inert for the solvents and additives normally used in conductive inks (e.g. glycols, pyrrolidone, sulphonic acids, some alcohols, methyl ethyl ketone). One of the main criteria in ink-substrate interface phenomena is proper wetting properties related to surface energy of substrate and ink, hydrophilic-hydrophobic properties, as well as ink viscosity and roughness/smoothness of the substrate surface. The surface energy of the substrate should be relatively high or at least higher than in ink. The most common method to analyse that is contact angle measurement. Hydrophilic-hydrophobic properties and viscosity typically defines the penetration of the ink at least in the paper-based substrates. In those the surface roughness or smoothness also becomes more an issue than in plastic-based substrates. [13]

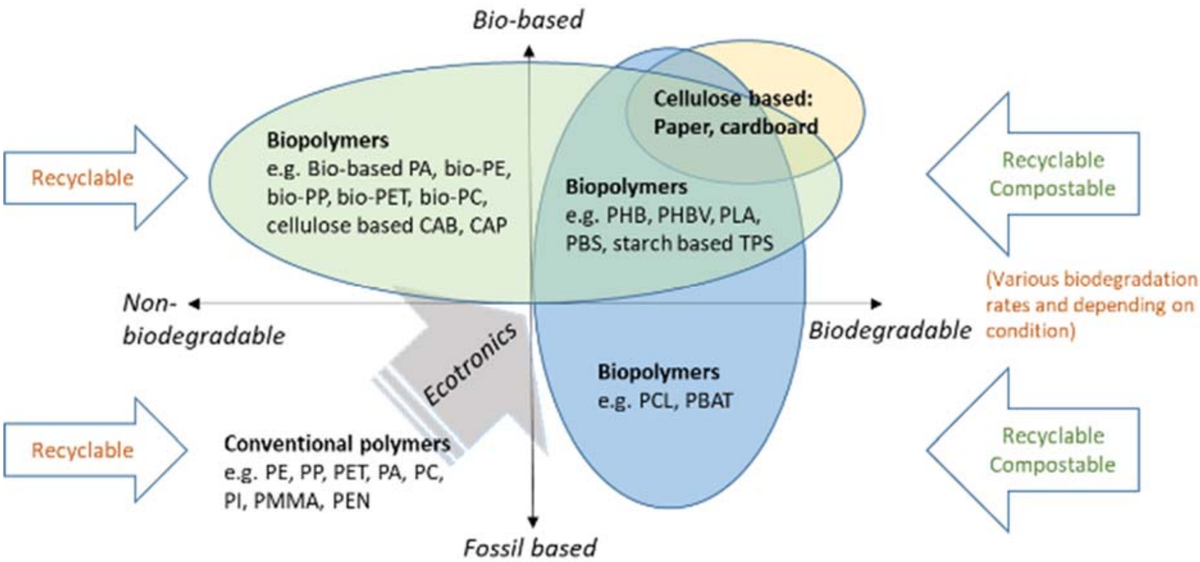

Figure 2. World of substrates used in printed electronics with Ecotronics approach added.

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The transition towards sustainable electronics also needs change in substrate material from oil-based substrates (e.g. PET or PI) commonly used in printed electronics towards renewable or bio-based substrates, such as cellulose based papers and cardboards, and biopolymers. Besides being from renewable based origin some of the materials are also biodegradable enabling their use in e.g. environmental diagnostics. All substrates selected for Ecotronics are recyclable. The material selection potential is illustrated in Figure 2.

Material properties of the substrate must be at a sufficient level from the point of view of electronics application, package manufacturing and end-product functionality. Smoothness, hydrophilicity, opacity, temperature resistance, stiffness, strength and convertibility are properties that are achievable at an adequate level from an industrial range of materials.

