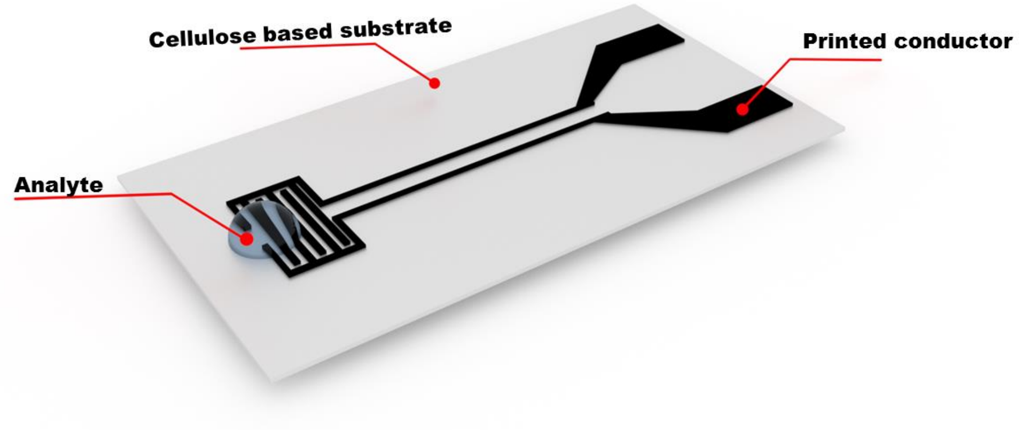

Guidelines for Green Electronics – Sustainability and Foresight

Introducing the concepts as a first step

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ISBN 978-91-89711-36-5

Summary

The society is transitioning towards a circular economy and the Digital Cellulose Center (DCC) that develops green electronics may play an important role in it.

The research within the DCC focuses on the topic of digital cellulose, where cellulose is combined with electroactive material, making it possible to develop electrically active cellulose products that can communicate with the digital world while remaining sustainable. This could mean entirely new types of active packaging solutions, able to sense and adapt to their surroundings, or paper rolls able to store energy from solar cells or wind power [1].

This document offers guidance for the DCC stakeholders on the choice of sustainable materials for green electronics, focusing on the two life cycle phases of a product:

- Raw materials
- End-of-life

Since the DCC green electronics are still in the development stage, a future scenario analysis has been applied in order to envision the possible future outcomes. The DCC green electronics have been explored in two opposite future scenarios:

- *Stuck in the Mud* – A business-as-usual scenario, where the year 2045 is more or less the same as year 2022.
- *Circular Dawn* – Where the circular economy has become a new normal and the whole society is thriving in a resource-efficient, circular and biobased economy.

The guideline contains a sustainability checklist adapted to the needs of the DCC stakeholders for more informed decision-making and for being able to drive the development towards a circular economy, i. e. the future scenario *Circular Dawn*.

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Glossary

Abbreviation	Explanation
5G	Fifth generation mobile networks
B2B	Business to Business
CRM	Critical Raw Material
DCC	Digital Cellulose Center
ECHA	European Chemicals Agency
EEE	Electric and electronic equipment
EPR	Extended Product Responsibility
EU	European Union
EV battery	Electric Vehicle battery
GHG	Green House Gas
IoT	Internet of Things
LCA	Life Cycle Assessment
PaaS	Product as a Service
RoHS	Restriction of Hazardous Substances
SDG12	Sustainability Development Goal 12
UN	United Nations
WEEE	Waste from Electrical and Electronic Equipment

1 Introduction

The society moves towards a circular economy. This means that it is moving from a linear set-up where products are produced, used and wasted to a repetitive circle of produce, use, reuse and recycle. There are many reasons for this shift, but just considering that some materials are originating from finite sources requires that after use they must be circulated and not just wasted. This also means that the materials used in a product and how these materials are mixed in production and are separable in the end-of-life will be given more attention.

The shift towards a circular economy requires products that are described as sustainable. To label a product as sustainable requires that all stages of the product's circular life is assessed from several perspectives, for example: environment, health, finance, social etc. For each product there will likely be both pros and cons when evaluated.

New technology and possibilities in the future will require updated assessments if a product is to be considered sustainable or often rather more sustainable than other choices of products providing the same functionality. Laws and regulations that are adapted (or not adapted) for emerging technologies like digital cellulose solutions may also affect the assessment.

This guideline has been developed by RISE Research Institutes of Sweden for the Digital Cellulose Center (DCC) and its stakeholders.

