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Sustainability screening in the context of advanced material development for printed electronics☆

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Abstract. Flexible, ultra-light and wafer-thin – the future of electronics is printed! The cornerstones for this development are conductive inks and adhesives that connect components and sensors with each other, integrating them into a printed environment. A decisive role hereby is played by advanced materials, such as functional inks, and their interaction in final devices for application in various use-cases. For this purpose, various particle structures in the nanometre range are created that enable the required conductivity, while keeping material input of the conductive substance as low as possible. Due to the excellent properties, the versatile functionalities, the possible high production volumes and the associated reduced production costs a wide range of applications is facilitated through printed electronics and mass markets become accessible. Therefore, associated environmental impacts as well as the security of the supply chain are expected to gain further relevance in the future. Yet, as most of the processes are in a development stage, prospective assessments before the start of production are essential, if development of printed electronics shall be aligned with sustainability goals. In order to address environmental consequences of future implementations of advanced materials for printed electronics at an early stage, this contribution is considering and evaluating the sustainable effects in a comprehensive assessment even before the physical start of product and material development. To this end, a procedure was developed, in which underlying methodology enables development engineers to identify hotspots at an early stage and to address and mitigate them early on. This way, challenges of tomorrow's circular economy are already being addressed today and critical sustainability pitfalls can be avoided.

Keywords: sustainability screening / printed electronics / design for environment / LCA / life cycle thinking

1 Introduction and goal

Printed electronics is a rapidly growing industrial sector that is progressively claiming its place as a production paradigm for electronic products and devices such as RFID-technology, flexible labels, and many more. A wealth of publications over the last years reinforced this trend, particularly in the field of advanced and functional materials. The cornerstones for the evolution are printable conductive inks and adhesives on flexible or curved substrates. Hereby, a decisive role is played by advanced materials with various particle structures in the nanometre range, enabling required functionalities such as conductivity, while keeping material input of the functional substance as low as possible [1–4].

The versatile functionalities, along with low-cost and high-throughput manufacturing enable a wide range of applications, making mass markets become accessible [5]. Therefore, associated environmental impacts as well as the security of the supply chain are gaining further relevance, which can be expected to continuously grow even further in the future [5]. In order to address environmental consequences of any future implementation of advanced materials and printed electronics at an early stage, this contribution is considering and evaluating the sustainability effects in a comprehensive assessment even before the physical start of product and material development.

The procedure developed for the sustainability screening and the underlying methodology enable stakeholders to identify hotspots at an early development stage and to address them accordingly. This early consideration is a vital aspect for the environmental evaluation of printed electronics, as previously stated by Kunnari et al. [4]. In addition, the results give insights regarding the use-phase

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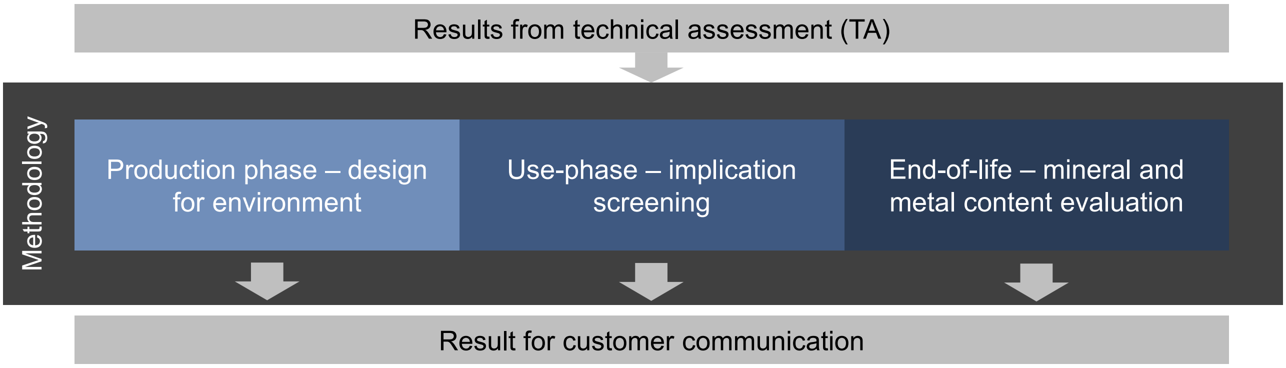

Fig. 1. Workflow of the sustainability screening for printed electronic products (PEP).

and end-of-life phase helping to gain a holistic view over the entire product life cycle.

The specified aim of the presented sustainability screening is to deliver easy understandable and clearly structured results regarding the environmental performance of printed electronic products (PEP) by focusing on the needs and interests of the customers (i.e., people or organisations applying printed electronics) and developers. The overall goal is to calculate a range of environmental impacts and to identify environmental hotspots. Ultimately, the intention is to inform customers about environmental implications of their engagement with printed and embedded electronics on material and device level. Furthermore, the timeline of the sustainability screening assessment is kept as short as possible, while the effort for customers is minimised.

The above mentioned general goals are a result of discussions and feedback from customers and engineers and are directly addressed over the entire life cycle of printed and embedded electronics from production and use-phase to the end-of-life of the device through specific parts of the developed sustainability screening assessment [5]. All of this is important to enable easy access to environmental consideration even for non-experts in the field of sustainability analysis.

2 Workflow of the sustainability screening

The production is assessed quantitatively by using a design for environment approach, before the use-phase is addressed through an implication screening, and finally the end-of-life is evaluated based on involved resources. All of these assessments are highly dependent on data provided by the customer and the preceding technical assessment. In any case, missing or incomplete data significantly hampers the quality of the sustainability screening outcomes.

The sustainability screening is one part of the phase 1 assessment developed in the publicly funded EU Horizon 2020 project LEE-BED. Figure 1 shows the developed workflow to address all the goals of the individual life cycle phases.

