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Executive Summary

The use of information and communication technologies has been steadily increasing over the past decades and is expected to continue growing in the future. While IoT technology and other IT sectors can improve energy and material efficiency, thereby reducing greenhouse gas emissions in the sectors where they are applied, it is important to ensure that their production and use do not contribute to increased emissions. The current electronics industry has notable direct and indirect environmental impacts, such as significant energy consumption during manufacturing, high demand for critical raw materials (CRMs), and the generation of electric and electronic waste (e-waste).

To address these challenges, it is crucial to not only evaluate the lifecycle of electronic products but also to innovate towards more sustainable manufacturing and recycling processes. Efforts must be directed at reducing the dependency on critical raw materials by identifying alternatives or improving resource recovery from e-waste. Advancements in design and technology, play an essential role in mitigating these environmental pressures.

Studying the environmental impacts caused by different IoT technologies and developing alternatives with lower impacts are among the main objectives of the SUPERIOT project. This deliverable presents an updated version of *D1.3 Methodologies for Sustainability (1)*, which originally introduced various methods for analyzing environmental impacts, along with potential environmental impacts associated with technology production and use.

This deliverable evaluates the climate impacts of manufacturing methods for microelectronics systems, comparing a baseline system with printed components developed in the project. Life Cycle Assessment (LCA) results show that transitioning from traditional microelectronics to printed electronics yields only minor differences in most environmental categories, with printed electronics showing slight improvements in areas such as freshwater eutrophication and human toxicity (cancer), but potentially higher impacts in land use and fossil resource consumption. Specific manufacturing processes can strongly influence these outcomes. Benchmarking against a LiPo battery system revealed similar overall impacts, though the battery system performed better in certain categories.

The overall environmental single scores for all systems studied are similar due to impact weighting, which reduces the influence of categories with large absolute differences. Sensitivity analyses indicated that switching to renewable electricity for printed electronics manufacturing can significantly lower climate impacts, though each energy source has its own trade-offs, such as increased metal demand and potential toxicity from wind power infrastructure or water consumption from hydropower. Solar energy also offers greenhouse gas reductions but presents challenges in ozone depletion and resource extraction.

Limitations in the LCA include data gaps, reliance on multiple databases, use of proxy data, and uncertainties related to electricity mixes and device specifications. These factors affect the accuracy and comparability of results. Future research should ensure systems are functionally comparable, improve data consistency and availability, and consider real manufacturing conditions to enhance the reliability of LCA findings. Attention should also be paid to end-of-life options for printed electronics, focusing on recycling processes, material recovery, and eco-design principles to facilitate dismantling and reduce hazardous substances.

Importantly, the functional lifespan of printed electronics must be considered, as shorter lifespans could offset sustainability gains by increasing resource use and waste through more frequent replacements. Future studies should incorporate durability assessments to fully understand environmental trade-offs, ensuring sustainability evaluations reflect real-world scenarios and support the development of robust, long-lasting printed technologies.

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1 Acronyms

CO₂	Carbon dioxide
CO_{2e} / CO_{2eq.}	Carbon dioxide equivalent
CRM	Critical Raw Material
ETNO	European Telecommunications Network Operators' Association
GHG	Greenhouse Gas
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
KEPI	Key Environmental Performance Indicators
LCA	Life Cycle Assessment
LCD	Liquid-Crystal Display
LCSA	Life Cycle Sustainability Assessment
LiPo	Lithium Polymer
MADM	Multi-Attribute Decision Making
OPV	Organic photovoltaic
PEF	Product Environmental Footprint
PWB	Printed Wiring Board
RER	Rest of Europe
SC	Supercapacitor
SDG	Sustainable Development Goal
SNS JU	Smart Networks and Services Joint Undertaking
SUPERIOT	Truly Sustainable Printed Electronics-based IoT Combining Optical and Radio Wireless Technologies
TFT	Thin-film transistor
TPI	Toxic Potential Indicator
UN	United Nations
WEF	World Economic Forum

2 Introduction

The goal of keeping global warming below 1.5 degrees requires very deep cuts in anthropogenic greenhouse gas emissions within the next decades. Despite the limitations in greenhouse gas (GHG) emissions set by different countries, emissions are constantly growing. According to the Intergovernmental Panel on Climate Change (IPCC), with the present growth rate, global temperature is expected to increase by 2.4-3.5 degrees Celsius by the year 2100 in comparison to the pre-industrial times [1]. In addition to climate change, biodiversity loss has been recognized as a major environmental problem during the past decade by several actors, for example in the Sustainable Development Goals (SDGs) [3] of the United Nations (UN). While it is enhanced by climate change¹, there are also many other factors affecting it.

The significance of information and communication technologies has been consistently on the rise over the past decades, with expectations for continued growth in the future. Mobile communications can be argued to have become the basis of the connected world, not just in Europe but also globally. Mobile communications were initially developed for personal communications, and today, after a few decades since their inception, there are more than seven billion subscribers to mobile services worldwide. In recent years, there has been a growing interest in providing connectivity to other entities than users, such as computers, machines, and vehicles. The ultimate connectivity frontier is defined by the paradigm of the Internet of Things (IoT), aimed at virtually connecting any object. IoT can be seen as the final connectivity challenge, as billions and even up to trillions of entities could be connected. According to an estimate made by the European Telecommunications Network Operators' Association (ETNO), there were approximately 204 million active IoT connections in Europe in 2021 [4]. These are estimated to grow to 370 million in 2024, and further to 770 million by 2030 [4]. The proliferation of IoT devices is expected to be significant, particularly in the automotive and smart building sectors, with anticipated growth across various other industries.

Sustainable development was first introduced in a report by the Brundtland Commission of the UN in the late 1980s. The subsequent crucial milestone is the Rio de Janeiro meeting in 1992 where it was agreed that the concept of sustainable development is an attainable goal for people worldwide. Since the beginning, sustainable development has been regarded as a combination of the three sides of sustainability: environmental, economic and social. Presently the sustainable development goals that are typically raised by different actors, including companies, are the Sustainable Development Goals (SDGs) set within the UN in the 2030 Agenda for Sustainable Development. These goals were adopted by all the member states of the United Nations in 2015 along with the 2030 Agenda for Sustainable Development.

6G is widely being developed across the globe, and the driving forces behind the development of this upcoming technology are not only advanced technical capabilities and high performance but also sustainability. In general, energy issues are the dominant topics considered when considering sustainability of wireless communication systems. Energy is a highly relevant aspect of the sustainability equation, but other factors need to be considered as well. This is the approach followed by SUPERIOT. Creating a fully sustainable wireless communication network is a colossal, if not impossible, task given the intricacies of the existing networks (e.g., cellular networks and smart phones), and the current state-of-the-art of technology. Nevertheless, owing to its typically limited performance, simpler requirements, and reduced complexity, IoT presents itself as the perfect technology to be developed holistically in a sustainable manner. Implementing and demonstrating a sustainable IoT system will serve as an inspiring example setting the stage for other technologies to pursue similar objectives. Several forecasts predict that the number of IoT devices in the next decade will be in the order of tens or even hundreds of billions. One can just imagine the amount of energy and material needed to manufacture these billions of nodes. Moreover, the disposal of billions of nodes as electronic waste at the end

¹ Climate change affects biodiversity e.g. by changes in temperature that affect the environmental conditions and thereby the living conditions for different species. For more information, see e.g. [2].

of their life cycle is a concerning reality. These issues have been among the motivating factors of the SUPERIOT project.

While IoT technology as well as other IT sectors, such as mobile technologies, can enhance energy efficiency and material efficiency, and thereby reduce environmental impacts in the sectors applying them, it is important to ensure that their production and use inadvertently contribute to increased emissions. The present electronics industry poses significant direct and indirect environmental impacts, such as large energy consumption during manufacturing, great demand for critical raw materials (CRMs)², and production of electric and electronic waste (e-waste) (e.g. [5], please also refer to Section 4.2).

In their paper published in Science in 2019, Hittinger and Jaramillo [6] discussed the different and complex impacts IoT may have on energy consumption. The smart functionality achieved through IoT in an appliance may allow it to operate more efficiently and save energy, for instance, by automatically adjusting lighting or initiating energy-saving modes when occupants leave their home. However, the IoT also has remote energy use through wireless data communication, sensing and processing. Furthermore, IoT applications have additive material, energy and processing requirements in comparison to non-smart alternatives [6].

Studying the environmental impacts caused by different IoT technologies and developing alternatives with lower impacts are among the main objectives of the SUPERIOT project as well. The purpose of this report is to introduce different methods available for analysing environmental impacts together with some of the potential environmental impacts related to technology production and use. Finally, results from the life cycle assessment (LCA) conducted in the project are presented.

² Critical raw materials are mineral and metal resources that are essential to the economy and whose supply can be disrupted. Different actors have provided lists of minerals that define as critical.

3 Methods for sustainability assessment

3.1 Review of different methods for (environmental) sustainability assessment

Over the past decades, several methods have been developed to analyse the environmental sustainability of products or systems. Development of methods for assessing environmental impacts was particularly active in the 1990s and the first decade of 2000. During recent years, interest has increasingly been on life cycle assessment (LCA), and indicators based on LCA, such as carbon footprint or embodied energy.

In the following subsection, some of the developed methods / tools that focus on electronics are introduced, and their potential applicability in the SUPERIOT project is analysed. While some are based only on a single or a few indicators, others are very wide, aiming to analyse all environmental impacts, or even all sustainability impacts. In order to cover the different sides of sustainability, different tools have been developed, such as the multi-attribute decision making tools (MADM) [7]. The application of these on IoT applications has so far been limited, as the technologies are fairly recent [8]. As LCA and life cycle sustainability assessment (LCSA) have received such a large use during the past decades, they are presented separately in Section 3.2.

3.1.1 Earlier sustainability assessment methods

Park et al. 2005

One interesting example of an earlier method is the environmental assessment method based on combination of top-down and bottom-up approaches developed by Park et al. [9]. In the method, they propose a combination of LCA as a top-down method, and bottom-up approaches, enabling one to identify how and what to improve, and quantifying the eco-design aspects of a product. They present the method's applicability in consumer electronics development, more precisely mobile phones.

The method consists of five different modules that are marked with letters from A to E:

- A life cycle thinking of a product.
- B Environmental benchmarking
- C Checklist method
- D Ecodesign strategies
- E Environmental checklist information

In the first part, i.e. A, the key life cycle stage causing large environmental impact is identified. After this, environmental benchmarking is carried out. In part C, targets are set for the factors listed in environmental benchmarking. In the next part (part D) eco-design strategies are set for the product analysed. Finally, in part E, environmental design information is produced by linking both the top-down and bottom-up information. As the authors argue, their method can be seen as an effective and cost-efficient method allowing producers to identify potential environmental weaknesses of the product under development, and to develop corresponding eco-design strategies. This method shares similarities to the Greentool method developed by Hakola et al. [5] presented in Section 3.1.2.

Singhal et al. 2004

Another example of an earlier method is the Key Environmental Performance Indicators (KEPIs) approach proposed by Singhal et al. [10]. It has been developed by considering a designer who aims to reduce the environmental impacts of a product but has limited resources and understanding of the environmental terms. The indicators can be used for setting internal guidelines, and for benchmarking, monitoring, and improving environmental performance. They are also intended to be user-friendly, requiring minimum data and time for calculation.

Several points were considered when developing the indicators:

- Indicators have a scientific basis
- They are mutually exclusive and collectively exhaustive in considering the life cycle environmental impacts
- Easy to use and to understand
- They require little time and costs for calculations
- Give reliable results.
- Applicable in all geographic regions
- Easy to extend to other electronic products
- Provide clear-cut guidelines to the designers and require no interpolation from the environmental impacts.

To develop the indicators, first LCA perspective and legal perspective were applied. LCA was applied to identify the main factors that influence the products' life cycle environmental performance. The aim of the LCA was to identify those parts that cause most of the environmental impacts of the product type under assessment. For the indicators, it was then assumed that similar products cause their main environmental impacts through similar processes. The legal perspective was applied to identify those environmentally significant materials in the phone that account for its embedded toxicity. Finally, after identifying potential indicators, they were also tested for a desktop PC and notebook PC, and these were again assessed against results of LCAs conducted for the same products.

Finally, the KEPIs suggested for production phase were the following: amount of precious metals (specifically gold), total area of printed wiring board (PWB), areas of fabricated dies, amount of bromine, area of the liquid-crystal display (LCD), amount of solder paste, amount of copper used in charger and its cables. For transportation phase the proposed indicator was the number of components in the phone, and for use phase the proposed indicator was the standby power consumption of the charger.

3.1.2 Recently presented sustainability assessment methods

Chang & Lu 2014 [11]

In their paper, Chang and Lu present the software tool *EcoCAD*, which they have developed to be used for Design for environment (DfE). The purpose of the tool is to assist designers in reducing the time spent on complex environmental evaluations. Furthermore, the aim is to aid producers in developing products that can be more easily disassembled and have lower material toxicity. For analysing toxicity of the materials, they developed toxic potential indicators (TPIs) using a method from the Fraunhofer IZM. Information was taken from material safety data-sheet databases in order to develop the indicators for common industrial materials. In addition to these, they also developed toxicity indicators for printed circuit boards and some more generic electric / electronic components.

Simple structure of a product usually also makes it easier to disassemble. Chang and Lu pointed out that a component is usually simpler to remove from a product if it has fewer other components around it. This is one of the indicators on which the assessment of disassembly is built in the *EcoCAD*. The model is presented thoroughly in their paper. After introducing the concept and application of the method, it is applied on an MP3 player to demonstrate its practicality. Even though the *EcoCAD* is only used for the analysis of toxicity of materials and ease of disassembly, it could apparently be applied also for other environmental impacts. The authors suggest that it could also be combined with LCA databases to study for example climate or acidific impacts of different materials.

Bai et al. 2020

Industry 4.0 technologies concept emerged in the beginning of the 2010s decade [12]. It covers emergent and disruptive intelligence and information technologies, include for example additive manufacturing technologies, artificial intelligence, big data and analytics, block-chain, cloud

computing, IoT and simulation technologies [12]. IoT is an important part of many of these technologies. In addition, industrial IoT is present as a separate technology. As pointed out by Hittinger and Jaramillo [6], IoT technologies can provide direct energy savings, and other environmental benefits as well. However, the overall impacts of their production and use needs to be assessed in order to determine whether the anticipated benefits are really achieved [6][8]. For such an analysis, Bai et al. presented a framework based on the United Nations Sustainable Development Goals³ thereby covering all the three dimensions of sustainability (environmental, economic and social sustainability). In addition, they developed a multi-situation decision method that integrates hesitant fuzzy set, cumulative prospect theory and VIKOR⁴. They then test the methods using secondary information provided by the World Economic Forum (WEF).

The analysis presented by Bai et al. is very wide and covers all the three sides of sustainability [8]. Yet, it is based on the secondary data collected from WEF. Furthermore, even though the decision-making methods are valuable, they are always partly based on qualitative data.

Hakola et al. 2023 [5]

The GreenTool developed by Hakola et al. [5], aims to provide a streamlined and holistic tool for sustainability assessment of the different printed electronics products to support their design and development. In the GreenTool, different aspects related to sustainability are listed to provide a product designer with limited previous knowledge on the issue, an understanding of what aspects should be considered. It is a qualitative tool for analysing the sustainability of electronics. its effectiveness lies in presenting diverse sustainability aspects to a product developer, who may not be deeply familiar with these aspects.

A further strength of the GreenTool could be argued to lie in its wide-focus and its simplicity. The method can be applied to various aspects of sustainability on a simple way. There is an increasing pressure for companies and product developers to improve their sustainability performance. Yet, the analysis is often very time-consuming and requires thorough expertise. GreenTool gives a quite simplified qualitative framework for the analysis of the relevant sustainability indicators. Through this approach it can give the user insights into the issues that seem the most significant for the product and that require further analysis. Yet, as also pointed out by the authors of the paper, more comparisons are required to support its adaptability for other electronic concepts beyond the smart label study case presented in the paper.

3.2 Life Cycle Assessment (LCA) as a method

3.2.1 Introduction

LCA is a tool for quantitatively and systematically evaluating the potential environmental impacts of a product or system throughout its whole life cycle. As LCA concentrates on all the inflows and outflows of substances, and the impacts they generate within a certain system, it provides a means to identify effective policy options. It can also be argued to be a tool to support decision-making and to avoid a narrow view of environmental problems. Such knowledge also reduces the risk of problem shifting, i.e., situations where an improvement in one part of the life cycle leads to weakening in another time or place.