1.1 Definitions

In tandem with the new technologies that emerge within the area of Digital Cellulose, there are new concepts that arise to help describing the sustainability of the prepared products. These concepts include "biobased electronics" and "green electronics". While it is natural to think that "biobased electronics" are products where the raw materials come from biobased sources, the concept of "green electronics" may be more difficult to grasp. In this work we consider that electronics fall under the "green electronics" umbrella, if the products are associated with activities such as:

- Using material with low environmental impact
- Using bio-derived or recycled materials
- Using biologically and materially recyclable materials
- Reducing energy use
- Shifting from subtractive to additive manufacturing processes

In the context of this report under the term electronics are included: sensors, actuators, communication hardware (e.g., antenna), circuits, energy harvesters and energy storage solutions.

1.2 Life cycle phases

In the circular economy, the life cycle of a product is described in terms of different life cycle phases, see Figure 1. The cycle starts from the extraction and processing of raw materials, virgin and/or recycled ones. In the design phase, the relevant raw materials are selected, and the product is designed according to product requirements, which followed by the production phase where the raw materials are combined into a final product. Under the use phase the product is consumed and, finally, reaches its end-of-life when no longer being used.

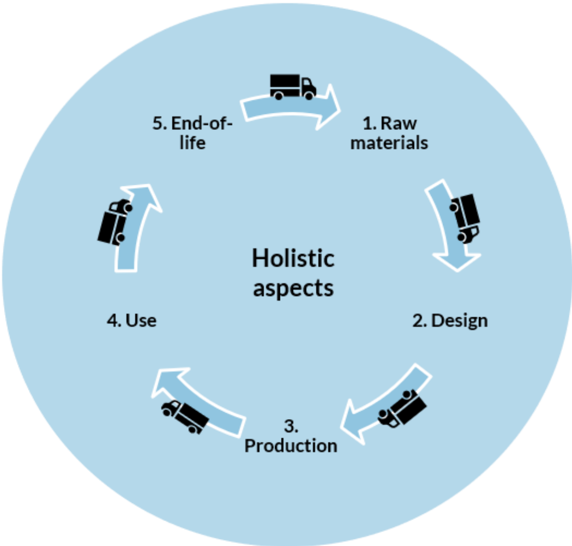


Figure 1 Life cycle phases of a product.

Adopting sustainable practices along the whole lifecycle of a product is a pre-requisite for enabling circular bioeconomy and at the same time serving as a competitive advantage.

1.3 Scope of this guideline

This guideline is intentionally short, acting as a hands-on sustainability assistance while developing green electronics within the DCC. It focuses on sustainability aspects in the following life cycle phases of green electronics:

- Raw materials
- End-of-life

These represent the start and the end of a life cycle and have been prioritized due to more and more stringent legislation requirements in EU as well as the fact that the choices made in the beginning of a life cycle may either lock or unlock the possibilities for a true circular set-up in the rest of the life cycle of green electronics.

1.3.1 Sustainability

We do appreciate that this is a complex task to assess whether a product is "green" or "sustainable" and this considering all the phases of a product life cycle. There are commonly used tools for this purpose such as Life Cycle Assessment (LCA), where all aspects of a product life cycle are mapped and also quantified in terms of environmental sustainability impacts such as global warming, acidification, eutrophication etc.

The mission of the current guideline is though to give a guidance through a number of broader sustainability aspects when selecting materials for the DCC green electronics. The guideline may be further advanced in the DCC phase 2.

1.3.2 Foresight

The future cannot be foreseen and therefore a scenario analysis of green electronics was applied, considering the interventions such as extent of stakeholder pressure and the extent of value-creating innovation.

In the scenario analysis, the emphasis was given on the two scenarios that represent extremes of a possible future for green electronics:

- *Stuck in the Mud* – a passive future development scenario, where the year 2045 is pretty much the same as year 2022.
- *Circular Dawn* – an active future development scenario, where a circular economy has become the new normal.

1.4 DCC materials

By combining different functionalities such as high electron conductivity, low electron conductivity (isolation properties), high ion conductivity, specific stimuli-responsivity, and barrier properties with the aim to achieve the required product functionality. Of these functionalities, it is perhaps most challenging to find biobased alternatives showing electron conductivity as high as of conductive metals.

Table 1 shows a generic list of materials being developed within the Digital Cellulose Center and their respective functions.