The workflow starts with the results from a technical assessment (TA) conducted in the initial phase. The term "technical assessment (TA)" in this publication refers to the process of systematically evaluating if in principle an idea can be realised through printed electronics, what the technical risks are, and what the production of materials or devices could look like. Theoretically this can be performed by the customer, but it is much more likely to be executed by experts in the field of advanced materials for printed electronics.

The TA is based on data transfer between customers and design engineers resulting in the user requirement specifications (URS), and a preliminary bill of materials (Pre-Bom). The URS hereby is a comprehensive data collection sheet, which contains questions to the customer to collect necessary information to run the foreseen assessments. The Pre-Bom can be seen as a first initial draft of a bill of material, which is most likely adapted before moving into production, yet already contains all required functionalities and types of materials. In the progress of PEP development, it is likely to be adapted.

The URS and Pre-Bom are transferred to the sustainability screening, as well as to other assessments in the project, evaluating ideas from the perspective of economics, safety and compliance, and intellectual property. The combination of these different perspectives enables a holistic assessment of PEP. Each assessment generates results for direct customer communication, where the main outcome is summarised and highlighted. The methodology and the results of sustainability screening in context of advanced material development for printed electronics is described in the following. The other assessments are not discussed further in this publication.

3 Methodology

In accordance with the overall goal of the sustainability screening, the three life cycle phases (1) production, (2) use-phase and (3) end-of-life form the structure of the entire assessment. The underlying assessment methodologies are described in the following.

Production phase – for making informed strategic decisions, the quantification of environmental impacts and the determination of environmental hotspots is of utmost importance. A big lever for increasing the product sustainability is during production; a design for environment approach based on LCA methodology is conducted with a unique set of primary data stemming from the project partners.

Use-phase – sustainability potentials exist for printed and embedded electronics during the use-phase. Yet, there are some applications that do not have a positive effect on the system they are embedded in, or even negatively influence their environmental profile. Therefore, identification of environmental implications by combining printed electronic products and their auxiliary systems with further product systems are screened in a qualitative fashion for the use-phase.

End-of-life – the use of valuable raw materials in printed and embedded electronics is considered a major challenge and closed-loop approaches are deemed indispensable for achieving product sustainability. Therefore, the developed evaluation includes a section on determining the content of minerals and metals in the printed electronic product and evaluates it regarding standardised methodologies.

The subsequent chapters are dedicated to one of these life cycle phase and are each subdivided into two parts: a general part and a customer part. This approach was selected to reduce time and effort required for the assessment of each use-case, while simultaneously maintaining high quality and meaningful results, accelerating the implementation of customer ideas. The general part describes the elements that have been developed for the assessment in a generic form and can be applied to each use-case without or with only minor adaptations. The customer part on the other hand describes the individual content that needs to be created specifically for each customer and each use-case. This data is collected by a developed data collection sheet (URS) Further a bill of material and technical description is necessary to guarantee sufficient background information on possible materials and manufacturing of the envisioned PEP.

4 Assessment of the production phase – design for environment

Firstly, the production of the printed electronic product (PEP) is evaluated with a design for environment view. The first chapter in this section explains the underlying methodology of design for environment; the second chapter describes the steps in accordance to the sustainability screening.

4.1 Underlying methodology

Design for environment in the scope of the developed sustainability screening is conducted by using the methodology of life cycle assessment (LCA). Similar concepts have been called "prospective" or "predictive" LCA by other authors before. To emphasise the goal of the assessment (i.e., enhancing environmentally sustainable design of PE), the authors chose to use the term "design for environment". An LCA is an ISO 14040 [6] and ISO 14044 [7] standardised method to assess the environmental impacts of products, processes and services along their value chain. LCA supports decision makers and engineers in addressing environmental aspects in their decisions, or during the development or improvement of processes and products. Furthermore, LCA results can be used to increase the efficiency of technologies and existing production routes, to support political decision-making processes, and marketing strategies. An LCA according to the relevant standards is performed in four stages: stage 1 – goal and scope definition; stage 2 – life cycle inventory; stage 3 – life cycle impact assessment; stage 4 – interpretation.

The workflow of the four stages is based on the ISO standards. Both parts general and the customer are integrated to support a time-efficient and straightforward approach. Generally applicable text blocks and templates for tables and figures are used to reduce time and effort wherever possible. In the customer part, these are further refined and adapted to the specific situation, whereas in the general part changes are only made if absolutely necessary. Subsequently, the four stages are described in more detail.

4.2 Stage 1 – goal and scope definition

As mentioned above, goal and scope form the basis for each LCA. The goal should be clearly defined and matched with the scope. The subsequent Figure 2 shows the workflow for goal and scope definition within the developed sustainability assessment in detail, subdivided into general and customer parts.

4.2.1 Goal definition

The first step, the goal definition, is identical for each use-case and data from the technical assessment is used. The intended application, the reason for conducting the study, and the target group are described. This is done by using LEE-BED project data and data provided by the customer. Due to the similar interest of customers and engineers for all sustainability-related questions on printed electronics, the goal forms a general part as following:

Goal of the assessment is the quantification of environmental impacts of the printed electronic product (PEP) and the determination of environmental hotspots. Furthermore, a simplified and understandable communication to non-experts in both areas, life cycle assessment (LCA) and printed electronics.

This information is interesting for the customer to get an overview of the environmental performance of the PEP and a rough estimate on its quantified impact. For engineers and developers the hotspot analysis is used to help substituting relevant materials whenever possible and/or to reduce the environmental impacts of production. This creates a better understanding of the impacts of integrating embedded electronics.

4.2.2 Scope definition

The second step is the scope definition. Hereby, for any use-case the system boundary (cf. Fig. 3) and the impact categories are identical. On the other hand, functional unit as well as limitations of the results are customer specific, as they depend on the specific use-case investigated. Data from TA is merged with predefined text blocks to create the assessment outcome.