LCA originates from methods developed as early as in the 1960s primarily focusing on energy production. It was extended to a more comprehensive environmental analysis in the 1970s and to a full life-cycle impact assessment method in the 1980s and 1990s [14]. Its use started to grow in the 1990s and the first decade of the 2000s, becoming a widely used methodology over the past 15-20 years. LCA has also been extended to life cycle sustainability assessment (LCSA) covering also life cycle costing and social life cycle assessment (e.g. [15]). LCA has primarily been applied to assess the life cycle impacts of products or services but it has increasingly been applied also for the assessment of technologies or regions (e.g.[16][17][18]).

³ <https://sdgs.un.org/goals>

⁴ VIKOR method refers to a multi-criteria decision-making model originally developed by Serafim Opricovic [13].

There are different standards on LCA giving guidelines on how it should be calculated. These standards include, among others, the ISO standards 14040, 14044 which form the basics of LCA, and the carbon footprint standard 14067⁵. Over the past decade, LCA has also received an important role in EU policy. In the EU Renewable energy directive, and LCA-based method is used for calculating the GHG emissions of the biofuel or bioenergy used. In addition, several other more detailed guidelines and tools on LCA exist. These include the GHG Protocol Product Standard of the Greenhouse Gas Protocol and the Product environmental footprint (PEF) guidance of the EU.

The assessed life cycle is not limited to single years and may often span over national borders. Typically, an LCA covers the life cycle of a product from 'cradle to grave' but it can also be limited to a certain part of the life cycle, for instance the use phase.

3.2.2 Application of LCA to IoT solutions

As mentioned earlier, LCA has seen extensive and widespread usage. In the following, a couple of examples on how it has been applied on IoT applications are briefly reviewed. Chiew and Brunklaus [19] analyzed in their report, how the use of IoT for route optimization and placement planning for increased operational efficiency in municipal waste management would affect environmental impacts of waste management (mainly GHG emissions). In their assessment, they first estimated the environmental impacts of the IoT system and the environmental impacts of the waste collection system using LCA. Then the life-cycle environmental impacts of the current waste management system were compared to a potential future waste collection system, which also included the IoT system. Based on their results, the future waste collection system needs to have at least 32% reduction in transport kilometres, or the number of trash bags needs to be reduced by 50 bins of the total of 160 bins to outweigh the extra CO₂-eq. caused by the IoT system.

Pirson and Bol [20] developed a parametric framework based on hardware profiles to evaluate carbon footprints of IoT edge devices⁶. They applied this framework to four use cases to assess their carbon footprints. Through their analysis, they showed that there is large heterogeneity between different IoT devices. It is evident that this needs to be analyzed when examining different IoT technologies. In addition, they predicted the potential global GHG emissions as a result of IoT technologies over a 10-year period, i.e. 2017-2027. They found that it could range between 22-562 MtCO₂-eq./year in 2027. From this, they concluded that environmental constraints must be considered when designing and using IoT edge services.

⁵ ISO:14040:2006+A1:2020 (Environmental management. Life cycle assessment. Principles and framework); ISO:14044:2006 + A2:2020 (Environmental management. Life cycle assessment. Requirements and guidelines); ISO 14067:2018 (Carbon footprint of products. Requirements and guidelines for quantification).

⁶ As pointed out earlier, carbon footprint refers to the climate impacts calculated with an LCA method.

4 Aspects of sustainability concerning IoT

4.1 Sustainable substrates

Use of plastic has grown exponentially over the past 60 years and over half of all the plastics produced have been manufactured during the past 15 years [21]. Plastic materials have become the main component in many applications. For example, most of the encapsulation materials are typically plastics. While plastics are highly applicable and useful materials for various applications, problems related to them have also been increasingly recognised. One major problem concerning plastics is the waste plastics dumped in nature which eventually break down into microplastics in the oceans. As a result of this, regulation on single-use plastics have been established within the EU but also other regions.

Over the last decade, interest in bio-based plastics, and plastics made of recycled material has been growing, and various technologies have been developed [22][23]. These materials can substitute fossil-based plastics, thereby promoting the use of environmentally sustainable and safe alternatives. Yet, even if they are biodegradable, they often require industrial-scale plants to achieve that. Furthermore, not all bio-based plastics are biodegradable. Their production also typically entails large material and energy inputs, which contrary to expectations, can result in larger carbon footprint than producing fossil-based plastics (Figure 1).

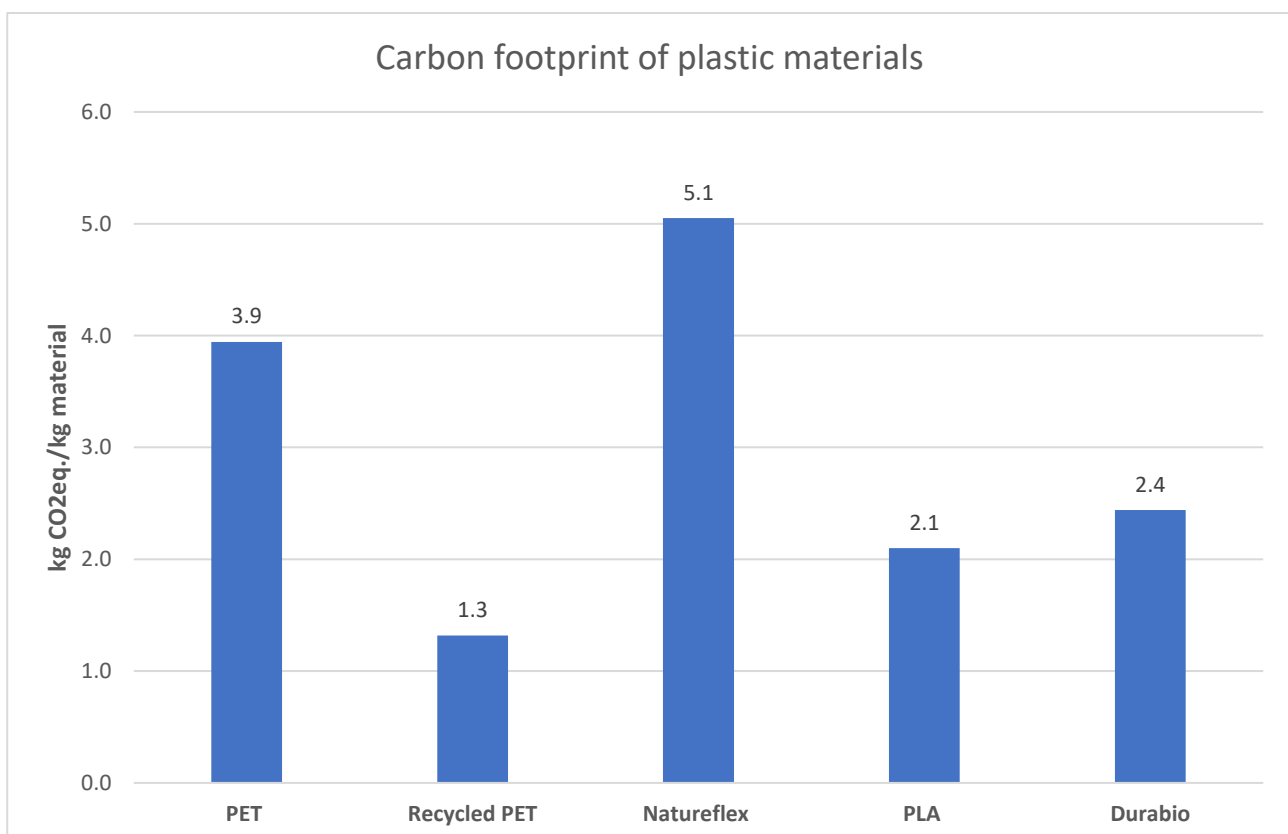


Figure 1. Comparison of the carbon footprint of fossil-based PET to some bio-based plastic materials and recycled PET (Data retrieved from [23][24][25][26][27][28][29]).

Furthermore, the use of bio-based substrates can, in many cases, be considered to enhance circular economy and contribute to the reduction of emissions provided the resources used are sufficiently available. In additions, sensors [30], antennas [31], other integrated electronics [32], and many other devices [33] have been printed on thin and flexible substrates, which can be recyclable or even biodegradable. Currently, advanced technologies are available that enable the substitution of traditional FR4-based printed circuit boards (PCB) with alternatives utilizing

plastic or paper substrates. These changes can lead to significant improvements in climate change impacts (Figure 2).

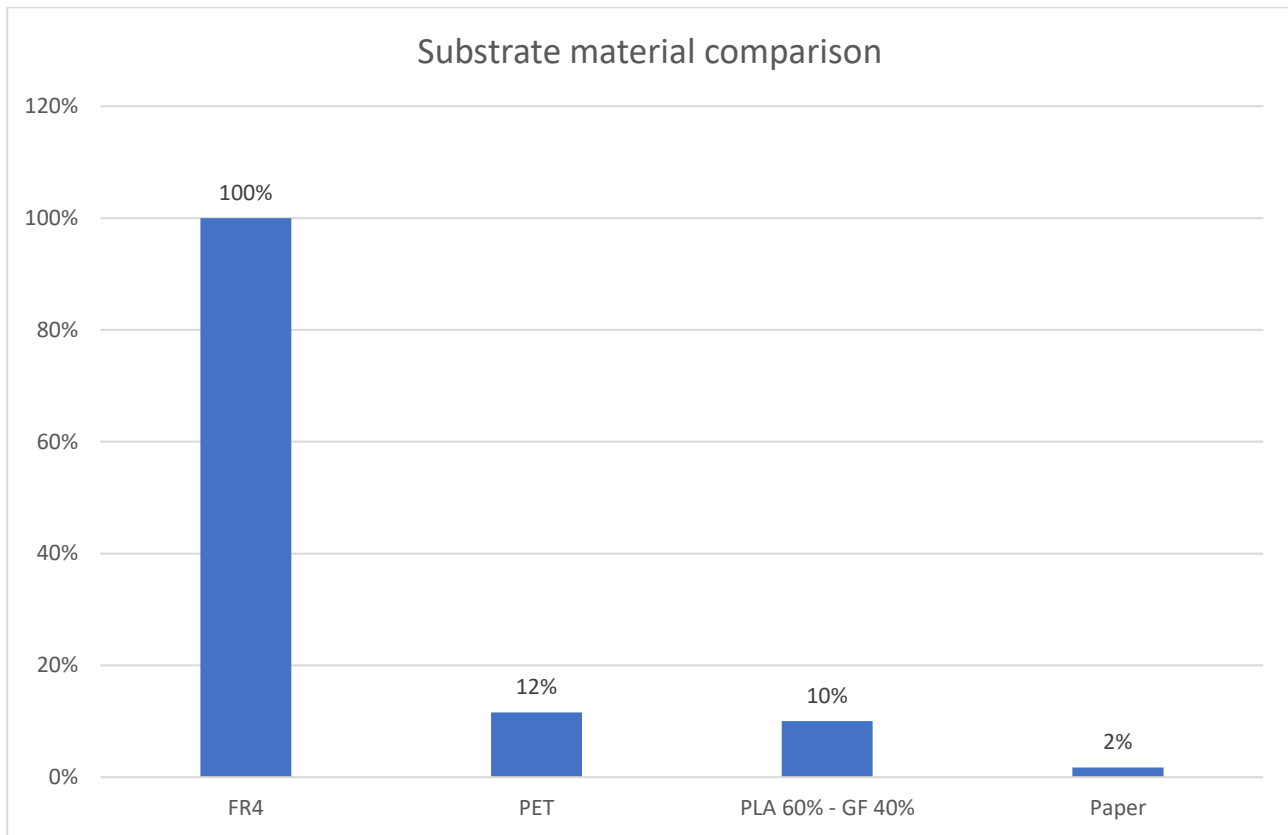


Figure 2. Carbon footprint reduction potential using plastic and paper-based substrates. Adopted from [34].

Traditional PCB is based on an FR4 board. Changing the substrate to plastic or paper alternatives can potentially decrease the climate impacts of PCBs by 98%. [34].

4.2 Use and replacement of critical minerals

Sustainable use of material resources requires consideration of the whole life cycle of the resource used. One important aspect there is the sufficiency of the resources used. As the use of electronics is increasing fast, the consumption of many critical raw materials is also growing fast. From a consumption perspective, the more gadgets the world is using, the more devices and more energy, especially off-grid energy, it will need.

As pointed out in the previous section, Internet of Things (IoT) has become an important element in our present technology driven world. However, in many cases the materials do not end up in well-organized waste management. Efficient material recycling and sufficient product lifetime typically do not occur. Furthermore, even if recycling works effectively, the predicted growth of resource consumption in many sectors, perhaps most importantly battery technologies and solar panels, is so high that there is a large risk of resource availability becoming a limitation for the growth of wireless devices. For that reason, there is a growing need for new, alternative technologies not reliant on critical resources. Here, the demonstrators of the SUPERIOT project play a very promising role.

The relationship between IoT technologies and critical minerals has not yet been studied much. Ku [35] conducted an analysis of the potential impact on the materials availability of two IoT case study products in the data storage sector. According to the results, potential market problems might develop with Germanium, Tellurium and Neodymium supply chains. Yet, the availability of substitutes indicates that the market disruption may well be limited [35].

Increased demand for resources requires more efficient utilization of resources following the principles of circular economy. More precisely, this entails the use of environmentally sustainable materials and product flows prioritizing sustainability over merely aiming for low cost.

4.3 Greener solvents in printed electronics

It is undeniable that the e-waste pile that keeps on growing every year represents an ecological threat. As described so far, a lot of efforts have been made when it comes to reducing the environmental impact of technologies by using biodegradable or recyclable substrates for device production. The same can be said regarding use of non-critical raw materials and sustainable alternatives. However, when considering device manufacturing, i.e., during the printing process, the use of harsh chemicals is not always properly addressed. Inks for printed electronics usually depend on harsh and toxic chemicals, such as silver-chlorides.

Besides being harmful for the environment when considering large-scale production, device printing is not often conducted in controlled environments. Therefore, workers can also be exposed to toxic chemicals. There has been a push towards the development of water-based inks for a set of printing coating methods. For instance, Franco et al, developed a graphene-based water ink for the screen printing of temperature and deformation sensors [36]. Similar work was reported by Overgaard et al [37]. Although water is the golden standard for ink formulations, due to its high viscosity it may as well pose some problems, like in the case of ink-jet printing, such as on how easily it moves during the printing. Additionally, as water-based inks are composed of polymers to stabilize the active materials, there is inevitably a loss in terms of electrical conductivity. Moreover, temperature curing of the samples could be needed to remove the polymers.

Therefore, greener organic solvents are also being extensively studied for ink formulation, such as Cyrene (Dihydrolevoglucosenone), Rhodiasolv® PolarClean and Rhodiasolv® IRIS (Dimethyl 2-Methylglutarate). Despite being developed for other chemical processes, it was discovered that they exhibit properties similar to those of NMP (N-Methyl-2-pyrrolidone). This chemical has been considered for years as the best solvent for graphene and other two-dimensional materials processing and stabilization [38]. However, due to its toxicity, the large-scale production of 2D materials has been considerably pushed back. The new green solvents, represent a game change in the development of nanomaterials inks [39][40]. Tkachev et al, have already developed spray coated touch sensors based on graphene exfoliated in Cyrene [41]. Similar studies have also been done in SUPERIOT-project ([42][43]).

3D-printed electronics are also possible using bio-renewable solvents such as cyrene and glycerol carbonate [44]. Moreover, the evaluation of green solvents for printed electronics can be performed using an open-source algorithm [45].

5 SUPERIOT sustainability approach

This section introduces the holistic sustainability approach used throughout the SUPERIOT project⁷. The holistic approach considers sustainability aspects in all the stages of the system's life cycle, including the system development, implementation, use and end of life stages. Four principles are defined for each life cycle stage, namely: 1) Sustainable by Design, 2) Sustainable by Implementation, 3) Sustainable by Usage and 4) Sustainable Disposal.

Figure 3 depicts the sustainability approach used by the project. Even though all these principles are important, the roles of design for sustainability and implementation for sustainability are fundamental. Clearly, these principles need to be considered proactively.

One of the promising research paths explored by the SUPERIOT project is the use of printed electronics technologies to implement the IoT nodes. The project will investigate, develop and demonstrate that IoT nodes can be based on the use of printed electronics technology, including the use of sustainable substrates, inks and printed electronic components.

