

# Accelerating sustainable development and production of nanomaterials and printed electronics

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**Abstract.** Printed and embedded electronics are considered game changing for electronics industry, and various R&D groups worldwide have already achieved remarkable progress. In the EU, limited access to these developments for industry and businesses still hampers wide rollout. Additionally, technology evaluation is often strictly focused on performance, i.e. whether technical functionalities meet specified requirements. For multiple reasons, a more holistic evaluation could contribute to more sustainable innovation. The EU-funded LEE-BED project has therefore created an open innovation test bed for printed electronics (PE), offering a time-efficient three-step process accessible via an online single entry point for easy involvement. The approach fosters evaluating ideas, developing prototypes, and transferring knowledge to interested parties from SMEs to global OEMs with or without previous involvement with PE. The first step (LEE-BED Phase 1) includes a multi-dimensional assessment of technical feasibility, economic viability, environmental sustainability, safety, and intellectual property before developing any prototype. This has successfully been applied to industry partners from construction, automotive, labelling, and luxury brands, offering novel functionalities and additional aesthetics through PE in their business practices. In this way, LEE-BED has established a collaborative platform for PE innovation sharing key learnings and opportunities.

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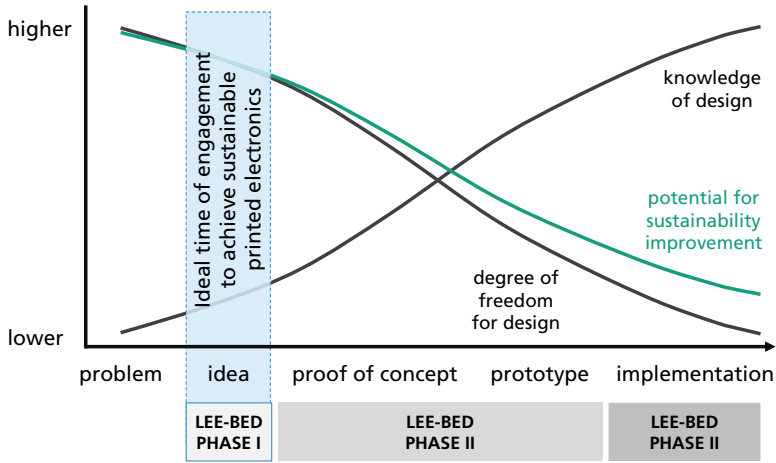
## 1 Introduction

Printed electronics (PE) is a paradigm for additive production of electronic circuits and devices continuously unfolding its full potential in the industry. PE are mostly based on nanomaterials transferred to a wealth of substrates via ink systems or gas phase to form functional patterns. It is already commonly seen as a faster, simpler and cost-saving approach for manufacturing, which equally allows for mass production, e.g. based on roll-to-roll printing traditionally used for newspaper printing, as well as highly individualised products with a lot size of one. Ultimately, PE offer the ability to implement electronic functionalities into applications that were formerly unfeasible. Printable components include antennas for connectivity, various sensors for temperature, humidity, pressure, and touch, as well as batteries, photodetectors and solar cells. However, there are only a few mass applications at an industrial scale to date. This might be due to missing knowledge of potential users and challenges regarding technology and accessibility. Another challenge is meeting today's sustainability goals set out for every technological innovation. While PE are often perceived as a "green" manufacturing technology due to reduced chemical use and waste compared to conventional manufacturing, sustainability plays a subordinate role in most applications. Rather, the selection of suitable materials and PE solutions is typically based on technology and economy, i.e. whether the design can meet functional and cost requirements. Lately, sustainability of PE over the entire life cycle has been another key focus point [1-4] and is already recognised accordingly by respective technology associations [5].

In the publicly funded EU project LEE-BED, an interdisciplinary team of R&D experts for PE technology and its assessment collaborated with industry to tackle current challenges with accessibility and implementation of pilot-cases at industrial scale. Hereby one goal is to ensure economic, environmental and technical sustainability along the entire PE value chain while meeting functional and design requirements. This paper describes the holistic assessment that was developed within the project and gives an outlook on its future roll-out.

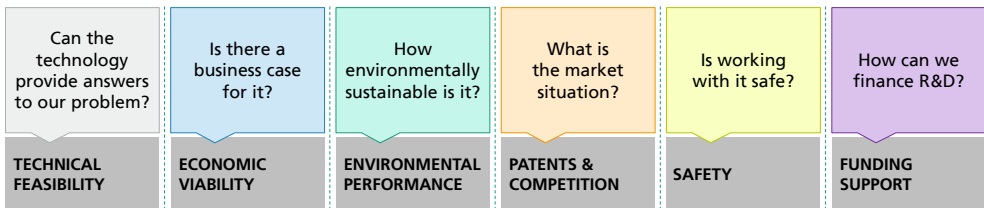
## 2 Holistic assessment of PE pilot-cases

One major challenge in product development in general and for PE in particular is the trade-off between knowledge of design and the possibility for sustainability improvement. This phenomenon has been discussed inter alia by Bhandar et al [6] and can be transferred to PE and LEE-BED project pretty straightforwardly (cf. Fig. 1). From an initial problem or idea to implementation, the design degree of freedom steadily decreases, as does the potential for improving sustainability performance, owing to the reduced options to choose from.