3.1 Fiber-based materials

Fiber-based materials are versatile materials, however some characteristic features limit their use in some applications. Poor barrier properties and sensitivity to elevated moisture levels are the most significant of them [14]. These properties can be substantially improved by coating them with a barrier layer, where most commonly fossil-based polymer films are used to improve the water resistance of fiber-based materials, but repulping this kind of coated material is difficult. In addition, coating of the fiber-based substrate creates a smoother and low porosity surface and decreases the excessive absorption and wetting of the ink. Together with the surface strength, the coating layer can also improve rub resistance, which enables the production of higher quality printed images. When considering more sustainable materials, bio-based polymers can be utilized for coating. Due to their characteristic features, bio-based coatings often require a combination of different materials to achieve target properties [15]. Multi-layer type coatings are one possibility to improve the material and coating properties, since a single biopolymer layer rarely has properties that can compete against synthetic films [16].

Several commercial material options are available to implement the targeted packaging solution presented in Figure 1. Suitable sustainable fibre-based materials include for example solid bleached sulphate board (SBS), folding boxboard (FBB) and other board alternatives. These are compostable and bio-degradable materials that can also be pulped and recycled.

3.2 Bio-polymer based materials

Biopolymers for Ecotronics are selected according to application needs. Selection criteria can be potential for recycling in existing recycling streams, or recycling logistics in future, or whether it needs to be biodegradable. Some of the applications need long term durability and stability during processing and in use conditions. The natural replacement for oil-based polymers is to use their bio-based counterparts (e.g. PET vs. Bio-PET)

3.3 Inks

In addition to substrates, sustainable electronics requires inks which do not contain materials or chemicals of ‘high concern’ either when ending up in the environment, or disturbing the recycling process. Sustainable inks can be biodegradable or from renewable based raw materials, they contain no heavy metals and have only low or no volatile organic compounds (VOCs) during the printing process. For example, according to the USA National Association of Printing Ink Manufacturers (NAPIM), a bio-renewable ink is derived from plant, or animal origin. These can include resins, gums, oils, waxes, solvents and other polymer building blocks. It can also contain water. NAPIM’s Biorenewable Content (BRC) program assigns inks an index number, which gives an independent verification that an ink contains a certain percentage of bio-renewable content [17-18]

In electrically conductive inks the sustainability is highly related to conductive particles used in ink. Typical selection for high conductive purposes is silver nanoparticles containing inks, which can be replaced with aluminium or copper nanoparticles in lower cost applications. To avoid their oxidation sintering is sometimes needed, that however cannot be applied on heat sensitive substrates e.g. some bioplastic or paper. One solution is to go to carbon based such as carbon nanotubes or graphene-based inks or even nano-diamonds. [19-21]

4 Process requirements

One of the building blocks for the ECOtronics demonstrator is OPVs. As part of the energy module, it can harvest energy both outdoors and indoors, utilizing sunlight and artificial light sources even in low light conditions. Until now, OPVs have reached power conversion efficiency (PCE) of 17% under solar irradiation, and 28% under fluorescent light. [22-23] Furthermore, OPVs are able to generate the same level of voltage under various lighting conditions, which demonstrates compatibility for small energy autonomous systems, e.g. in IoT and wearable applications. [24]

OPV structure comprises ultra-thin layers of materials, where each has a thickness typically from a few tens of nanometres to ten micrometres. This means that the material consumption is extremely low. In addition, the fabrication can take place exploiting wet deposition methods, in particular well-established high volume manufacturing R2R processes, namely printing and coating techniques. [24-25]. Recent progress shows 13 % efficiency for R2R fabricated OPV under fluorescent and LED light sources, using materials that have already been up-scaled in larger production quantities to enable R2R fabrication. [24] The fabrication under ambient conditions allows replacing energy-intensive inert atmosphere or vacuum processes, improving the production efficiency through conservation of materials and energy. The energy payback time (EPBT) of OPVs is the shortest among photovoltaic technologies and it describes the time that the solar cell needs to produce the energy required for its production, including e.g. the production of all raw materials. According to the literature, EPBT has reached few months but even a one-day EPBT could be possible in the future. [26]