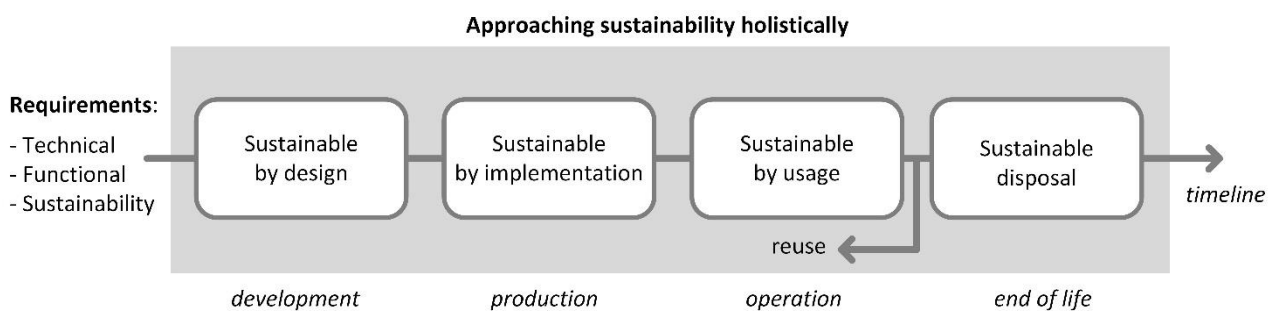


Figure 3. The holistic sustainability approach advocated by SUPERIOT.

At the design phase of the communication system, other relevant sustainability-related techniques will be followed, including the use of very low-power electronics, energy efficient communication protocols and resource allocation algorithms, wake-up modes, etc. The design phase is closely related to the implementation phase when considering the use of printed components. The availability of printed components, their technical specifications as well as their limitations need to be well known at the design phase. The reconfigurability of the nodes and network, as defined in the SUPERIOT concept, is also part of the design process. Another approach investigated by the project is the possibility of using a sustainable component partition in the implementation of the IoT nodes. Some of the developed IoT nodes are implemented in a hybrid fashion, namely combining printed and silicon-based components. If these components are distributed on the substrate following only basic design rules, the components will be spatially mixed. At the end of the life of the IoT node, separating these components for further disposal will be time and labour consuming, and hence, quite likely such an environmentally friendly disposal will not be economically attractive. However, if the components can be spatially separated, as suggested by Figure 4, removing and disposing components could result in an appealing solution. As shown in Figure 4, printed components are grouped on the left side of the IoT node board while Si-based components are on the right side. The substrate could be pre-marked, and thus the board could be simply divided into two parts after the device is no longer in use. Of course, the proposed partition is not trivial, as there could be certain dependencies between components of different technologies, for instance. These need to be solved case by case.

⁷ All three aspects of sustainability (environmental, economic and social) are considered on an overall level, but the actual assessment focuses on environmental sustainability.

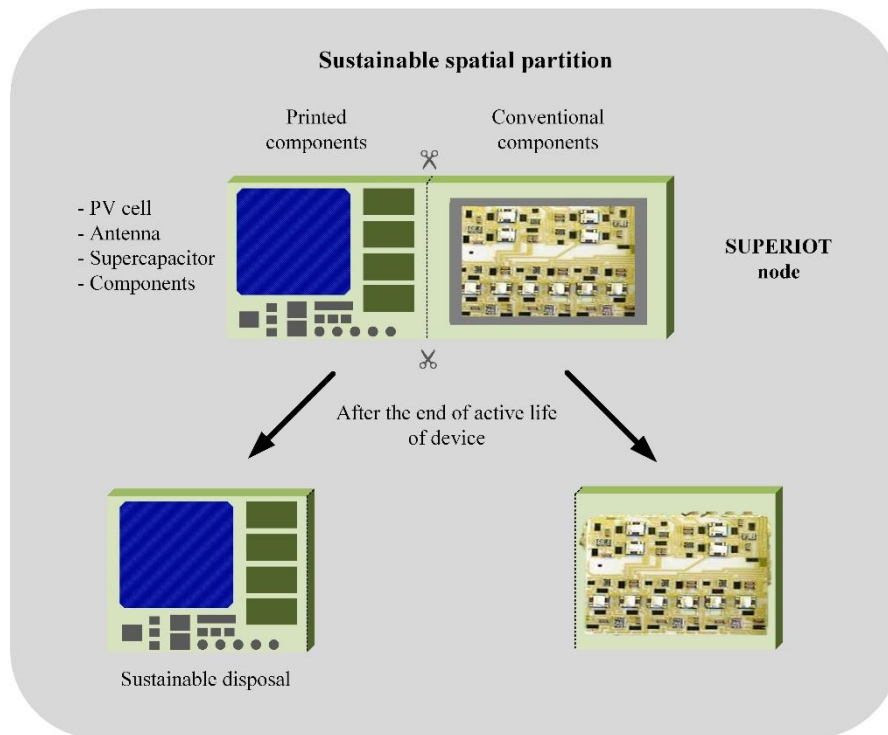


Figure 4. A sustainable partition of the IoT board.

As an example of how to analyse sustainability, let us consider the reconfigurable intelligent surface (RIS) technology, addressed by SUPERIOT Demonstrator 4 (Large area IoT node). We can analyse how the proposed holistic approach to sustainability is followed at all 4 levels (design, implementation, use and disposal) (see Figure 5):

Sustainability by design	
Multi-mode communications :	light- and radio-based wireless connectivity <i>performance, adaptability, flexibility, energy efficiency, infrastructure reuse</i>
Multi-mode energy harvesting :	light- and radio based <i>energy autonomy, reliability</i>
Multi-mode positioning :	light- and radio-based <i>robustness, accuracy</i>
Reconfigurability :	at node and network levels <i>adaptability, flexibility, repurposability, security, reliability</i>
Sustainable implementation	printed electronics technology (node)
Sustainable use	smart energy harvesting and management, batteryless IoT nodes, reconfigurability
Sustainable disposal	printed electronics technology (node)

Figure 5. Mapping SUPERIOT technical features and advantages (italic) to the holistic sustainability principles.

Sustainable by design: the general concept of RIS as a relay node in wireless communications networks intends to optimise the energy consumption of wireless networks as a whole and therefore can be seen as a sustainable approach to the design of wireless networks. At the design stage we also focus on the use of techniques that allow to reduce the power consumption of the RIS, namely the usage of non-volatile memristor switches, allowing for the scale-up of the RIS design to large areas (while avoiding power spending for maintaining static configurations). Additionally, the design of a transparent RIS allows for its employment in front of solar cells without degrading its efficiency, allowing for a more efficient utilization of the physical space occupied by the RIS, e.g. in building facades.

Sustainable by implementation: the use of printed electronics techniques for the manufacturing of the whole RIS, especially considering inks produced with non-toxic solvents as well as printed electronics implementation based on additive manufacturing techniques are generally more sustainable than subtractive manufacturing, as well as low temperature processes which are typically less energy consuming and effective, can ensure the implementation of sustainability.

Sustainable by usage: the re-use of the same physical space for both RIS and solar cells also accentuates its sustainable usage, allowing for better electromagnetic performance of the environment (and therefore energy savings through the RIS relay functionality) as well as energy generation and storage (through the solar cells).

Sustainable disposal: The usage of recycled substrates such as recycled PET ensures that the RIS material is suitable for being recycled at the end of life.

6 Environmental sustainability assessment study

The sustainability analysis focuses on environmental sustainability aspects. The main method used is LCA which is introduced in Section 3.2. In the study, LCA covered process-specific inputs and outputs, including both materials and energy.

6.1 Goal and scope

Goal of the study was to compare a baseline microelectronics system with selected printed components developed in the project to find out the climate impacts of both manufacturing methods. The study was based on materials and process energy consumption. Impact assessment was done using Product Environmental Footprint (PEF) version 3.1 impact assessment methodology recommended by EU commission [46]. All 16 impact categories were assessed.

Three case studies based on the project Demos were chosen for the analysis:

1. Baseline microelectronics system (The combination of solar cell, supercapacitor and power management are benchmarked against battery).
2. Hybrid system, where organic photovoltaic (OPV) solar cell and supercapacitor (SC) of the baseline system, are replaced with printed options available from WP2.
3. Almost fully printed system, where printed TFT available from WP2 is included in the hybrid system. PCB substrate is FR4 even though in demo 3, other options were envisaged.

The systems studied were modelled using two LCA softwares. LCA for Experts⁸ with its integrated databases and SULCA⁹ together with ecoinvent 3.11 database.

6.2 System boundaries

Each case study was analysed using cradle to gate system boundary. Therefore, the scope of the analysis included all processes from raw material acquisition up to, and including, component assembly, contingent on data availability. Usage and end of life stages were left out but they are briefly discussed in section 7.

For the baseline system, raw material acquisition for component manufacturing, manufacturing energy and auxiliaries were considered in the LCI-datasets.

For printed OPV, raw material production for the needed substances was considered but not the energy demand of substance manufacturing as no data was available. OPV printing energy was also considered.

For the printed supercapacitor's raw materials, chemical substances were considered but there was no energy data for substance manufacturing. The energy consumption associated with SC printing and ink manufacturing was considered.

The datasets utilized and modelling assumptions made are discussed further in section 6.3.

6.3 Life cycle inventory

The hybrid node designed by UOULU, as illustrated in Figure 6, was used as a baseline for the LCA comparison. It consists of five modules: e-ink display, solar cell, supercapacitor, power management unit, and node core. Following a comprehensive literature review ([47][48][49][50]), it was discovered that data on e-ink display production is not readily available and e-ink displays are often modelled as LCD displays. The same assumption was used

⁸ Sphera LCA FE version 10.9.3.0. <https://sphera.com/solutions/product-stewardship/life-cycle-assessment-software-and-data/> (formerly GaBi)

⁹ SULCA LCA software version 5.3.4 <https://www.semantum.fi/products/SULCA/>

in this study. The solar cell was made from a-Si and the supercapacitor had an activated carbon anode and cathode. Material and energy data for SMD supercapacitor manufacturing was taken from [51]. Power management and node core bill of materials for components were received from UOULU. Best available data from both Sphera and ecoinvent databases were used. Selected LCI datasets are listed in Table 1 and Table 2.



Figure 6. Baseline microelectronics system from UOULU.

Table 1. LCI data used to model the energy carrier PCB. Data sources are either Sphera database or ecoinvent 3.11 database.

Primary category	Dataset name	Source
Capacitors	Capacitor ceramic MLCC base metals (size accordingly 1206, 0603 or 0402)	Sphera
Capacitors, IND-SMD	Capacitor ceramic MLCC base metals (size accordingly 1206, 0603 or 0402)	Sphera
Chrystals/oscillators, resonators	Oscillator chrystal 500 mg	Sphera
Connectors/FFC, FPC	GLO: Connector IC single-row (2 g, 10 pins, gold plated)	Sphera
Connectors/USB connectors	GLO: Connector USB micro-AB THT/SMD 5-pin socket (260mg) 7.5x5.0x2.5mm Sphera	Sphera
Diodes/schottky diodes	Diode signal SOD123/323/523 (9.26mg) 2.4x1.6x1 with Au-Bondwire	Sphera
Inductors/coils/transformers	Coil miniature wound SDR0302	Sphera
Inductors/coils/transformers	Coil multilayer chip 0402	Sphera
Optoelectronics/photodiode	electronic component production, active, unspecified	ecoinvent
Optoelectronics/infrared LED emitters	LED SMD low-efficiency max 50mA (35mg) without Au	Sphera
Optoelectronics/Infrared remote receiver (IRM)	IC DFN 10 (22.3 mg) 3x3 mm CMOS logic (14 nm node)	Sphera
Optoelectronics/LED indication discrete	LED SMD low-efficiency max 50mA (35 mg) without Au	Sphera
Power management (PMIC)/Battery management	battery management system production, for Li-ion battery	ecoinvent

Power management (PMIC)/Power distribution switches	electronic component production, passive, unspecified	ecoinvent
Resistors	Resistor thick film flat chip 0603 (2.1mg)	Sphera
RF and wireless/RF Transceiver ICs	GLO: IC QFN 76 (578.8 mg) 10x11 mm CMOS logic (14 nm node)	Sphera
RF and wireless/RFID ICs	GLO: IC TSSOP 16 (59mg) 4.4x5.0 mm DRAM (57 nm node)	Sphera
Sensors/temperature and humidity sensor	IC LGA 1366 (ca. 5g) 45x42.5x ca. 2.5 CMOS logic (14 nm node)	Sphera
Transistors/thyristors/MOSFETS	Transistor signal SOT23 3 leads (10mg) 1.4x3x1	Sphera
e-ink display Outline dimension: 29.2mm × 59.2mm × 1.05mm	Liquid Crystal Display (LCD), Panel Assembly LED TFT, mixed TN-IPS technology (mobile phone), in sqm	Sphera
FR4 TG155 empty 70x76,99mm 4-layer	Printed Wiring Board 4-layer rigid FR4 with HASL finish (Subtractive method)	Sphera
solder paste	Solder paste SnAg3Cu0.5 (SAC-Lot)	Sphera

Table 2. LCI data used to model the node core. Data sources are either Sphera database, ecoinvent 3.11 database or literature.

Primary category	Secondary category	Dataset name	Source
Capacitors	Multilayer ceramic capacitor MLCC - SMD/SMT	Capacitor ceramic MLCC base metals (size accordingly 1206, 0603 or 0402)	Sphera
FR4 TG135-140 PCBA empty 73,8x84,4mm 2-layer		Printed Wiring Board 2-layer rigid FR4 with HASL finish (Subtractive method)	Sphera
Inductor/coils/transformers	Power inductor	Capacitor ceramic MLCC base metals (size accordingly 1206, 0603 or 0402)	Sphera
Key/switc	tactile switch	Key switch Dip (79mg) 11.39x4.5x1.5	Sphera
Key/switch	Slide switch	Dip switch	Sphera
a-Si PV		photovoltaic laminate production, a-Si	ecoinvent
Power supply chip	Battery management ICs	battery management system production, for Li-ion battery	ecoinvent
Resistors	Chip resistor - surface mounted	Resistor thick film flat chip 0603 (2.1mg)	Sphera
Resistors	Multilayer ceramic capacitor MLCC - SMD/SMT	Resistor thick film flat chip 0402 (0.75mg)	Sphera
Sensors	Attitude sensor/Gyroscope	electronic component production, passive, unspecified	ecoinvent
Solder paste		Solder paste SnAg3Cu0.5 (SAC-Lot)	Sphera
Supercapacitor	electric double layer EDLC 470mF 5,5V		[51]
	Supercapacitor electrode material	carbon black production	ecoinvent
	Supercapacitor electrode material	polyvinylfluoride production	ecoinvent

	Supercapacitor electrode material	activated carbon production, granular from hard coal	ecoinvent
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The hybrid system of case 2 (see 6.4.2 for results) uses the same node core and energy carrier PCB. A printed OPV and a printed supercapacitor were swapped in place of the corresponding traditional photovoltaic and SC components from case 1 (see 6.4.1 for results). Printed OPV was modelled based on primary production data from VTT. Table 3 presents the LCI data sources and datasets to model printed OPV. Electricity and thermal energy for all manufacturing stages requiring it and where energy demand was available, was modelled using Rest of Europe (RER) electricity and thermal energy mixes from Sphera, which corresponds to average European production.

Table 3. LCI data used to model the printed OPV. Data sources are either Sphera database, ecoinvent 3.11 database, Plastics Europe, literature or technical datasheets from manufacturers.