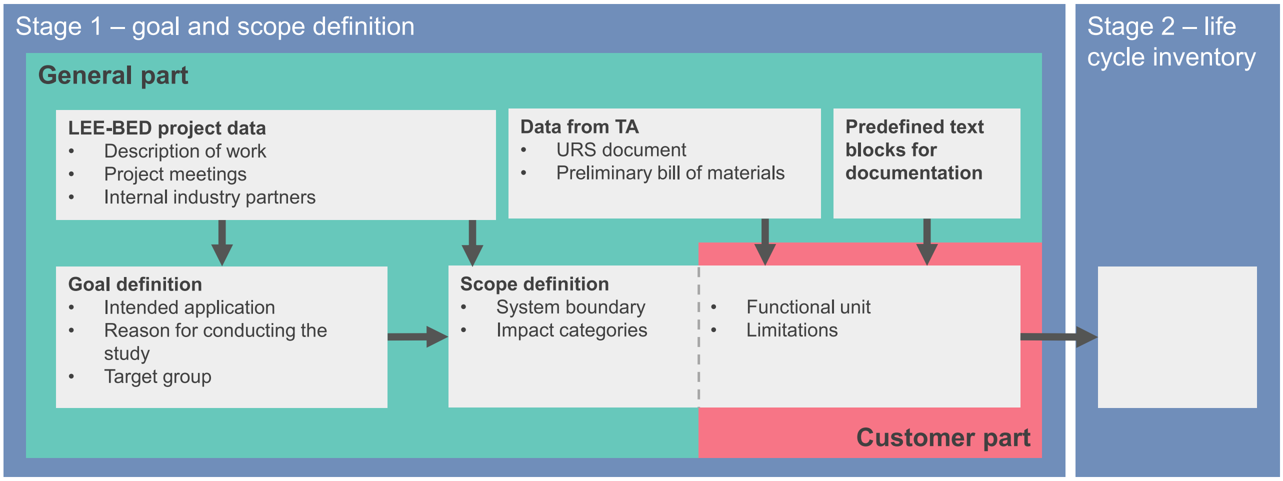

Fig. 2. Workflow of design for environment stage 1 – goal and scope definition.

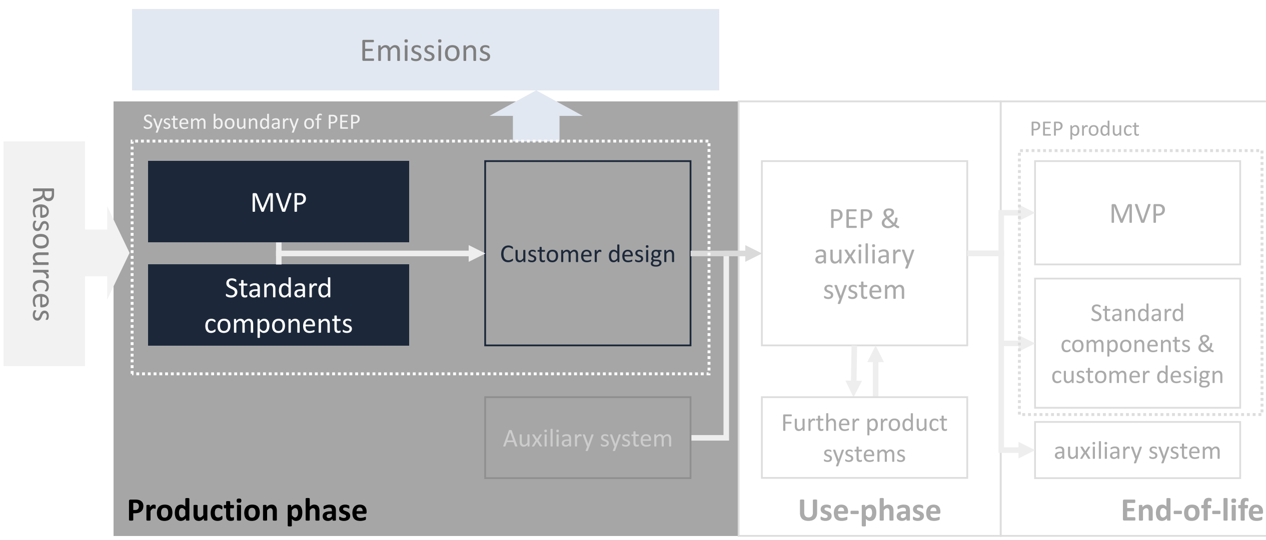

Fig. 3. System boundary for design for environment of printed electronic products (PEP).

The printed electronic product (PEP) system boundary mandatory involves the minimum viable product (MVP) and the standard components, as well as optionally the customer design. The minimum viable product (MVP) in this publication refers to a PEP development stage that includes all required functionalities of a customer idea and serves as the baseline for the sustainability screening. Although final device might be differing regarding some specifications, the MVP is considered a robust starting point as it enables early on environmental evaluation of PEP. The customer design is included if LCA data from the customer is available and can be used to give an estimate on the ratio between existing product (customer design) and the other parts (MVP and standard components). The auxiliary system is not part of the assessment.

The evaluated impact categories are defined generally for the sustainability screening for comparability of results. The environmental performance of the product is described by using the environmental footprint (EF3.0) methodology recommended by the European Commission [8] for the following relevant impact categories:

– Climate change [kg CO_2 eq] – due to relevance of greenhouse gas emissions in view of current climate goals of the European Union;
– Resource use – minerals and metals [kg Sb eq] – due to relevance of raw materials used for printed electronics and components and the desire to reduce the demand of critical and rare elements.

The reference unit for each sustainability screening is customer specific and is defined based on input data from technical assessment and customer. Typically, this unit is defined as 1 piece of PEP, but in some cases it might be more practical to refer to the mass of the PEP, e.g., in g of PEP.