**Fig. 1.** Trade-off between knowledge of design and potential for sustainability improvement with the optimum point of engagement to achieve sustainable printed electronics, based on Bhandar et al. [6]

For achieving the most sustainable product design, it is vital to engage with sustainability considerations as early as possible, ideally during ideation. This is pivotal for successfully influencing product development and minimising sustainability risks in mass production. When offering assessment services for industry, it proved crucial to understand the different levels of knowledge of potentially interested parties. On the one hand, there are stakeholders experienced with technologies, materials, and printing processes which have not yet matured and scaled up to industrial production. On the other hand, an even large number might profit significantly from the application of PE, but are not aware of opportunities, do not know how to seize them, or sometimes both. This challenge needs to be addressed through a personalized approach. Moreover, industry attracted by a novel technology often quickly wants to know if it has potential. This leads to a contradicting requirement of fast services that need little to no customer involvement in terms of personnel and financial resources but provide detailed insights for sound business decisions. This apparent dilemma has been circumvented by determining the questions most relevant for industry regarding any new technology, and addressing them in the form of “quick-checks” in a set of standardised, modular services. The identified concerns mostly revolve around six aspects (cf. Fig. 2).



**Fig. 2.** Key industry concerns regarding printed electronics and derived LEE-BED phase I services

In addition, industries require low-barrier access to facilities for prototypes and small series before they deploy knowledge and train their own employees. In response to the outlined specific questions and demands, the LEE-BED consortium developed a three-stage, integrated program that provides the European industry with a rapid but sound assessment at any level of previous involvement with PE, access to state-of-the-art pilot line facilities, and final knowledge transfer services. To ensure sustainable and lasting business impact, particularly the initial evaluation (phase 1) plays a key role. In the following chapters, the distinct elements are described and their importance in the context of PE are highlighted.

## 2.1 Technical feasibility

The initial question for PE concerns capabilities that can be achieved with the technology. An assessment of these requires electromechanical and production design and modelling and results in the identification of limits and relevant risks for the specific application. To determine technical feasibility, technology experts need to thoroughly understand the customer vision and existing product systems in which the technology will be used. Thus, a comprehensive user questionnaire and consultation with technology experts helps to sharpen the focus of a PE pilot-case. At the same time, it enables developers to select the most promising technological approaches and define material requirements to meet industry needs. Key elements of the service are therefore: (1) proving the **technical feasibility** (go/no-go decision), (2) determining the **risk level** of technical development, (3) defining required elements to create a functional device (**system architecture**), and (4) **referring to pilot line technology** best suited for the PE pilot-case.

Since functionality is the fundamental requirement in any PE pilot-case, the technical assessment is pivotal for the entire process and needs to be conducted first. Yet, evaluating technical feasibility should be limited to the very basic functionality to avoid developing detailed solutions during screening before other aspects have been addressed. The assessment of the idea then provides input to the subsequent stages, either as one specific solution or multiple discrete options.

## 2.2 Economic viability

Typically, another critical challenge for potential industrial users of PE is economic aspects connected to PE pilot-cases. If no viable business case can be found, the technology is unlikely to be adopted into business practice. Therefore, an assessment to evaluate the economic viability of technically feasible pilot-cases forms a crucial step for the production and development of sustainable PE. The assessment developed within the project includes analysing the cost-revenue structure of a pilot-case based on the information provided by the customer and obtained from the technical assessment. Additionally, qualitative information about the product's business model and market will help to ascertain the feasibility and risks of the project. Key aspects to understand the economic viability of PE pilot-cases were found to be: (1) proving the **economic feasibility** (go/no-go decision), (2) determining the **economic risk level**, (3) providing **supply benchmarking** to identify cost-hotspots in production, (4) sketching a **business model canvas** to find financially sustainable business cases, and (5) conducting a **PESTLE analysis** to understand markets and potentials early on.

## 2.3 Environmental performance

Predicting environmental impacts over the entire life cycle of PE, from raw materials to device disposal, is a crucial subject for ensuring their sustainability. Yet, this is still a major challenge [3, 4]. High quality life cycle assessment (LCA) data sets on components, materials and processes based on primary data are still rare, while little published material reveals detailed formulation or processing steps that allow LCA experts to build up inventory data from scratch. Key environmental challenges for each life cycle stage are: (1) contribution to relevant impact categories per component during **production**, (2) impacts caused by device, as well as the equipped product systems during **use**, and (3) dissipation of valuable resources due to a lack of reuse or recycling at the **end-of-life**. To address these challenges, a comprehensive view over all three life cycle phases is required that extends beyond a simple LCA study. Thus, individual findings of the assessment developed in the project include insights into hotspots and key drivers for environmental impacts, as well as benchmarks for

reference, and ultimately support mitigation of environmentally harmful designs of the envisioned product. Moreover, they include an evaluation of impacts PE can have during their use phase directly and indirectly through the equipped product system. Lastly, a wide range of indicators supports understanding material criticality and potential business risks related to sourcing and pricing. Insights into the evaluation principles for environmental sustainability [2] and the influence of design properties of PE on their environmental profile [4] have been published separately.