Material	Description	Dataset name/assumption	Source
PEDOT:PSS ink	≤ 1.3 % PEDOT: PSS	RER: Propene (propylene) mix; RER: Ethene (ethylene); DE: Acetic acid from methanol (low pressure carbonylation) (Monsanto process); DE: Polystyrene granulate (PS) mix; RER: Sulphuric acid (96%); RER: Water (deionised); <i>Sodium sulfate production</i> ; RER: <i>Dichloroethane (ethylene dichloride)</i>	[52], Sphera, <i>ecoinvent</i> , Plastics Europe
	Isopropanol	DE: Isopropanol	Sphera
	Ethylene glycol	RER: Ethylene glycol (from ethene and oxygen via EO)	Sphera
Active material ink NF3000	NF3000-P, Polymer	modelled as P3HT DE: Toluene (from pyrolysis gasoline); RER: Process water from surface water; <i>Hexane production, Bromine production</i>	[53], Sphera, <i>ecoinvent</i>
	NF3000-N, Small molecule	modelled as PCBM DE: Toluene (from pyrolysis gasoline); RER: Ammonia (NH ₃) production mix, without CO ₂ recovery (carbon dioxide emissions to air); RER: Oxygen (liquid); RER: Process water from surface water; <i>production of pentane, production of hydrogen chloride, production of sodium hypochlorite, production of sulphur trioxide</i>	[53], Sphera, <i>ecoinvent</i>
	O-xylene	RER: o-Xylene	Plastics Europe
	1,8-Diiodooctane (DIO)	exluded	
Lithium Fluoride, LiF		Lithium fluoride production	ecoinvent
	powder manufacturing	indium tin oxide powder production, nanoscale for sputtering target	ecoinvent
Aluminium		Aluminium ingot mix IAI 2019	Sphera
	powder manufacturing	indium tin oxide powder production, nanoscale for sputtering target	ecoinvent
Natureflex NVO30	substrate	Only climate impact available	Manufacturer

H30	coating	RER: Tap water from groundwater; DE: Ethanol (96%) (hydrogenation with nitric acid); GLO: market for chemical, inorganic	Sphera
PET	barrier	RER: Polyethylene terephthalate fibres (PET); GLO: Plastic Film (PE, PP, PVC)	Sphera
PSA	barrier	RER: Polyethylene terephthalate fibres (PET); GLO: Plastic Film (PE, PP, PVC); RER: Methyl methacrylate (MMA)	Technical datasheet, Sphera, Plastics Europe

Case 3 (see 6.4.3 for results) further expanded the hybrid system by introducing a printed thin film transistor (TFT) to replace microelectronic transistor components. The TFT was modelled based on primary data from VTT. Table 4 presents the LCI data sources and datasets to model printed TFT. Electricity and thermal energy for all manufacturing stages requiring it and where energy demand was available, was modelled using RER electricity and thermal energy mixes from Sphera, which corresponds to average European production.

Table 4. LCI data used to model the printed TFT. Data source is either Sphera database or ecoinvent 3.11 database.

Material	Description	Dataset name/assumption	Source
Polyimide	Substrate	GLO: Plastic film (PE, PP, PVC) / Assumed PET proxy	Sphera
Titanium	Evaporation layer	GLO: market for titanium	ecoinvent
Gold	Evaporation layer	GLO: market for gold	ecoinvent
Al ₂ O ₃	Dielectric layer	RER: Alumina production 2019 IAI	Sphera
Semiconductor ink	In(NO ₃) ₃	RER w/o RU: market for nitric acid, without water, in 50% solution state	ecoinvent
		RER: indium production	ecoinvent
	2-methoxy ethanol	RER: dimethyl ether production, from methanol dehydration	ecoinvent
	Ethylene glycol	RER: Ethylene glycol (from ethene and oxygen via EO)	Sphera
PDMS blanket	Polydimethylsiloxane	RER: Silicone sealing compound (EN15804 A1-A3) / Assumed proxy	Sphera
	CAT-RG	GLO: market for chemical, inorganic / Assumed proxy	ecoinvent
ROP resist ink	Poly(4-vinylphenol)	DE: Polymethyl methacrylate granulate (PMMA) mix	Sphera
	Ethyl lactate	1-butanol / Assumed proxy	Sphera
	Ethyl acetate	RER: ethyl acetate production	ecoinvent
	BYK-355	GLO: market for chemical, inorganic / Assumed proxy	ecoinvent
Etchant	Oxalic acid	GLO: market for oxalic acid	ecoinvent
Ethanol	Lift-off, Cliche cleaning	DE: Ethanol (96%) (hydrogenation with nitric acid)	Sphera
Distilled water	Lift-off	RER: Tap water from groundwater / Assumed proxy	Sphera
Acetone	Cliche cleaning	RER: Acetone by-product phenol, methyl styrene (from Cumene)	Sphera

6.4 Life cycle impact assessment

Impact assessment was done using the PEF3.1 impact assessment methodology considering all 16 impact categories. This section presents the impact assessment results, derived using a contribution analysis approach.

Contribution analysis helps to identify which processes, materials, or life cycle stages contribute most significantly to each impact category. By breaking down the overall environmental impacts, contribution analysis enables a clearer understanding of the main drivers behind the results, such as the materials used, energy consumption, or production processes involved. This insight is critical for targeting improvements and prioritizing actions to reduce the overall environmental footprint of the product or system under study.

6.4.1 Case 1 – Baseline microelectronic system

Case 1 was the baseline microelectronics system consisting of five modules: e-ink display, solar cell, supercapacitor, power management and node core. This section breaks down the modules even further to provide clearer insight into the factors contributing to environmental impacts. Solar cell, supercapacitor and power management are presented together to create the energy harvesting carrier while e-ink display in part of the node core. Figure 7 and Figure 8 show the results of contribution analysis for node core and energy harvesting carrier.

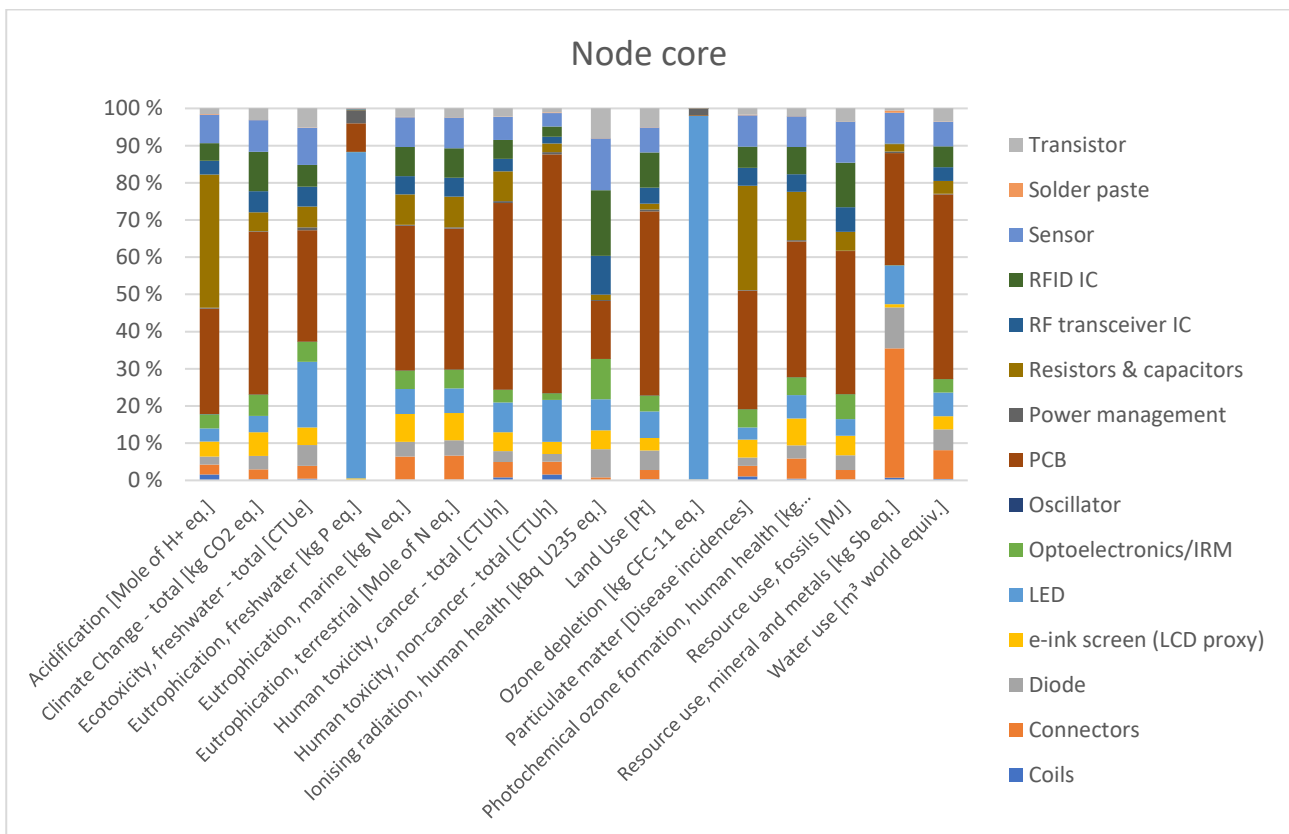


Figure 7. Node core - contribution analysis by categories.

Within node core, certain components exhibit substantially higher impacts across specific environmental categories. Connectors contribute notably to resource use concerning minerals and metals, while their influence remains minimal in other areas. LED components are associated with significant effects on freshwater eutrophication and ozone depletion and maintain moderate impacts elsewhere. The empty FR4 PCB demonstrates considerable impact in most categories, except for freshwater eutrophication and ozone depletion. Resistors and capacitors present

elevated impacts regarding acidification and particulate matter but show limited effects in other domains.

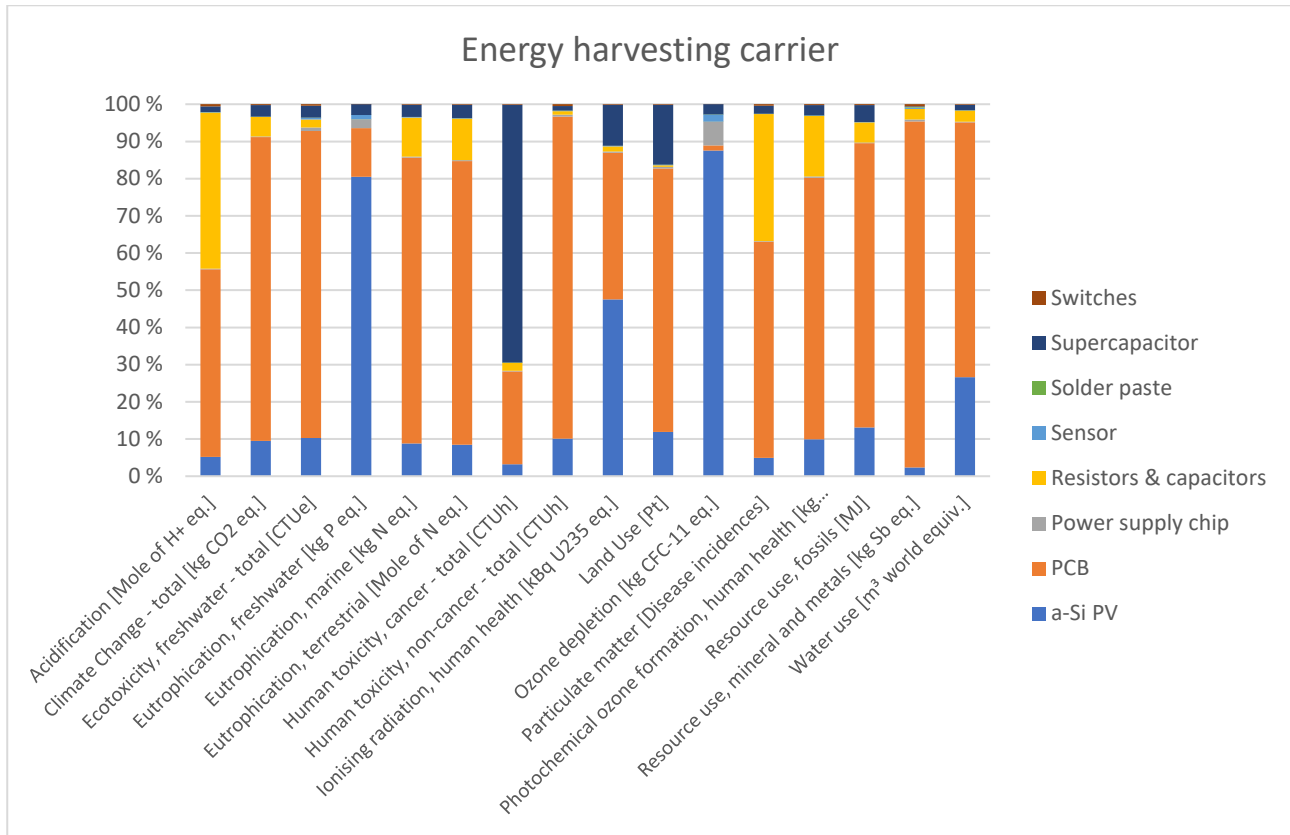


Figure 8. Energy harvesting carrier - contribution analysis by categories.

In energy harvesting carrier, the a-Si PV module significantly affects freshwater eutrophication, ozone depletion and ionising radiation while also having a meaningful impact on water use. FRF4 PCB contributes the most to all impact categories except where solar cell or the supercapacitor dominates. Resistors and capacitors notably influence acidification and particulate matter, while supercapacitor primarily impacts carcinogenic human toxicity.

6.4.2 Case 2 – Hybrid system

Case 2 was the hybrid system where a-Si PV and SC from case 1 were replaced by printed alternatives. Figure 9 and Figure 10 show the results of contribution analysis for printed OPV and printed SC, respectively.

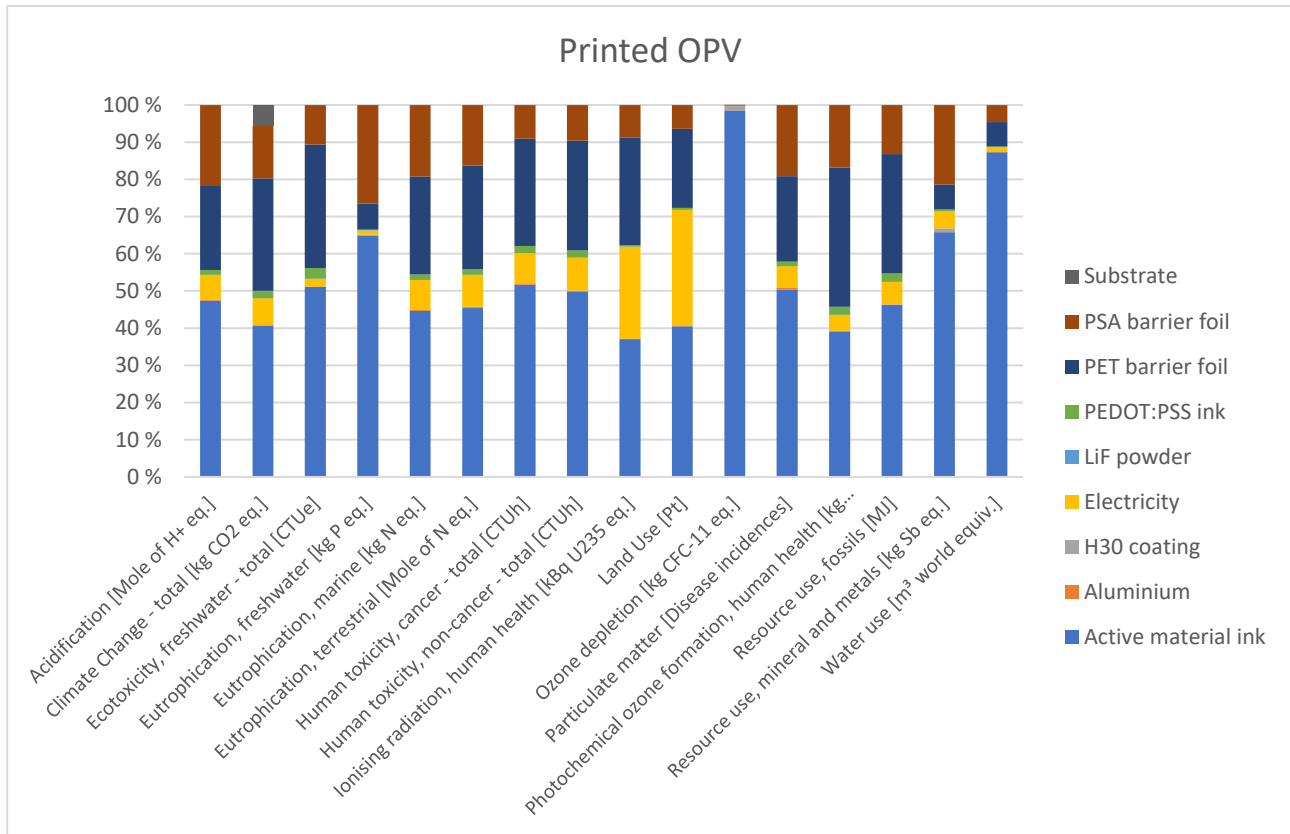


Figure 9. Printed OPV - contribution analysis by categories.

In the context of printed OPV, active material ink contributes most significantly to all assessed impact categories. This is primarily due to the fullerene-based chemicals present in the ink. Electricity consumption during OPV production is primarily associated with ionizing radiation and land use impacts due to the production profile of European market electricity mix.

PET barrier foil represents the second largest source of environmental impacts in nearly every category, while PSA barrier foil is notable in select areas. Vast majority of ozone depletion effects originate from active material ink.