The data quality for the design for environment approach is subject to certain limitations, e.g., the technological, geographical, and temporal coverage is

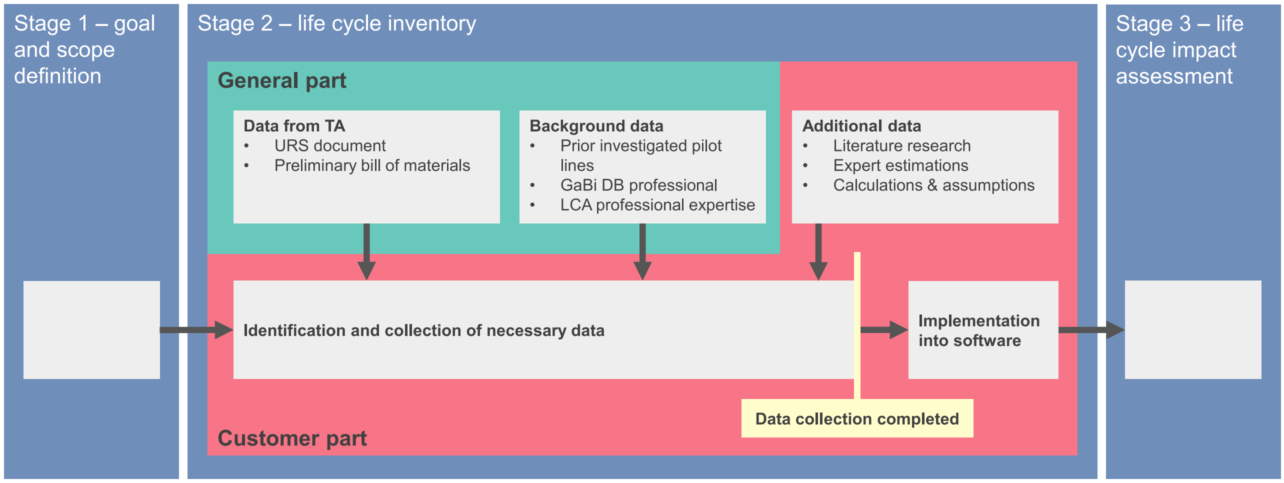

Fig. 4. Workflow of design for environment stage 2 – life cycle inventory.

limited to a defined scope. Therefore, all results should only be used to identify hotspots and optimise the production of PEP from an environmental perspective, not for comparative studies with other technologies.

4.3 Stage 2 – life cycle inventory (LCI)

The second stage of the LCA is the life cycle inventory (LCI). Main task is the identification and collection of necessary data. In general this a time intensive process and a clear structure and approach is essential to reduce time and effort while guaranteeing high quality results. Figure 4 illustrates the life cycle inventory workflow in more detail, subdivided into the parts general and customer.

The identification of necessary data as well as the collection is customer specific. Necessary data is identified based on information from stage 1 – goal and scope definition as well as data from TA, including URS and Pre-Bom. This data is necessary to determine and quantify components and materials used for the production of PEP and consequently the associated environmental impacts.

For the quantification of these impacts, materials and components are matched with data from previously investigated pilot lines, GaBi life cycle engineering database [9] and LCA professional expertise. For remaining data gaps, literature research, calculations, expert estimations and assumptions can be used. This hierarchical approach ensures that data is always acquired at the highest confidentiality level resulting in the lowest possible uncertainty.

4.4 Stage 3 – life cycle impact assessment (LCIA)

The third stage of the LCA is the life cycle impact assessment. Figure 5 shows the workflow and the general and customer part.

The steps classification, characterisation and result calculation are general parts and run automatically after implementation into the software. Only the completeness check is customer specific. In the completeness check it is verified, that a characterisation factor exists for all assessed materials in both evaluated impact categories. If no characterisation factor is defined in the EF3.0 methodology, the material will not be assessed and a respective disclaimer will be included.

Classification means the summarisation of emissions according to their contribution to the impact categories climate change and resource use – minerals and metals. Within the completeness check it will be verified, if each emission or resource (elementary flow) has an impact and a scale factor to the reference substance. Especially regarding the impact category resource use – minerals and metals is this important and has to be checked carefully. Next step is the characterisation, each elementary flow, which influences the impact category, has a scaling factor to the reference substance. Result calculation is done by multiplying amount of elementary flow with scale factor and sum up the results. Those results are transferred to stage 4 – interpretation.

4.5 Stage 4 – interpretation

The fourth stage of the LCA is the interpretation of the results. Figure 6 shows the workflow with general and customer part.

The results are transferred from stage 3 – life cycle impact assessment to stage 4. The first step is the integration and visualisation of the results. The format of the figures and tables are predefined to reduce the required effort. The integration of the results and final visualisation check are customer specific as well as the description and discussion of the results. This is done by using predefined text blocks and suggestions for descriptions from the ISO 14044 [7]. This basis is then used for the discussion of the results. Hot spots and findings will be determined and the figures, tables, parts of the description and discussion are transferred to the customer. The general part result integration and visualisation using predefined figures and templates. For hotspot visualisation a pie chart is used. The quantified impact is given as range (minimum to maximum).