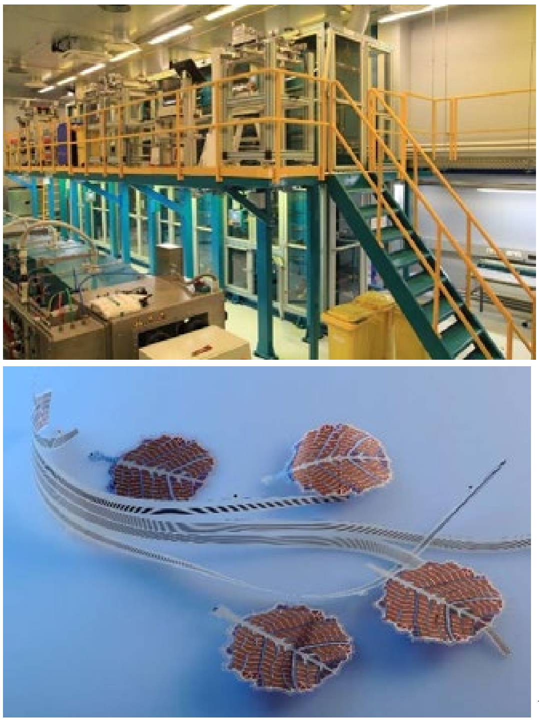
a)
b)

Figure 3. a) R2R pilot fabrication equipment at VTT and b) printed free-form OPVs [27].

OPVs are possible to fabricate using non-toxic, non-hazardous materials. Devices can also comprise materials inspired by nature. For instance, utilization of materials such as amino acids and peptides are possible in charge transportation. [28-29].Fabrication of OPVs using renewable materials that are safe and not suffering from excessive consumption, provides an environmentally acceptable alternative to complement the sustainable energy production.

As a part of the energy module and packing solution, OPVs are possible to fabricate as a part of a monolithic structure. Flexible and lightweight devices allow the printing of customized structures into any 2D shape, providing freedom of design. [30]

5 Environmental impact

Life cycle assessment (LCA) is a method for assessing the environmental impacts of product, service or system throughout its life cycle, i.e. starting from raw material acquisition extending to the grave, i.e. to waste management [31-32]. Life cycle assessment offers a tool for assessing the environmental impacts of a product of a system comprehensively, instead of only looking at the impacts of one life cycle phase (e.g. production), and thus prevents transfer of problems from one life cycle phase to another. In principle, LCA quantifies all the energy and material inputs used, and all the emissions and waste materials produced throughout the product’s life cycle. Through the assessment, an understanding of the environmental impacts of the product is established. LCA is based on the ISO standards 14040 and 14044.

Several studies have applied LCA for assessment of printed electronics. These include Liu et al. [33] who assessed the environmental impacts of paper-based printed circuit boards (P-PCBs). Their study found that the P-PCBs have about two orders of magnitude lower impacts than the reference organic PCBs.

Main sources of particularly climate impacts in the printed electronics typically stem from the substrate materials and metals used. For instance, in the case of OPVs, large part of the carbon emissions have been found to stem from the substrate, particularly when it is sputtered with indium-tin oxide (ITO) [34]. In order to reduce the environmental impacts of the substrate materials, fossil-based plastic substrates have been replaced with renewable substrate materials. Use of alternative substrate materials in printed and hybrid electronics not only potentially supports climate actions, resource sufficiency and industrial renewal, but also enables exploring the materials with better technical properties and, improving the user interface experience.

The problem in recycling and reuse of printed electronics typically lies in the separation of the different fractions. The product would be part of the waste from electric and electronic equipment. As e.g. the product studied in this paper would be small in size, it would most likely end up in the shredder light fraction, which typically goes to energy utilization. With the present price rate and technology, it is unlikely that the metals contained in small electronics would be recovered from shredder light fraction or incineration ashes. However, in the future with higher price level and more sophisticated technologies, there is potential for separation of some metals or other substances, from either incineration ashes, or through mechanic separation from the shredder light fraction. Recycling of product components can be advanced through product design. Characteristics advancing utilization include easy removability and maintaining of existing properties to as high degree as possible. Collaboration between recyclers and producers can also enhance recycling and recovery.