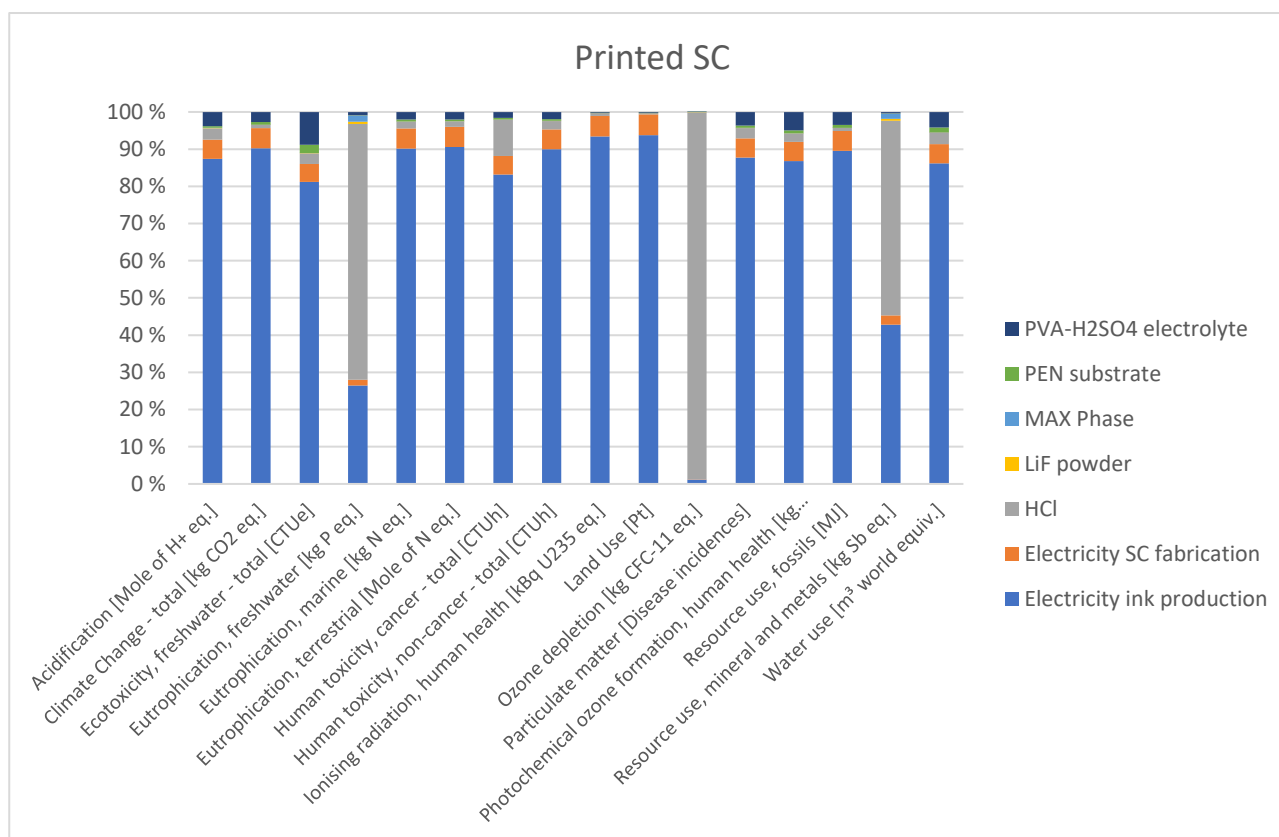


Figure 10. Printed SC - contribution analysis by categories.

For printed supercapacitors, electricity for ink production is the main contributor in nearly every category. Hydrochloric acid (HCl) is the largest factor only in freshwater eutrophication, ozone depletion, and resource use of minerals and metals. Other material impacts are minimal.

HCl production impacts freshwater eutrophication and ozone depletion due to the nature of its manufacturing processes and the associated chemical emissions. During the production of HCl, hazardous by-products can be released, which contribute to freshwater eutrophication. Additionally, certain chlorinated compounds generated or used in HCl production can contribute to ozone-depleting emissions if released into the atmosphere. The production of HCl requires sodium chloride in the upstream process chain which in Europe is mostly mined causing impacts to resource use (minerals and metals).

During the modelling process, electricity consumption was represented using the average European market mix. This approach was chosen to ensure consistency and comparability across all cases analysed, allowing for a more balanced evaluation of environmental impacts. However, it is important to note that in actual production of printed supercapacitors, renewable electricity is utilised, which can lead to different environmental outcomes. This was further studied in the sensitivity analysis. The studied SC fabrication is not at full industrial scale; therefore, energy savings are possible with process optimization.

6.4.3 Case 3 – Almost fully printed system

In case 3, the hybrid system from case 2 was expanded to include a printed TFT (thin-film transistor). The sample size for TFT fabrication was 361cm² which means approximately 1000 circuits. One (1) circuit is enough to replace the transistors of case 1. Figure 11 presents the contribution analysis by categories for printed TFT fabrication divided into production stages.

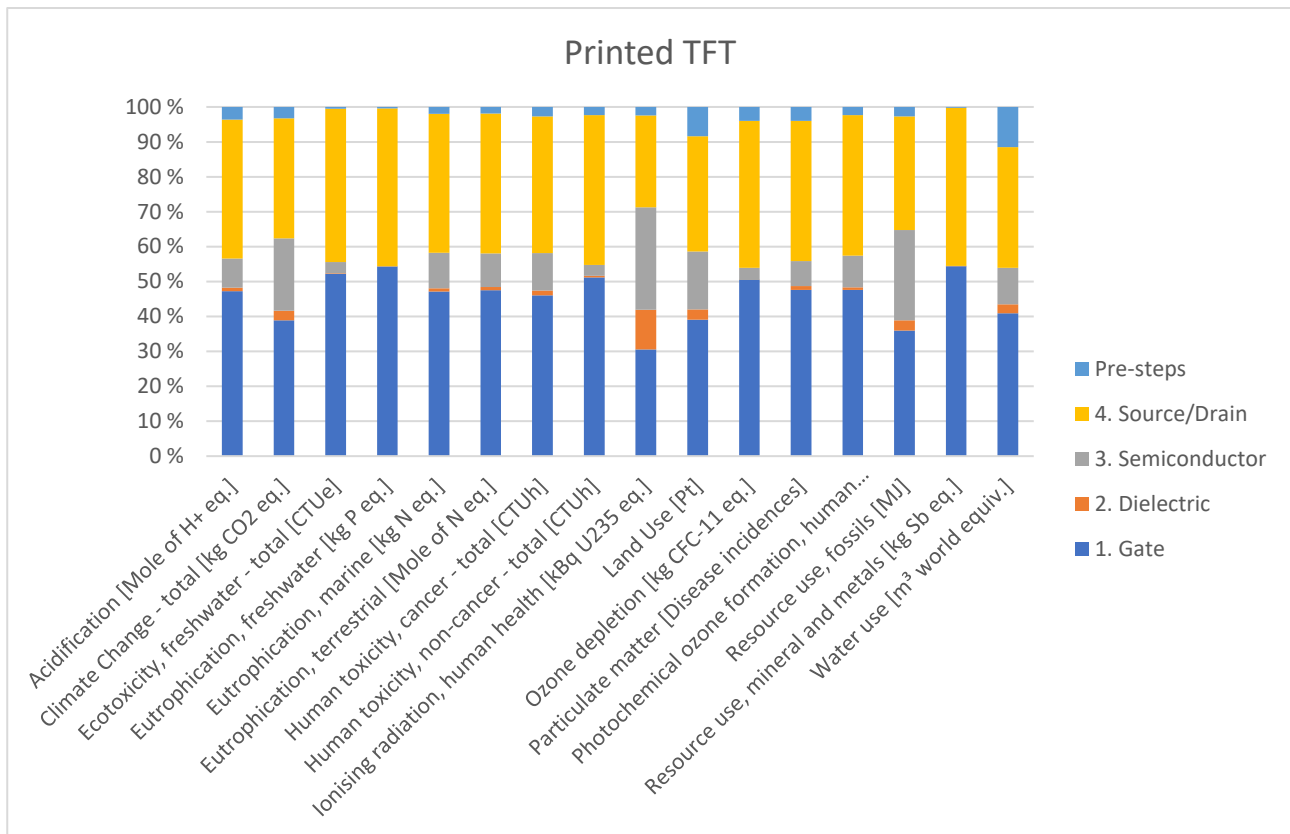


Figure 11. Printed TFT - contribution analysis by categories.

Main contributors to the environmental impacts of TFT fabrication in many impact categories are the gate and source/drain steps. Their impacts come primarily from material production for evaporation of Ti/Au and the electricity needed for the evaporation process. Especially gold extraction is resource-intensive, involving significant energy consumption and the use of chemicals that can lead to land degradation, water contamination, and increased greenhouse gas emissions. The use of these metals in the evaporation steps thus heightens the overall environmental burden of TFT production, particularly in impact categories related to resource use (minerals and metals), climate change, and ecosystem toxicity. This is especially important, as the evaporation step has significant material losses which were not considered at this stage. It was assumed that overspray can be recycled but that might not always be the case.

The semiconductor step (3.) involves processes like printing, etching, and other treatments that use electricity, as well as the production of chemicals required for these tasks. This stage makes a noticeable contribution to ionizing radiation, primarily because the average European electricity supply contains about 30% nuclear power—an energy source with a significant impact on ionizing radiation. Semiconductor steps contribution to resource use (fossil) and climate change are also related to the electricity mix.

6.4.4 Comparisons

The goal of this study was to compare the baseline microelectronics system (case 1) with selected printed components developed in the project to find out the climate and other environmental impacts of both manufacturing methods. Figure 12 provides a comparative analysis of the environmental impacts across the three cases: baseline microelectronics system (case 1), a hybrid system with printed OPV and SC components (case 2), and an almost fully printed system with printed TFT (case 3).

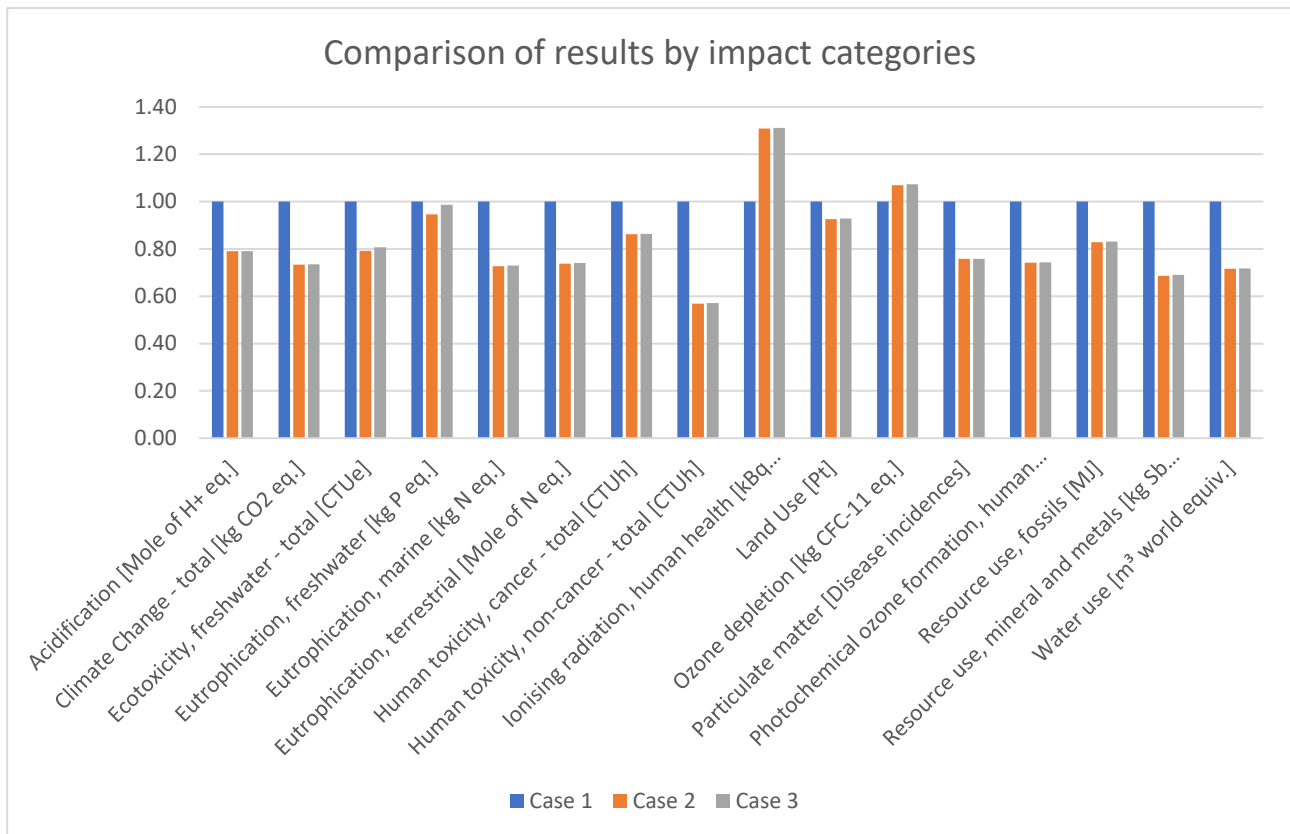


Figure 12. Relative impacts of cases 1,2 and 3 by impact categories. Case 1 is set to 1.

In this comparison, case 1 is set as the reference point (value of 1) for each impact category. The results indicate that the transition from traditional microelectronics (case 1) to printed electronics (cases 2 and 3) can potentially lead to lower or higher environmental impacts, depending on studied impact categories.

While some categories show increase in environmental impacts, the overall trend suggests that printed electronics offer comparable or better environmental performance to conventional microelectronics. Especially in human toxicity (non-cancer), printed options could lead to significant impact reductions but at the same time categories such as ionising radiation (human health) and ozone depletion could potentially have increased impacts. Other impact categories with moderate reduction potential are acidification, climate change, ecotoxicity, marine and terrestrial eutrophication, particulate matter, photochemical ozone formation, resource use (minerals and metals) and water use.

However, it is important to note that specific processes within the printed systems, such as the use of metals in TFT fabrication and electricity consumption for ink production in printed SC fabrication, can influence certain impact categories more heavily, as discussed in the sections above. Overall, the comparison demonstrates that while printed electronics present some opportunities for environmental improvement, the magnitude of difference relative to traditional systems remains modest across the main indicators evaluated.

In another comparison, the combination of a-Si PV, supercapacitor and power management from case 1 were benchmarked against a Lithium Polymer (LiPo) battery. This comparison is shown in Figure 13.

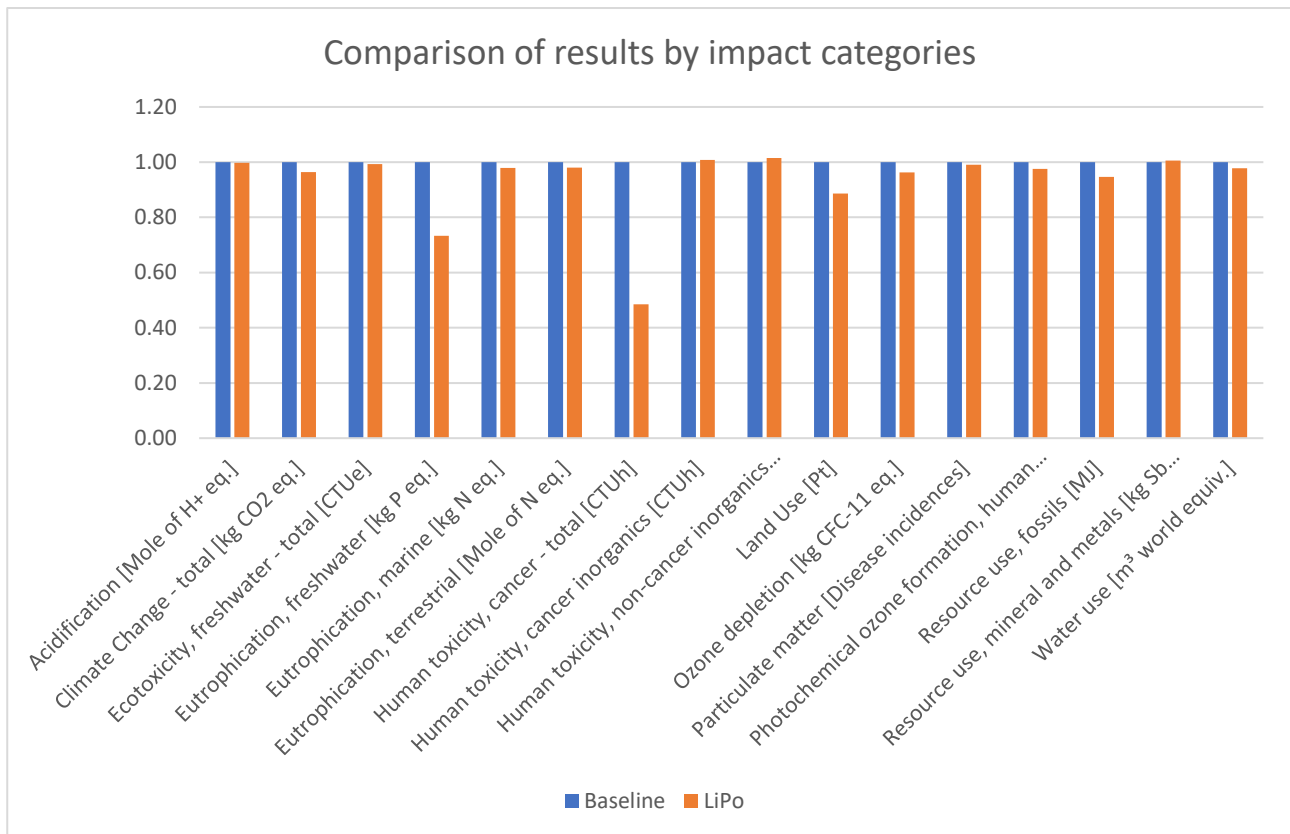


Figure 13. Relative impacts of baseline system (case 1) and LiPo battery. Baseline is set to 1.