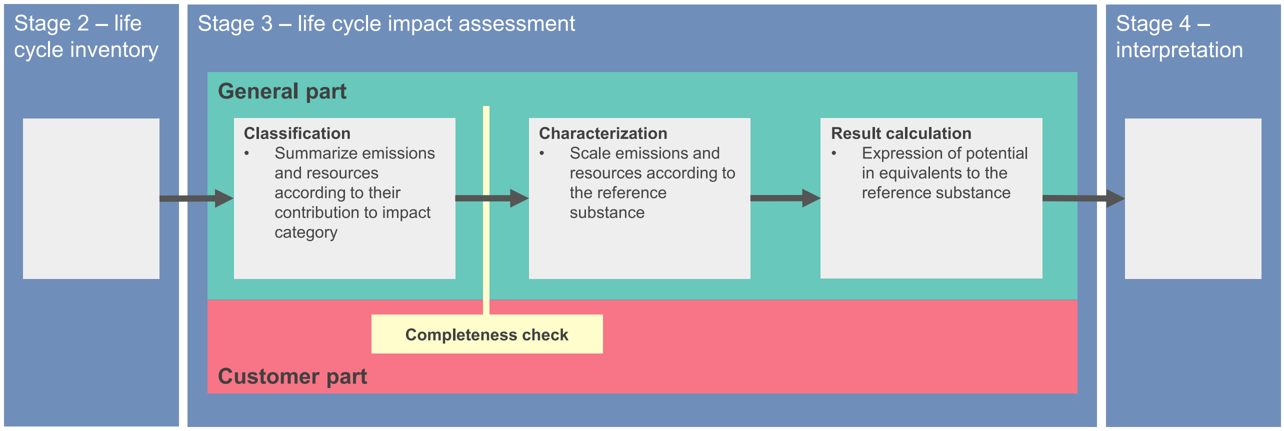

Fig. 5. Workflow of design for environment stage 3 – life cycle impact assessment.

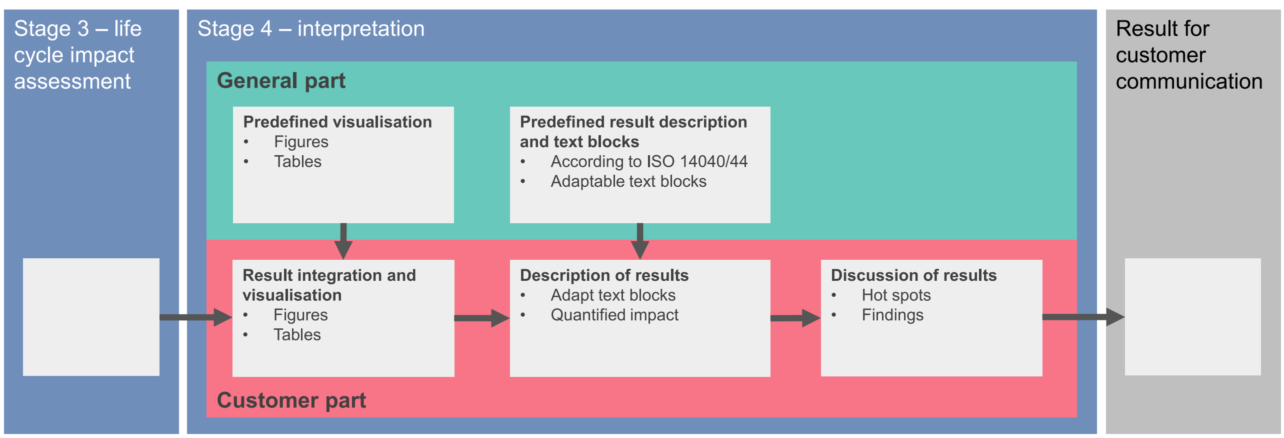

Fig. 6. Workflow of design for environment stage 4 – interpretation.

Table 1. Terminology of DIN EN ISO 14040 and 14044 combined with dependency level for customer communication.

Ranking	Contribution (%)	Dependency level
Most important, significant influence	> 50	Very high
Very important, relevant influence	25–50	High
Fairly important, some influence	10–25	Medium
Little important, minor influence	2.5–10	Low
Not important, negligible influence	< 2.5	Very low

To address the dependency of the overall system environmental impacts on the contribution from one material or component, the terminology of ISO 14040 [6] and 14044 [7] is used (Tab. 1).

5 Assessment of the use-phase – implication screening

For the use-phase, the environmental implications and influence of the printed electronic product (PEP), in combination with the auxiliary system, on further product systems which they will be integrated and briefly discussed. Figure 7 shows the considered systems in the use-phases.

Figure 8 shows the workflow of the implication screening subdivided into general and customer part.

First step is the identification of possible environmental implications from combining PEP and auxiliary system and their interactions with further product systems. The customer only needs to provide very little necessary information. This can be realised for example by filling in tick boxes in a questionnaire as illustrated in Table 2. LCA professional expertise is used to review and evaluate the implications based on this information, while findings are based on predefined text blocks giving general insights on the possible influence executed by the PEP.

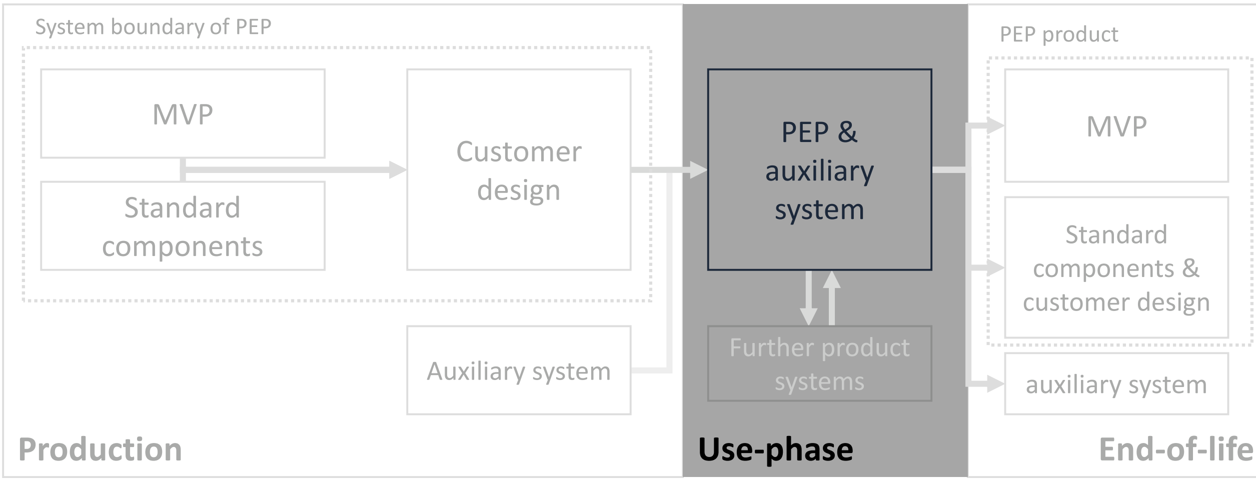

Fig. 7. Use-phase and its systems printed electronic product (PEP) and auxiliary system.