## **2.4 Patents & competition**

For strategic business orientation, it is important to be familiar with competition, potential alliances, and relevant patents. At the same time, it is becoming increasingly complex for PE as research in academia and industry as well as issued patents proliferated significantly over the last years and applications in various branches can be observed [7]. The overall aim of early-stage patent evaluation is mapping relevant technology trends, solutions, and competition for project ideas. It thus provides strategic knowledge and enables the evaluation of opportunities for initiating technological development and commercialisation of projects.

Without knowing the technical solution that will be applied, a freedom-to-operate (FTO) statement poses a significant challenge. Thus, patent mapping in the scope of LEE-BED aims at more general aspects of intellectual property that are relevant before product development even starts. Initially, industry needs to understand the uniqueness and innovation potential of their own PE idea and know market and competition landscape. This ultimately leads to making fact-based decisions on whether and when to enter a market. For patents and competition, the user questionnaire, technical assessment, as well as individual consulting provides all necessary information. The evaluation follows a simple process including the identification of patent codes (CPC or IPC codes), patents related to PE and the envisioned case, their ranking based on relevance as well as the screening for similar patents based on the latter. Key players (potential competitors or collaborators), competing technologies and IP barriers are an output of this mapping. Details of patent mapping as a service in the context of PE [8] and global trends [7] have been published separately.

## **2.5 Safety**

Particularly when working with nanomaterials required in many ink formulations of PE, safety over the entire life cycle, from production to use and end-of-life, deserves special consideration. Safety and regulatory issues for both material and processes need to be reviewed to determine any potential barriers for technical solutions presented in the technical assessment. Key aspects are case-specific information on health and safety regulations, information on which nano-safety aspects (i.e. toxicology, workplace exposure, and consumer safety) need to be investigated in depth, and comprehensible explanation for industry to understand why certain regulations and issues are relevant for their PE pilot-case. In the framework of the project, a nano-safety screening platform has been developed in order to enable developers and producers of PE to easily find possible regulatory aspects about nanomaterials in any of the steps of the product life cycle. This platform also allows to find physicochemical and toxicological properties of nanomaterials and offers a fast communication way to ask for different nano-safety services.

## **2.6 Funding support**

One major obstacle, in particular for SMEs, is the initial funding of evaluation and prototyping required to deploy novel technologies in their business. This is of central interest

in the case of PE, as SMEs typically do not know if and how benefits through PE can be achieved, while research is often too cost-intensive for them to conduct. Consequently, a support mechanism was set up to help industry apply for funding schemes on regional, national and European level facilitated through a network of involved LEE-BED partners.

### **3 Initiating prototyping and deployment of PE**

After having conducted the full phase 1 assessment, the industrial partners receive a comprehensive overview over the results in the form of a report (“fact-book”). This allows to move forward to prototype manufacturing on several pilot lines within the project, which are optimised for different materials, printing geometries, and lot sizes. At the same time, general findings from the evaluation of PE pilot-cases are continuously shared with material developers and technology experts to support their research. This includes, for example, the development of alternatives to silver nanoparticles within the project [9].

To date, four industrial LEE-BED partners from construction, automotive, label making and crystal manufacturing industries included additional functionality and aesthetics into their products with PE. Conducting the described services hereby provided a foundation for subsequent stages and offered a preview of challenges and opportunities of the assessment concept. Currently, all pilot-cases are moved to LEE-BED phase 2 for prototyping and will receive services for long-term technology deployment in sound business cases in phase 3.

### **4 Conclusion and outlook**

The growing field of printed electronics (PE) and functional materials represents very promising technologies that are still in the process of claiming their place in large-scale industrial applications. There is a variety of reasons for the lack of mass applications so far, mostly based on missing knowledge and certain hesitation because of unpredictable implications and challenges in applying PE. This article presents a framework for evaluation supporting the general topic of sustainability in development and application of PE. To this end, key questions were presented that need to be answered to enable easy access to the technology, and subsequently to pilot line facilities and knowledge building capabilities.

In the scope of LEE-BED project, a service package for the identified key questions was developed including: (1) technical feasibility, (2) economic viability, (3) environmental performance, (4) patents & competition, (5) safety, as well as (6) funding. The services can be sustainability enablers for PE, as they consider pilot-cases holistically and from the beginning of ideation to avoid pitfalls later. This helps selecting and shaping promising business cases and discarding weaker ideas, avoiding the allocation of resources on projects that have no realistic chance of implementation. Simultaneously, it fosters building knowledge and awareness among potential industrial use of PE. The fundamental notion is a fast fail of unpromising ideas and swift restart of ideation, driving both sustainability and technological innovation. Research is still ongoing regarding the transfer of the developed services into business practice and the use of findings to select fitting pilot lines within the open innovation test bed. Results of the project will be continuously updated on the website [www.lee-bed.eu](http://www.lee-bed.eu), where interested parties can get involved through a single entry point.

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