Figure 13 presents a comparison between the baseline system (case 1), including a solar cell, supercapacitor, and power management, and a LiPo battery highlighting the environmental impacts of these different energy storage and management options. The comparison reveals that the two systems generally exhibit comparable impacts in several categories. Most notably in eutrophication (freshwater) and human toxicity (cancer), the system utilizing LiPo battery shows significant decrease in impacts. It should be noted that inventory data for a LiPo battery was not available, so an NCA battery was used as proxy. This may lead to some uncertainty in the results concerning battery manufacturing.

6.5 Normalization and weighting

Normalization and weighting are optional elements of LCA that are used to further analyse the results. Normalization involves determining the magnitude of category indicator results in relation to reference data [54]. The purpose of normalization is to enhance understanding of the relative significance of each indicator result within the product system being evaluated. In PEF3.1, normalization is done by global population [55]. Weighting is the procedure of translating normalized indicator results across various impact categories by applying numerical factors that reflect value-based judgments [54]. In this section, all 16 impact categories from PEF3.1 were studied using normalization and weighting with the PEF3.1 normalization and weighting factors from [55]. Figure 14 and Figure 15 show the normalized and weighted results for node core and energy harvesting carrier from case 1. After that, Figure 16 and Figure 17 present the same for printed OPV and supercapacitor from case 2 respectively followed by Figure 18 for printed TFT from case 3.

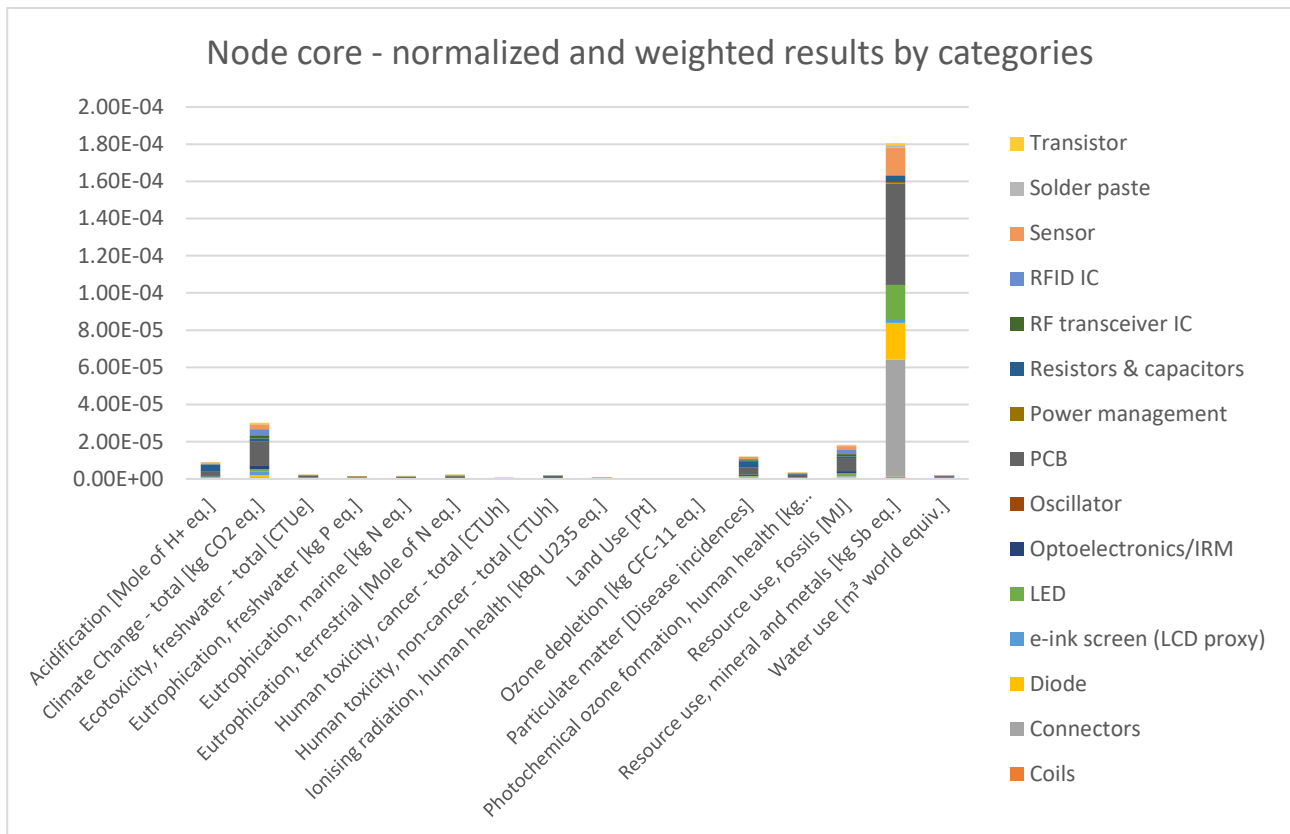


Figure 14. Node core - normalized and weighted impacts by categories.

The results indicate that certain impact categories contribute more to the overall environmental profile of the node core, and they should therefore be the focus of possible mitigation actions. For instance, categories such as resource use (minerals and metals), climate change, resource use (fossils), particulate matter and acidification stand out after normalization and weighting, highlighting their greater relevance. Of these categories, resource use (minerals and metals) is shown to have a huge contribution to the overall environmental impacts of node core. PCB and connectors contribute the most in this impact category, probably related to low material efficiency of production and the use of metals such as gold and copper.

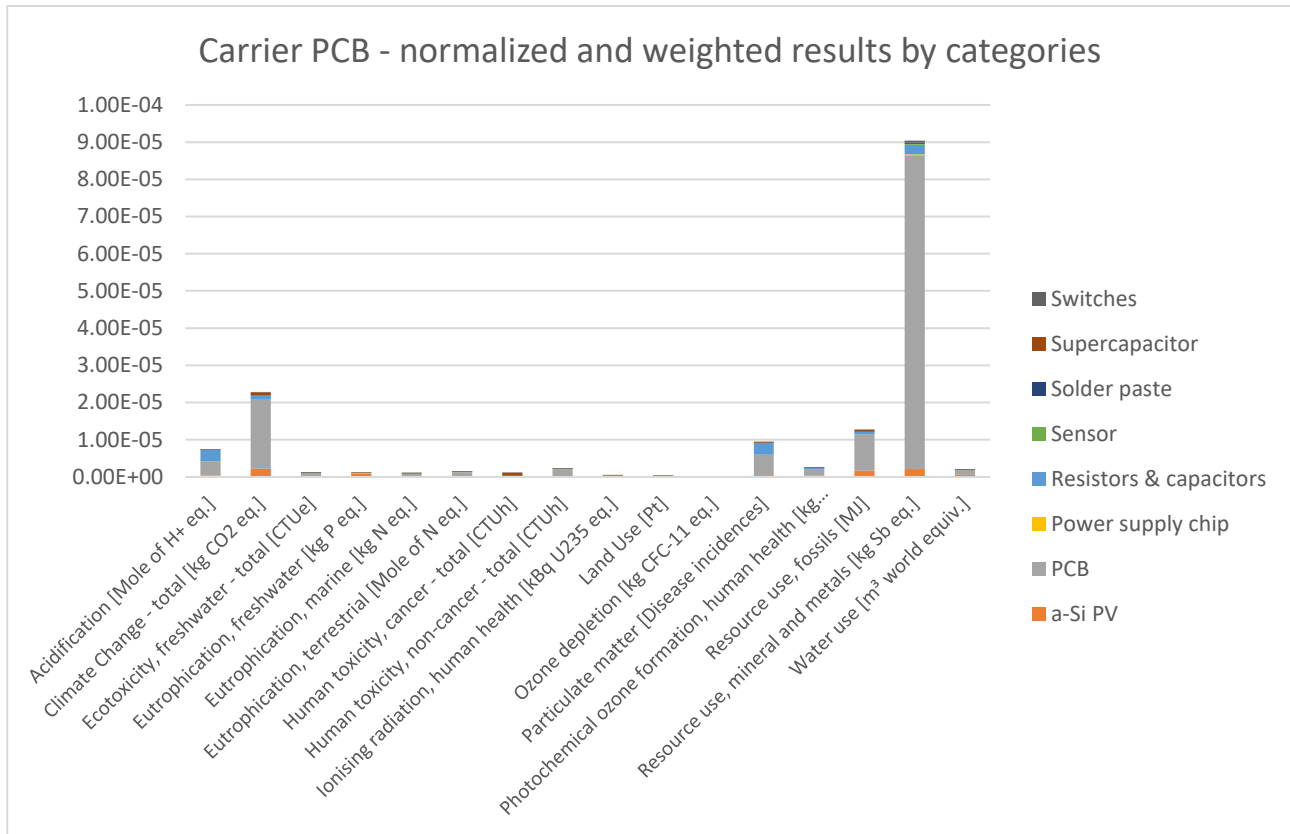


Figure 15. Energy harvesting carrier - normalized and weighted results by categories.

Similarly to the node core, normalized and weighted results for energy harvesting carrier show that resource use (minerals and metals), climate change, resource use (fossil), particulate matter and acidification stand out amongst the impact categories. Across the categories, impacts come predominantly from PCB production. PCB stands out in categories such as resource use (minerals and metals), climate change, and resource use (fossil), where its contribution significantly outweighs those of other components. This dominant impact is likely attributable to the material-intensive nature of PCB manufacturing, especially the use of precious and base metals like gold and copper, as well as the energy demands associated with their production processes.

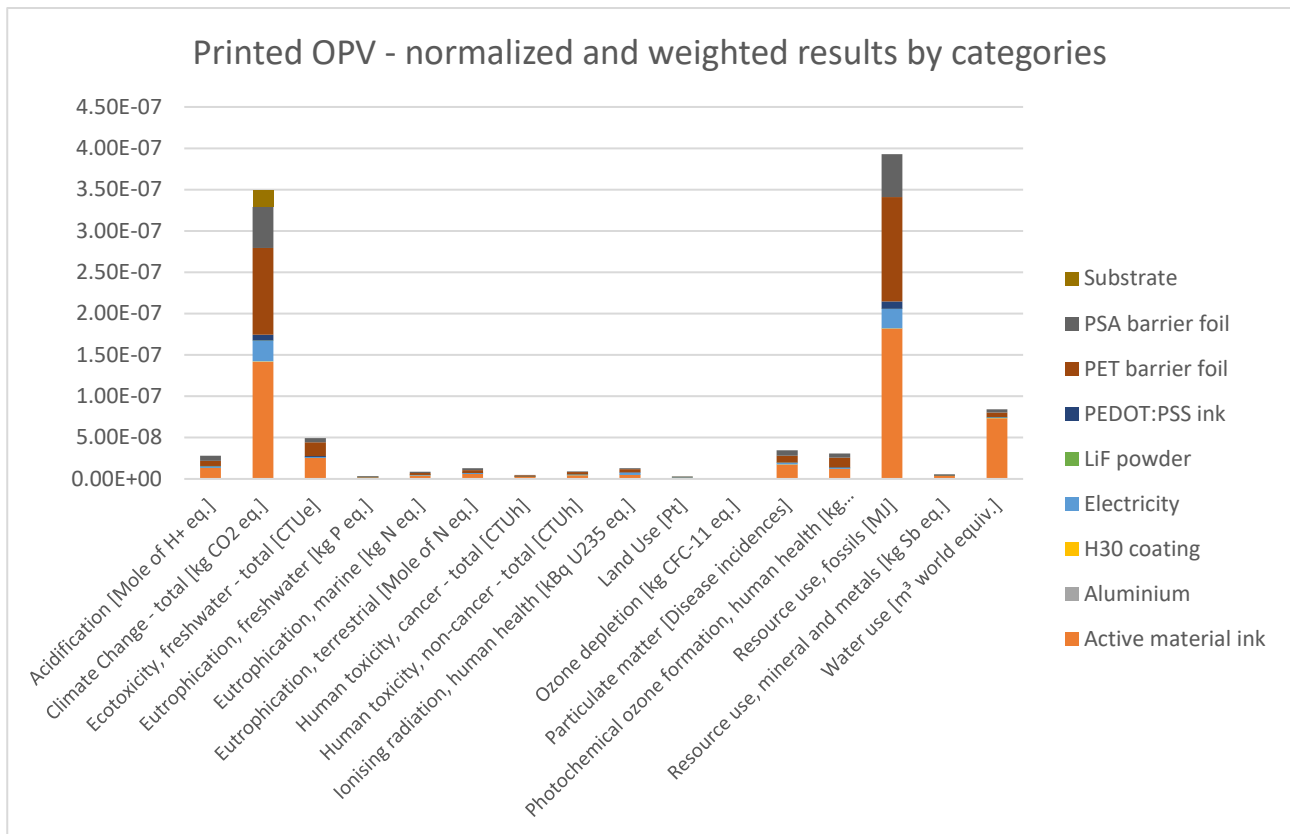


Figure 16. Printed OPV - normalized and weighted results by categories.

Figure 16 presents the normalized and weighted environmental impacts for printed OPV. From all impact categories, resource use (fossil) and climate change stand out. The PET barrier foil, manufactured from fossil-based polyethylene terephthalate, contributes notably to resource use (fossil) and climate change impact categories, due to its petroleum-derived origin and associated greenhouse gas emissions. The active material ink, primarily carbon-based and containing fullerene derivatives, also affects resource use (fossil) and climate change as well as water use due to its highly energy intensive manufacturing.

For printed SC, the normalized and weighted results reveal that resource use (minerals and metals) and climate change are the most significant impact categories, much as observed for the other parts of the system, as depicted in Figure 17. Notably, the process of ink manufacturing stands out as a key contributor to the overall environmental impacts of printed SC, primarily due to its substantial electricity consumption. This high energy demand during ink production elevates the impacts in categories associated with climate change and fossil resource use, underscoring the importance of addressing energy efficiency electricity in future process improvements.