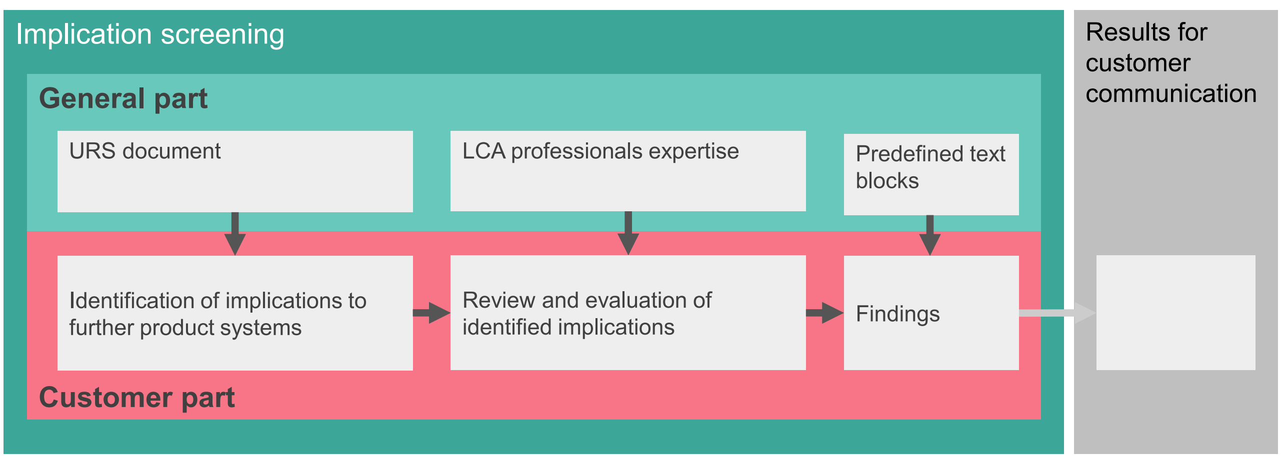

Fig. 8. Workflow of implication screening.

Table 2. Identification of the implication of the customer's idea/product to other systems.

Influence on...	Reduction	No impact	Increase	Unpredictable
Energy demand	☐	☐	☐	☐
Material demand	☐	☐	☐	☐
Transport	☐	☐	☐	☐

The implications to the further product systems regarding energy demand, material demand and transport are addressed as these are deemed the most relevant. The customer is asked to estimate if their idea/product is likely to reduce or increase the material and energy demand or the required transport. Transport hereby refers to efforts for logistics, i.e., mass or volume transported per distance. It is also possible, that no impact to the systems is expected or that the impact is unpredictable at the time the questionnaire is answered. Based on the insights, predefined text blocks are adapted and integrated into the results for customer communication to give a short and precise input to the customer regarding influence and relevance of each of the considered aspects.

6 Assessment of the end-of-life – mineral and metal content evaluation

The goal of the qualitative analysis is to investigate and evaluate the importance and the attractiveness of material recycling for minerals and metals in PEP as they are considered the probably most relevant sustainability challenge in printed and embedded electronics [10,11].

In this chapter, firstly the underlying methodologies are explained, before the required data and the combination and application of the methodologies is described.

6.1 Underlying methodology for mineral and metal content evaluation

The end-of-life assessment is based on a group of relevant indicators that have been established by other authors and institutions before. The combination of them aims at a holistic view on all aspects relevant for minerals and metals in PEP. The selected metrics are briefly explained below.

"Cut-off grade" is the minimum concentration required in order for a mineral or metal to be economically mined (or processed) and it is used for a comparison against mineral and metal concentrations in the investigated PEP. Concentrations above this grade can be considered as ore, while concentrations below this grade are considered as waste for disposal. The cut-off grade changes as the economic environment develops with regard to metal prices and mining costs, and is therefore constantly changing.

"Resource use – minerals and metals" is used to assess resource depletion in LCA. It is an EF3.0 impact category recommended by the Joint Research Center of the European Union [8]. The model behind the impact category is the Abiotic Resource Depletion, "ultimate reserves" version, described in van Oers et al. (2002) [12], based on the methods of Guinée et al. (2002) [13]. It is quantified in kg of antimony equivalent (kg Sb eq).

The "average mineral and metal price" is used to assess the economic perspective of material recycling. The indicator in the scope of this assessment is defined as the price average of the last 5 years. Additionally, the maximum positive and negative deviation from the average could be used as an additional information for expressing the volatility of the price in this period. The data can be sourced, e.g., from stock exchange places.

The "weighted country risk (WCR)" indicator is used to describe the accessibility of raw materials. The WCR is the sum of the amount of reserves in a country multiplied with the country risk index (CRI) divided through the amount of reserves. The CRI is the average of six indicators from the Worldwide Governance Indicators (WGI), a research dataset summarising the views on the quality of governance. It is provided by a large number of enterprise, citizen and expert survey respondents in industrial and developing countries. The result of each assessment describes the governance performance from weak (−2.5) to strong (2.5). Values above 0.5 are classified as low, values between +0.5 and −0.5 are classified as moderate and values below −0.5 are classified as critical risk. Details on the underlying data sources and the methodology can be found in the WGI methodology paper "The Worldwide Governance Indicators: A Summary of Methodology, Data and Analytical Issues" [14].