A large proportion of the materials used in printed electronics are plastics. Presently only about 20% of plastics in electronics are recycled [35]. One key reason preventing the recycling of the plastics in the Waste Electrical and Electronic Equipment (WEEE) directive is that the waste stream contains several different types of plastics. Furthermore, the recycling process needs to be quite complicated in order to separate pure enough polymers that can be extruded and compounded to secondary resources, which also comply with the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), and Restriction of Hazardous Substances (RoHS) regulations [35]. Bio-based plastics could potentially be composted, but at the moment their share is small making it unprofitable to separate them.

On the other hand, the conventional printed circuit board contains heavy metals such as copper and lead, which are harmful to the environment if improperly disposed. An estimated mass of 20-50 million tons of WEEE are discarded annually, and a major part of them are informally collected and recycled in developing countries [36]. Use of non-metallic materials such as carbon-based inks decrease the overall human and environmental toxicity hazard.

5.1 Recycling

Application of eco-design has a primary role in improving the environmental performance of new products, such as the intelligent packaging demo assessed in this study, throughout their life cycle. A key step in improving the recycling potential of the different components in such applications would be to develop the structures in such a way, that the different layers of materials are more easily separable from one another.

Use of printed electronics in new applications like intelligent packages, increases the challenges related to recycling of the electronic equipment and materials. In the end-of-life, the electronics are collected and treated with packaging waste. Those processes are designed for recycling of plastics, cardboard or paper materials, and the separated impurities usually end up in incineration or landfill, depending on the waste management infrastructure. For effective recycling of the integrated electronics, they should be designed so that they are easily separable either in the source separation phase by the last user of the package, or in the mechanical separation phase, so that the valuable materials can be identified and separated in the further phases for recycling purposes. Both the packaging products and the waste management system has to be further developed for taking into account the increasing amount of integrated electronics and there will be lots of challenges in this development. On the other hand, it is possible to significantly reduce the environmental impacts of the packed products by using intelligent packages. These positive impacts, like reduction of food waste, can be much larger than the impacts of the electronics itself.

6 Conclusions

Resource sufficiency for the exponentially increasing future material needs is a global challenge concerning all businesses. Electronics, photonics and diagnostics industries need to tackle and manage this challenge by i) reducing the use of rare metals and increasing their recycling, and ii) reducing the carbon footprint through implementation of biobased materials as standard materials in printed electronics, energy technology, photonics and diagnostics. However, full exploitation of renewable materials is possible only after understanding and improving the performance of renewable materials, and after developing tailored manufacturing methods taking into account material properties. ECOtronics project aims to develop sustainable materials, processes and methodologies to meet this objective.

This paper has discussed the different aspects of environmental sustainability with a case-specific Ecotronics approach i.e an energy autonomous, temperature monitoring intelligent packaging solution realized through R2R compatible printed and hybrid manufacturing. In short, product sustainability can be contributed and improved through several routes:

- By replacement of fossil based substrate material with biopolymer alternatives. This is enabled through careful selection of the materials according to the application needs with respect to the properties required for the manufacturing process and in the use conditions of the final product. In addition, setting the product-specific requirements related to the waste management is crucial.

- By selection of sustainable functional ink alternatives without heavy metals and preferably based on bio-renewable raw-materials to decrease the use of rare and toxic raw materials. Inks with no or low VOC are also preferred to enable safe and sustainable processing. At the same time, the functional properties, conductivity being often the most crucial one, need to meet the application criteria.
- By optimized process through efficient material use, energy-efficiency, (low) material waste and additive manufacturing.
- By reducing the environmental impact in general by implementing eco-design and circular design principles through minimized material use, shift from fossil based materials to renewable materials, increasing the potential to separate materials and by designing products, which will as such impact sustainability.

To summarize, the printed and hybrid electronics and photonics implemented in Ecotronics demonstrator have a vast impact on sustainability as such e.g. through efficient material use as additive manufacturing and the flexibility for changeover to renewable material alternatives as discussed above. Moreover, through components and products realized using printed and hybrid manufacturing, the impact is increased even further e.g. through printed OPVs providing sustainable energy, lightweight structural electronics enabling fuel-saving in mobility applications, sensors decreasing product waste and loss, and also diagnostic solutions enabling early detection and prevention of medical conditions.

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