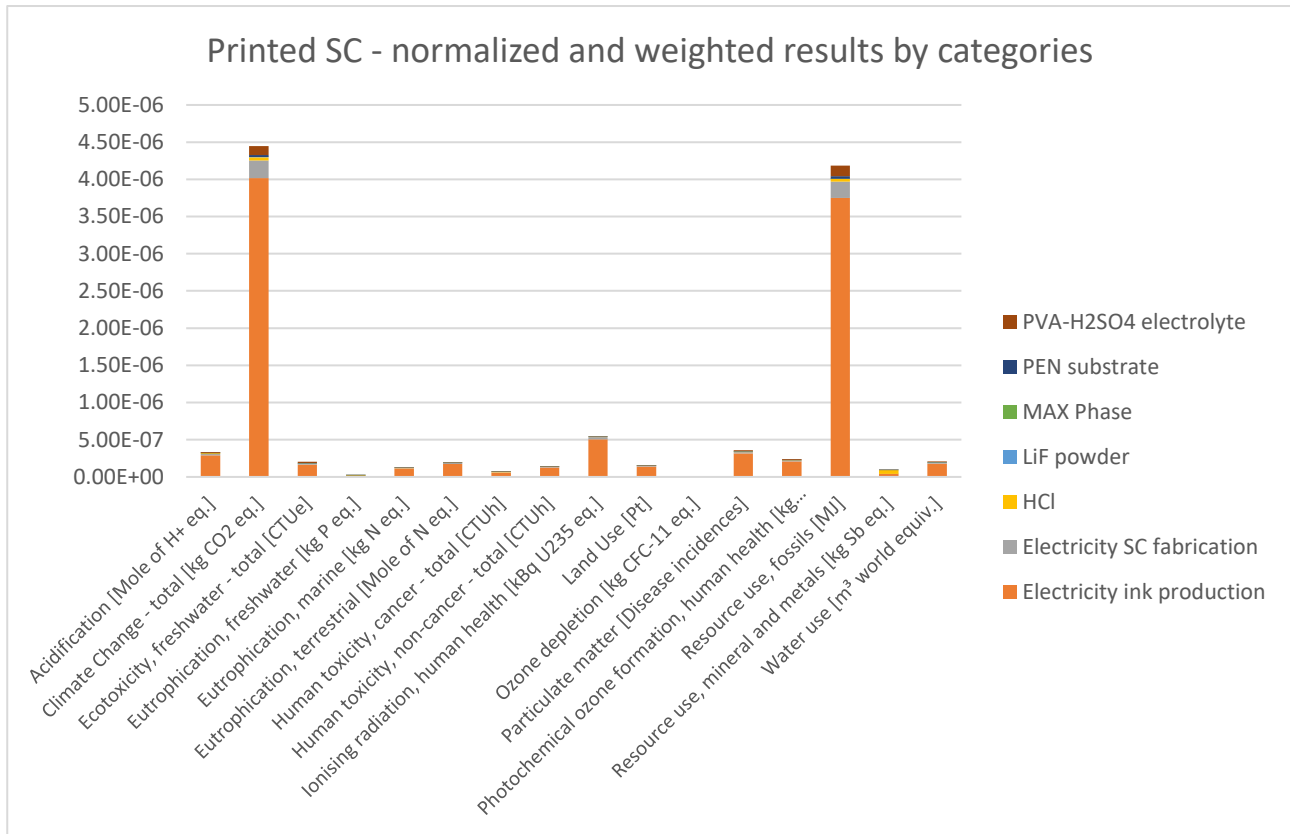


Figure 17. Printed SC - normalized and weighted results by categories.

Figure 18 presents the normalized and weighted environmental impacts by category for the printed TFT component of the system in case 3. The results illustrate that, like the other system parts previously discussed, certain impact categories are more prominent following the normalisation and weighting process. Resource use (minerals and metals) emerges as the most significant category for the printed TFT, indicating that it contributes disproportionately to the overall environmental profile of this component.

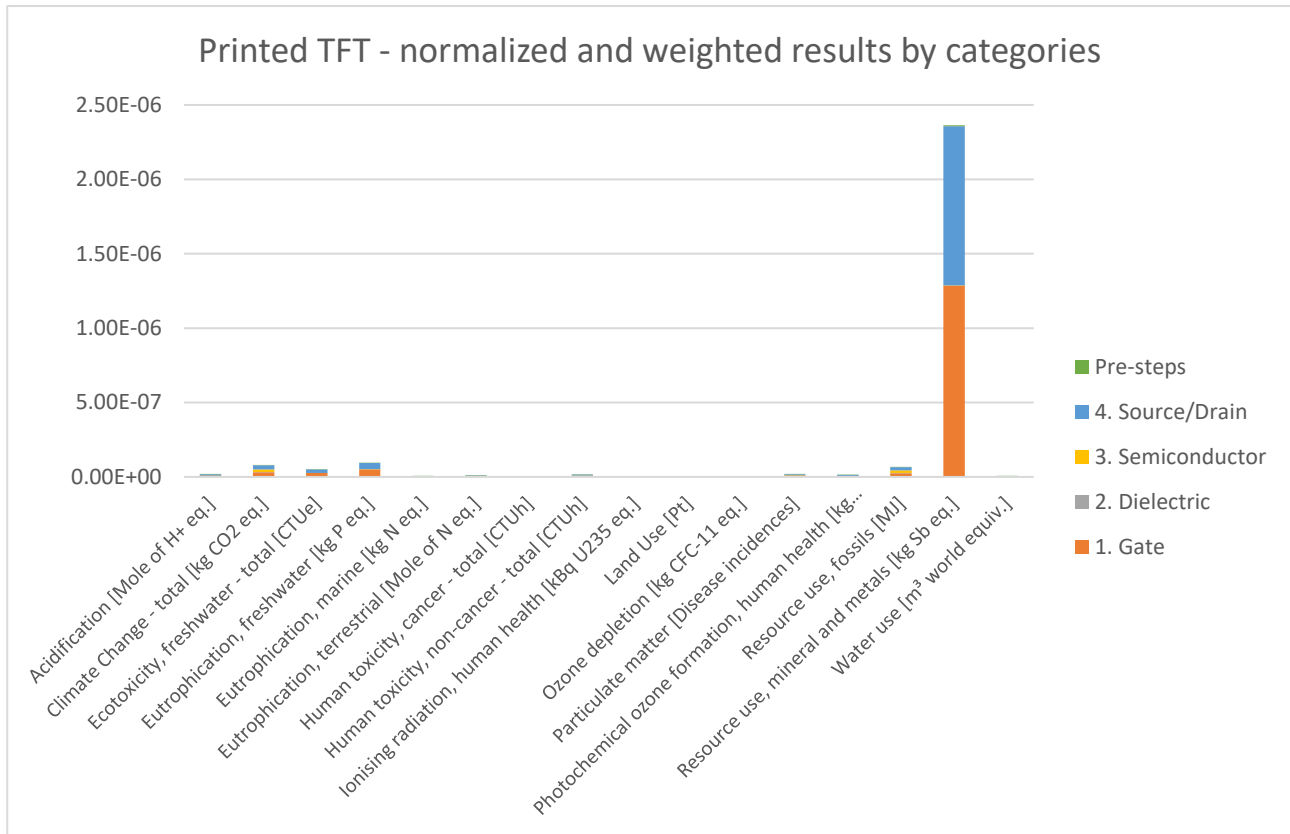


Figure 18. Printed TFT - normalized and weighted results by categories.

High impact in resource use (minerals and metals) is driven by the materials used to fabricate printed TFTs. The gate and source/drain steps include evaporation of gold and titanium which elevate impacts related to resource extraction. As with other components, addressing material efficiency in production is important for mitigating environmental impacts. It was assumed that overspray from evaporation can be recycled but that might not be the case so the impacts from gate and source/drain steps can potentially be even higher.

Normalization and weighting can also be used to compare cases 1-3 as well as case 1 and LiPo battery. Figure 19 shows the normalized and weighted impacts of the three cases, while Figure 20 shows the comparison between baseline system and LiPo battery using PEF single score. The PEF single score is a sum of all the normalized and weighted results in each of the 16 impact categories. It shows the overall environmental impact of the studied system and can be used to compare different options.

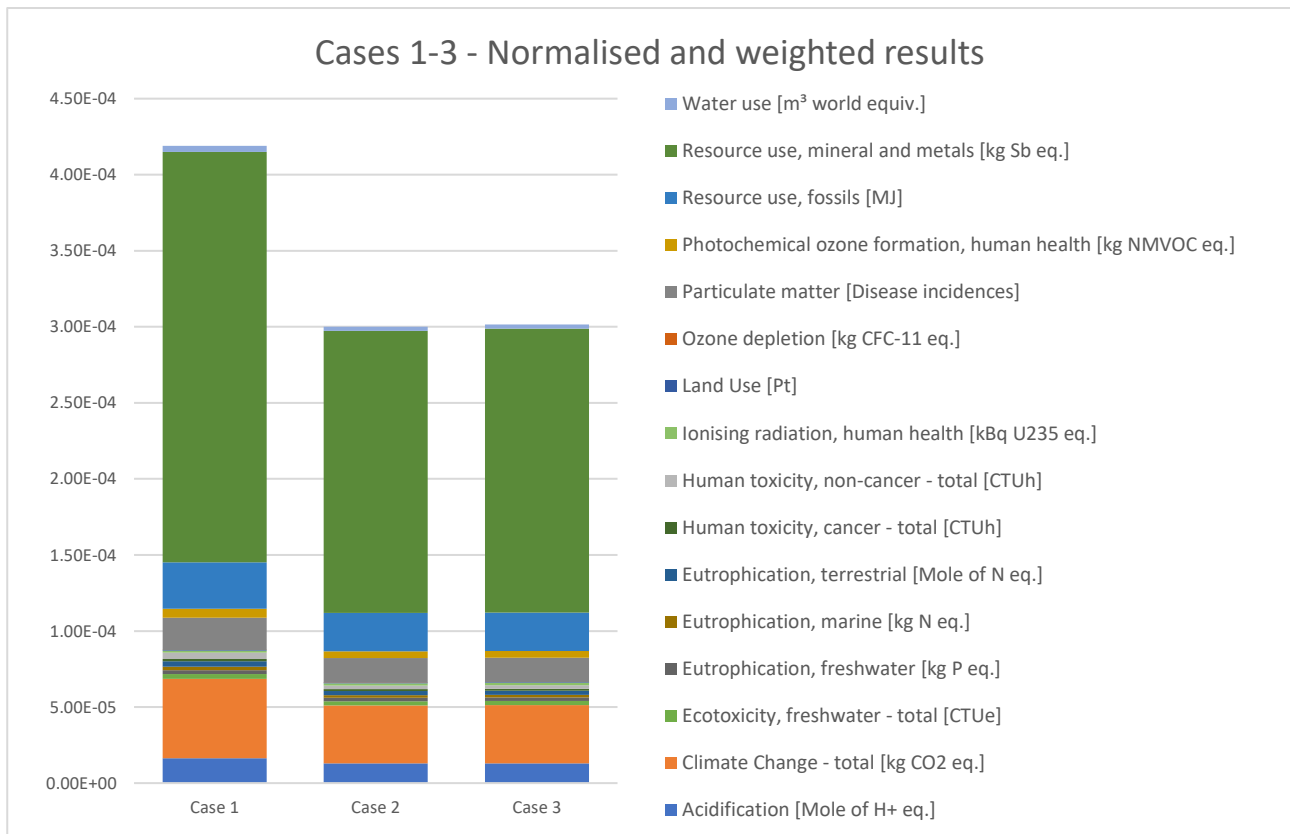


Figure 19. Cases 1-3 - Normalized and weighted impacts presented in PEF single score.

The PEF single score comparison shows cases 2 and 3 to have approximately 30 % lower impacts compared to case 1 baseline microelectronics system. This comes primarily from reductions in resource use (minerals and metals) where the main contribution is likely the change from a-Si solar cell to printed OPV which reduces the use of natural resources. Also, climate change and resource use (fossil) categories show reductions.

In several impact categories where absolute differences can be observed based on Figure 12—such as human toxicity and eutrophication—the assigned weights during normalization and weighting are relatively low. Consequently, although these categories may display significant variation in unweighted analyses, their contribution to the overall single score is considerably diminished, resulting in greater alignment of the total scores upon aggregation.

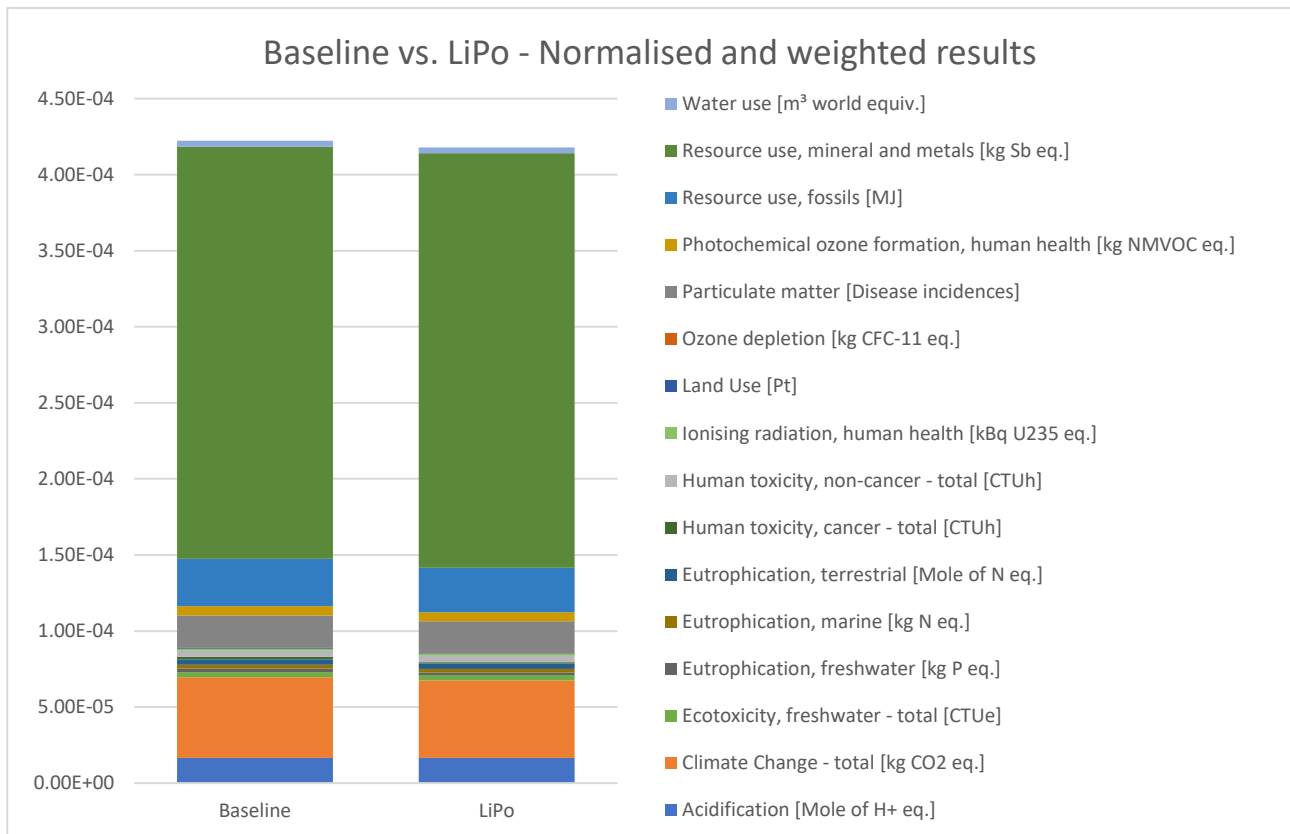


Figure 20. Baseline vs. LiPo battery - Normalized and weighted impacts presented in PEF single score.

Based on the analysis, there is little difference in the overall normalized and weighted environmental impacts between the baseline and LiPo system. This minimal disparity can be attributed to the same reason discussed previously for cases 1-3: the impact categories where the most significant absolute differences occur—such as freshwater eutrophication and human toxicity—are assigned relatively low weights during the normalization and weighting process. As a result, although these categories may appear to differ markedly in unweighted analyses, their influence on the overall single score is substantially reduced, leading to a convergence of the total scores when aggregated.

6.6 Sensitivity analysis

A sensitivity analysis was performed on the manufacturing of printed SC to see how using different renewable electricity options would affect the results. Figure 21 illustrates the relative impacts of using different renewable electricity options—wind, hydro, or solar—in the manufacturing of printed SC, with the European market mix set as the baseline. Figure 22 compares the normalized and weighted impacts of these different electricity options using PEF single score.