The "Herfindahl–Hirschman Index (HHI)" is a commonly accepted measure of market concentration. The HHI is calculated by squaring the market share of each enterprise competing in the market and then summing the resulting numbers. It takes into account the relative size distribution of the firms in a market. The value approaches zero when a market is occupied by a large number of enterprises of relatively equal size and reaches its maximum of 10 000 points when a market is controlled by a single firm. If the HHI is lower than 1500 the market is low concentrated, if it is between 1500 and 2500 points the market is moderately concentrated, and if the value is above 2500 the market is highly concentrated [15].

The "static range" is calculated by dividing the amount of worldwide reserves of a mineral or metal by the annual mine production. The static range therefore reflects the time period left, until the investigated mineral or metal will be fully mined under the assumption that the current mining remains unchanged (= static). The calculation is based on the most recent commodity summaries published annually by the U.S. Geological Survey (USGS) [16].

The "EU list of critical raw materials" is used additionally to lists critical raw materials according to their supply risk and potential impact on the European economy. The list is published every three years since 2011 by the European Commission and the current version for 2020 is used in the assessment and updated versions can be integrated in the future [17].

6.2 Mineral and metal content evaluation

In this chapter the underlying methodologies are used to determine and emphasise of minerals and metals contained in the MVP. Figure 9 shows the workflow separated in general and customer part. Hereby, the goal was not to create a single-score result but rather provide the set of investigated numbers individually. In the opinion of the authors this more detailed perspective is useful for developers of PEP, an assumption that seems reasonable after first discussions with partners involved in development or deployment of PEP.

Starting point is the identification and quantification of the minerals and metals in the MVP by using data from life cycle inventory. Next step is the combination of the quantified minerals and metals with the background data. The results are visualised, described and discussed by using predefined templates and text blocks. Hereby, the scope of the assessment is mainly dependent on data availability. Figure 10 shows the end-of-life subdivided in the systems MVP, standard components & customer design, and auxiliary system.

The three systems of the end-of-life (cf. Fig. 10) are considered in different detail. The main focus lies on the MVP as the system specifically developed with and for printed electronic technologies. The mass volume of minerals and metals involved in its system and the mass volume of the entire system is needed for the evaluation. Optional information ("nice to have") are the mass volume of minerals and metals in the systems' standard components & customer design and, if available, in the auxiliary system. This is considered less crucial, as the development within LEE-BED is focussed on the MVP and less possibilities for adaptation exist in the other systems. However, these elements of the PEP application might turn

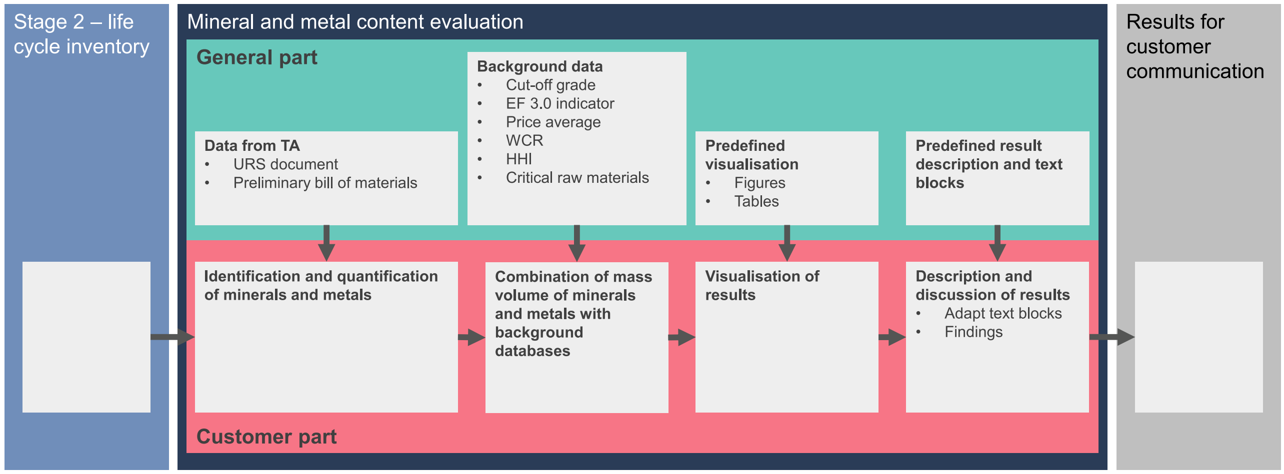

Fig. 9. Workflow of mineral and metal content evaluation for printed electronic products (PEP).

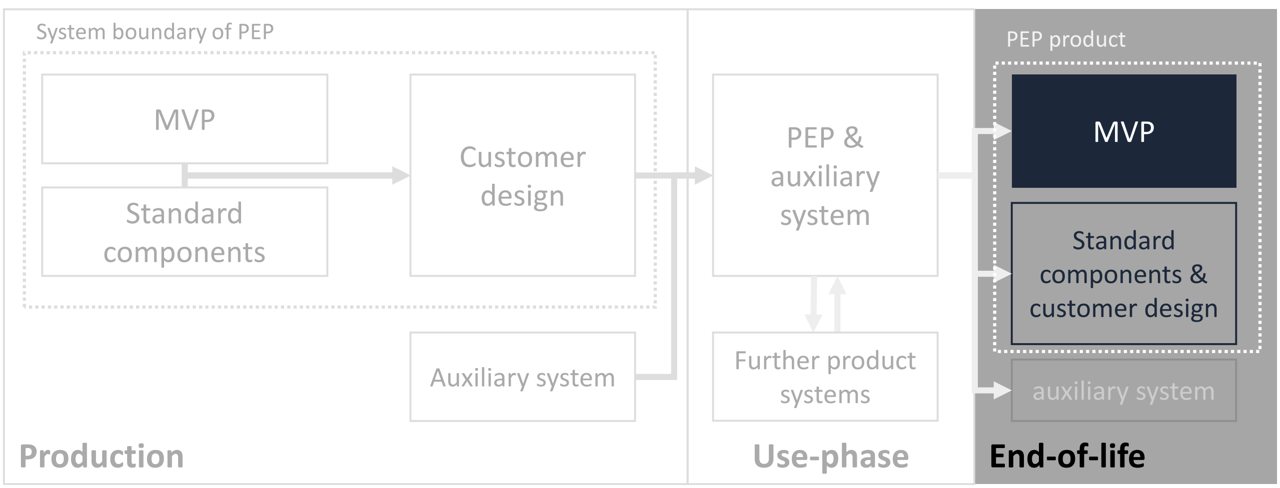

Fig. 10. System boundaries for different systems at the end-of-life.

out to be the most environmentally harmful contributors within the use-case. Therefore, it is paramount to reflect findings from the assessment with the system boundary in mind.

Next step is the data collection for the identified minerals and metals and the combination with the known masses. As mentioned in the underlying methodology section, the data for the identified minerals and metals regarding cut-off grade, resource use – minerals and metals, price, weighted country risk (WCR), the Herfindahl–Hirschman Index (HHI), static range, and the EU list of critical raw materials are publicly available and often even updated in regular time spans. After data collection from the background databases, some of the indicators need to be scaled to mass. Thus, the mass volume is multiplied with resource use – minerals and metals, and the price average. The Weighted Country Risk and the Herfindahl–Hirschman Index are dimensionless, so the mass volume has no influence to both categories.

The visualisation of results can be done by using a standardised template (cf. Tab. 3), which determines the attractiveness of each mineral and metal for material recycling by merging different perspectives like concentration, cut-off grade, resource depletion, accessibility, market concentration, price and criticality. A colour code can be used to indicate hotspots within the matrix, which seem particularly helpful if the amount of relevant minerals or metals is large.

From a resource perspective aiming at a circular economy, it makes sense, to try to recycle all minerals and metals. Yet sometimes a decision between one and the other has to be made, which mineral or metal should be focused. The results of the sustainability screening could then be used as decision support for identifying prioritised materials for immediate action. The different result categories enable engineers to determine the most valuable mineral or metal. This could be used for strategic material decisions during product development as well as future development of recycling technologies. It is noteworthy that the result is strictly addressed to one specific use-case as the weighting by mass for some of the indicators distorts the results.

It has been observed before that often the scarcity of resources is neglected in early product development stages, while it should be more focused. Therefore, the obtained insights from the end-of-life should be taken back to the

Table 3. Template for result table for evaluating attractiveness of recycling of each mineral and metal used in MVP.

Mineral or metal								
Content in system	Concentration in system	Cut-off grade	Resource use – minerals and metals	Total price (based on average)	Accessibility – WCR	Market concentration – HHI	Static range	EU list of critical raw materials
[mg]	[%]	[%]	[kg Sb eq]	[€]	[–]	[–]	[a]	[yes/no]

production in a rigorous design for environment approach aiming at the least environmental harmful solution for PEP.

7 Summary and outlook

The publication at hand describes the background, methodology and results of a sustainability screening assessment for printed electronic products (PEP) and advanced materials, which was developed as part of the phase 1 assessments within the European research project LEE-BED. Fundamentally, the authors support the idea that the sustainability of printed electronics cannot be evaluated for the technology as a whole but needs to be assessed in connection to materials, manufacturing technologies and, most importantly, the specific use-cases and applications.

Throughout the document two major parts are presented: a general part, including all content that has been developed independently of the investigated use-cases, and a customer part that needs to be adapted for each conducted assessment. The goal of this approach is a highly automated generic assessment offer that is tailored to the needs of customers in the field of printed and embedded electronics and can be conducted swiftly at low effort from customer and assessment provider. Therefore, the share of customer parts is reduced as far as possible.

The developed sustainability screening assessment consists of three parts over the entire life cycle of PEP products:

– **Production: design for environment**

For the production phase, a design for environment approach according the international standards ISO 14040 and ISO 14044 for life cycle assessment is used to quantify environmental impacts regarding the categories climate change and resource use – minerals and metals and to identify all relevant hotspots.

– **Use-phase: implication screening**

For the use-phase, environmental implications and influence of the PEP in combination with the auxiliary system, which they will be integrated in, and interactions to further product systems are briefly discussed.

– **End-of-life: mineral and metal content evaluation**

At the end-of-life, the attractiveness for material recycling of each mineral and metal contained in the product is investigated by merging different perspectives like concentration, resource depletion, accessibility, market concentration and price. This part of the evaluation aims at identifying interesting mineral and metal contained in the considered system.

With the developed assessment, an exhaustive view on the sustainability and environmental aspects can be provided quickly at low effort. This can be seen as a crucial first involvement with the sustainability of individual PEP applications. However, the results of the presented assessment can only be a starting point for environmental and sustainability considerations regarding PEP. Thus, the authors recommend conducting an additional ex-post life cycle assessment according to the relevant ISO 14040 and ISO 14044 standards as soon as the final product specifications and a final bill of materials (BoM) is available to gain an even deeper understanding. Most useful seems to be a regular update of the presented sustainability screening whenever specifications of the investigated product change. In this case, additional data is expected to continuously narrow down uncertainties and result in more precise results until a full LCA can be conducted.

The project is currently still in the processing phase. Internal pilot cases are currently being carried out and will be published later in the course of the project.

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