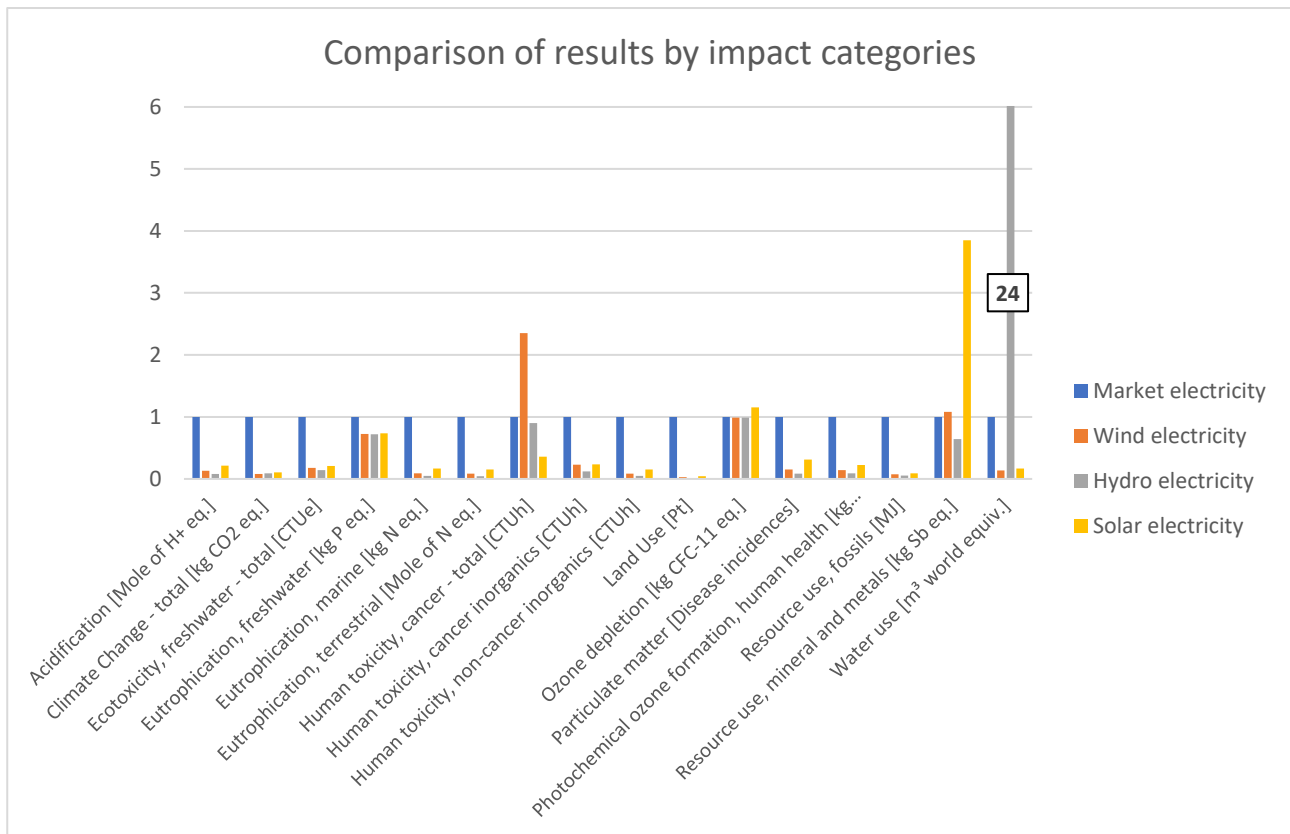


Figure 21. Printed SC – relative impacts using different renewable electricity options. European market mix is set to 1.

Figure 21 shows that shifting to renewable electricity sources can lead to notable changes in the environmental impact profile of printed supercapacitor manufacturing. For instance, adopting wind electricity generally results in a substantial reduction in climate change impacts due to its low greenhouse gas emissions during operation. However, this benefit may be counterbalanced by increases in other impact categories such as human toxicity and resource use (minerals and metals), particularly because the infrastructure required for wind energy generation demands significant quantities of metals and materials. Mining, refining, and processing these materials can release hazardous substances, including heavy metals and chemical by-products, which are associated with human toxicity. Similarly, while hydropower can lower fossil resource use, it elevates impacts related to water use. Thus, the results highlight that improvements in one environmental category, such as climate change, can sometimes come at the expense of increased impacts in others.

Solar power, while offering significant reductions in greenhouse gas emissions compared to the average electricity mix of Europe, can contribute to increased ozone depletion primarily due to the materials and manufacturing processes involved in PV panel production. The manufacture of PV panels often requires chemicals and substances, such as certain fluorinated gases and solvents, that have a high ozone depletion potential if released during production or disposal. Additionally, the extraction and processing of raw materials—including some metals and rare earth elements—used in solar technologies may involve industrial activities that emit ozone-depleting substances. Thus, while solar energy itself is clean during operation, the upstream impacts associated with its infrastructure can lead to a greater contribution to ozone layer depletion than other renewable options. The extraction of raw materials also has an increased impact on resource use (minerals and metals).

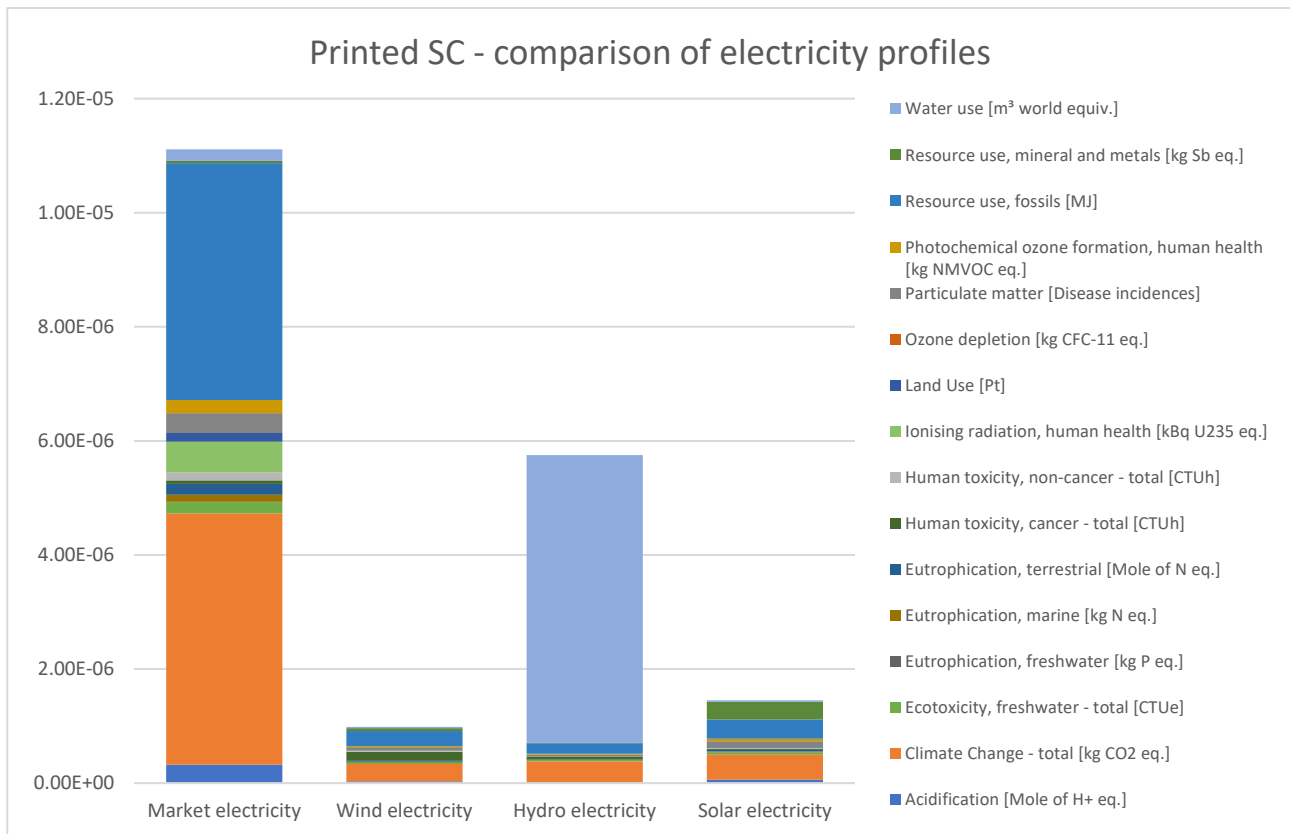


Figure 22. Printed SC - Normalized and weighted impacts of using different renewable electricity options presented in PEF single score.

When examining the total impacts in PEF single score, market electricity (represented by the European market mix) exhibits the highest overall environmental burden, particularly in categories related to climate change and fossil resource use, due to the continued reliance on fossil fuels within the mix.

Wind electricity, in contrast, demonstrates a marked reduction in total impacts, especially in climate change, owing to its minimal greenhouse gas emissions during operation. However, its total impact does not fall to zero, as resource use (minerals and metals) increases, reflecting the material intensity required for wind turbine infrastructure. Impacts related to infrastructure also persist and affect wind electricity’s environmental performance.

Hydropower also offers significant improvements over market electricity, reducing both fossil resource use and climate change impacts. Nevertheless, it stands out for increasing impacts in categories related to water use, due to the large volumes of water involved in hydropower generation and potential ecological effects.

Solar electricity exhibits a nuanced impact profile. While it achieves considerable reductions in greenhouse gas emissions and fossil resource use compared to market electricity, it incurs higher impacts in categories such as ozone depletion and resource use (minerals and metals). These increases are primarily associated with the raw material extraction and the manufacturing processes of photovoltaic panels, as well as the use of specific chemicals with high ozone depletion potential.

In summary, while all renewable options outperform the market electricity mix in terms of total climate change and fossil resource impacts, each comes with distinct trade-offs. Wind and hydro are generally preferable for climate and fossil resource categories, but wind increases metal resource use and hydro elevates water use. Solar stands out for reducing greenhouse gases but increases ozone depletion and natural resource impacts. This comparison highlights the need to consider a range of environmental categories when selecting electricity sources for manufacturing, rather than focusing solely on climate change or fossil resource use.

6.7 Limitations

The case studies could not be modelled with a single database due to limited availability of background LCI data in selected databases. In principle, this means that some parts of the modelling were done using software and database from Sphera while other parts utilized Sulca software and ecoinvent database. Impact assessment method was the same throughout the study regardless of software or databases. The use of two different databases may lead to differences in background data, assumptions and system boundaries within the LCI data. This in turn leads to possible inconsistencies in results. In general, it is acknowledged that both databases rely heavily on literature but may use different sources. Software choices had no impact on the results.

Reliance on literature also restricted the study, as primary data for some components and materials which were not available in any database was also unavailable in literature. This led to assumptions which may or may not be representative of the components and material under study. For some materials, like the substrate used for printed OPV, only carbon footprint data was available. This means that the material does not contribute to any other impact category besides Climate change in this study when in reality it would have impacts to all 16 categories of PEF3.1.

The use of average European electricity mix within the core analysis may lead to results not representing the actual manufacturing location of the demonstrators. This choice was made solely to maintain a standard basis for comparison between scenarios. The potential benefits of using renewable electricity in practice were specifically explored through sensitivity analysis on printed SC manufacturing.

Another important limitation to note is the absence of clear information regarding the size of the printed OPV and printed SC devices. This introduces uncertainty when comparing cases 1, 2, and 3, as it is possible that the microelectronics system in case 1 and the printed systems in cases 2 and 3 do not possess equivalent energy harvesting capabilities and therefore have different functional units in their LCAs'. As a result, the comparative analysis between these cases may be flawed, since differences in device size and corresponding energy output could significantly affect the environmental impacts and overall performance observed.

Additionally, directly comparing the baseline system in case 1, which uses a-Si PV and a supercapacitor, to a battery system is not entirely accurate. The available information on the size of the PV module and supercapacitor in the baseline system does not necessarily correspond with the size of the battery, which could again result in differences in energy storage and delivery capabilities. Furthermore, the specific battery chemistry used in the study—LiPo (Lithium Polymer)—was not present in the LCI databases, necessitating the use of NCA (Nickel Cobalt Aluminium) battery data as a proxy. This substitution inevitably affects the reliability and representativeness of the results, introducing further uncertainty into the comparative analysis.

Future studies should aim to ensure that the systems under evaluation are comparable in terms of their functional output, particularly energy harvesting capacity, to provide a more robust and meaningful assessment of environmental impacts across different technology options.

7 Conclusions and discussion

6G is widely being developed across the globe, and the driving forces behind the development of this upcoming technology are not only advanced technical capabilities and high performance but also sustainability. The present electronics industry poses significant direct and indirect environmental impacts, such as large energy consumption during manufacturing, great demand for critical raw materials (CRMs), and production of electric and electronic waste (e-waste). The IoT technologies can enhance energy and material efficiency, thereby reducing environmental impacts in the sectors where they are applied. However, it is important to ensure that their production and use do not inadvertently increase environmental impacts at the same time. Studying the environmental impacts caused by different IoT technologies and developing alternatives with lower impacts are among the main objectives of the SUPERIOT project.

The goal of this study was to compare a baseline microelectronics system with selected printed components developed in the project to find out the climate impacts of both manufacturing methods. Results from the LCA emphasize that while 6G and IoT technologies offer promising avenues for enhancing sustainability through improved energy and material efficiency, their production and deployment must be carefully managed to avoid unintended environmental consequences.

When comparing the absolute environmental impacts of baseline microelectronics system (case 1) with the printed options of case 2 and case 3, it was seen that switching from traditional microelectronics (case 1) to printed electronics (cases 2 and 3) leads lower environmental impacts in most environmental categories. Printed electronics generally perform similarly or slightly better environmentally, especially in human toxicity (non-cancer), where notable reductions are possible. However, impacts to ionising radiation and ozone depletion may increase. Specific processes in printed systems can significantly affect certain categories. Case 1 was also benchmarked against a system using a LiPo battery. Both systems had similar impacts overall, but the LiPo battery system showed notably lower impacts in freshwater eutrophication and human toxicity (cancer).

The overall PEF single scores for cases 1–3 show a 30% reduction in total environmental impacts when switching from conventional microelectronics to printed alternatives. This is primarily from reductions in resource use (minerals and metals) where the main contribution is likely the change from a-Si solar cell to printed OPV which reduces the use of natural resources. Alternatively, the PEF single scores for case 1 and the system with LiPo battery are similar because categories with large absolute differences, like freshwater eutrophication and human toxicity, have less influence after weighting. Thus, while some absolute impacts differ noticeably, their effect on the total score is minimal due to the weighting method.

In the sensitivity analysis, changing to renewable electricity was studied for printed SC manufacturing. Wind power can greatly reduce climate change impacts due to low greenhouse gas emissions but may raise human toxicity and resource use because its infrastructure requires substantial metals and materials, leading to hazardous by-products. Hydropower lowers fossil fuel use but increases water consumption. Solar energy also reduces greenhouse gas emissions versus Europe's average mix but slightly increases ozone depletion risk due to chemicals used in PV panel production and material extraction. The need for metals and rare earth elements in solar technologies heightens resource impacts even though solar operation is fossil free. Based on this, it should be noted that choosing electricity sources for manufacturing should weigh all environmental effects, not just climate or fossil concerns.

There were several limitations in the LCA study, including the necessity to use multiple databases due to gaps in existing life cycle inventory data, which introduces inconsistencies and uncertainties in the results. The reliance on literature and assumptions for certain materials, as well as the use of proxy data for components like batteries, further complicates the accuracy and comparability of findings. Additionally, the use of a standard European electricity mix and the lack of precise information on device sizes and functional output are identified as significant sources of uncertainty, potentially affecting the validity of comparative analyses between different cases.

Future research should focus on ensuring that systems are comparable in terms of their functional output, particularly energy harvesting capacity, to enable robust and meaningful environmental assessments. Additionally, future studies should strive for greater consistency in data sources, improve the availability of primary LCI data, and consider the actual manufacturing contexts of analyzed technologies. These steps will help reduce uncertainty and enhance the reliability of LCA results, ultimately supporting the development of more sustainable IoT and 6G technologies.

In addition to the aforementioned research priorities, the end-of-life treatment options for printed electronics should be considered in future studies. As printed electronics become more prevalent, understanding their disposal, recycling, and potential for material recovery is critical for minimizing environmental impacts. Research should investigate the development of effective separation and recycling processes tailored to the unique materials and structures found in printed electronic devices, including inks, substrates, and embedded components.

Further work is also needed to explore the integration of eco-design principles that facilitate easier dismantling and recycling of printed electronics at the product design stage. This could involve identifying sustainable materials, designing for modularity, and reducing the use of hazardous substances.

When evaluating printed electronics versus traditional microelectronics, it is crucial to consider not only their respective environmental impacts but also their functional lifespans. Printed electronics, while offering some environmental advantages such as reduced impacts in specific categories like freshwater eutrophication and human toxicity, may have a shorter operational lifespan compared to their conventional counterparts. This potential limitation could affect the overall sustainability of printed solutions, especially if shorter lifespans necessitate more frequent replacements, thereby increasing cumulative resource use and waste generation over time.

Therefore, future studies should address the durability and longevity of printed electronics as a key factor in comparative assessments. Incorporating lifespan considerations into life cycle analyses will provide a more comprehensive understanding of their true environmental benefits and trade-offs. This will ensure that sustainability evaluations reflect real-world usage scenarios and inform the development of printed technologies that are not only environmentally preferable in production but also robust and long-lasting in practice.

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