Table 1 Generic list of the materials used within the Digital Cellulose Center (DCC), including their respective functions

Function	**Material**	**Comments**
Electronically conductive	• Conducting polymers (e. g., PEDOT:PSS (poly(3,4-ethylenedioxythiophene)polystyrene sulfonate) • Metals (Al, Ag, Cu) • Carbon materials, e. g., graphite, graphene, carbon black	• Natural graphite is on the EU critical material list [2]. • Fossil-based natural graphite is used as a model for finding ways to produce its bio-based alternatives within DCC • Silver (Ag) is not on the EU 2020 critical list but may become a candidate in the future [3]. • Research is currently ongoing (in the DCC Projects 1, 3, 5, 6) with the aim to decrease the use of metals or to replace the metals by increasing the conductivity of conducting polymer composites and carbonized/ graphitized biomass.
Electronically non-conducting	• Lignocellulose (paper fibre pulp, nanocellulose, modified / functionalized cellulose) • Air	

Function	Material	Comments
	• Variety of polymeric inks, e. g., acrylate polymers or epoxy	
Stimuli-responsive	• Lignocellulose (paper fibre pulp, nano cellulose, modified / functionalized cellulose) • The polymer PEDOT:PSS (poly(3,4-ethylenedioxythiophene)polystyrene sulfonate) • Plant-based redox materials • Carbon nanotubes • Silicon (Si) particles	• All projects within the DCC work on responsive materials. E. g., biobased carbons in Project 1, redox materials in the DCC Project 2, swellable cellulose composites in Project 3, sensor materials in Projects 5 and 6.
Ionically conducting, i.e., electrolyte	• Salt water (NaCl, KCl, H_2O) • Cellulose hydrogels • Ionic liquids (salts with one part of a large organic molecule and the second part of a small inorganic anion or cation)	• Cellulose hydrogels are studied in the DCC Project 3, 4, and 6.
Barriers and semipermeable membranes which let selected ions pass through	• Lignocellulose (paper fibre pulp, nanocellulose, modified / functionalized cellulose)	• The DCC project 4 is currently studying membranes made of cellulose.
Casing / packaging	• Laminated paper (paper with thin layer of polymer or metal foil) and cellulose composites • Aluminum foils	• A common layer polymer is polyethylene (PE). • Aluminum foils are used in battery and supercapacitor applications.

2 Principles for sustainable material choices

This chapter summarizes principles for the choice of materials with lower sustainability impact, focusing on the two phases of a product life cycle: raw materials and end-of-life.

When applying the principles for comparison of different products with each other, it is important to consider functionality of a product (i. e. user requirements). An optimum combination of functionality and sustainability in products should always be sought. The recommended evaluation procedure to follow is to (see Figure 2):

1. Define the product idea or existing product to be analyzed and its function.
2. Evaluate the selected product systematically by applying the principles for materials choice.
3. Reflect over potential trade-offs between functionality and sustainability aspects while making material choices and suggest potential improvement options.

Figure 2 Recommended procedure for applying principles.

It should be mentioned that the principles are valid for all types of products regardless the application area. The evaluation results may serve as a robust ground for informed decision-making in R&D activities at universities, research institutes, companies and other societal stakeholders.

2.1 Raw materials

It is estimated that over 80% of all product-related environmental impacts are determined during the design phase of an energy-related product [4]. Making materials choices is an integral part of the product design process and hence an important exercise to do.

Below are the main principles for selection of raw materials for production of the DCC green electronics:

Choose renewable materials where possible

Renewable materials originate organic renewable resources such as living biomass that can be continuously replenished (e. g. such as wood, crops, algae etc). Inorganic renewable resources are coming from non-living sources such as waterm sund, and wind. They reduce demand for non-renewable virgin materials, including metals and fossil-based oils. In nature, unlike their non-renewable counterparts, the renewable materials form a biobased carbon cycle rather than contributing to extra fossil-based greenhouse gas (GHG) emissions.

While the biomass used for production of renewable materials should be grown and harvested using sustainable, responsible practices, the energy utilized in production of renewable materials should also be renewable. Cellulose is an example of an *organic* renewable resource and solar power is an example of an *inorganic* renewable resource.

The amount of renewable materials (and renewable energy) in a product can be expressed as a percentage of the total material (and total energy) quantities in that product, respectively (0-100%).

Choose recycled materials over virgin materials where possible

Recycled materials generally use less energy, water and other necessary resources in production, emitting lower amount of greenhouse gas (GHG) emissions, if compared to producing virgin materials of the same type. Recycled materials may also offer cost savings due to the above-mentioned reasons. When introducing recycled materials into products the following aspects are to be considered: technical feasibility, regulatory requirements, e.g., safety, food contact, if relevant, and consumer acceptance.

The amount of recycled raw materials in a product can be expressed as a percentage of the total material quantity in that product (0-100%).

Increased utilization of recycled raw materials in new products facilitates recycling and increase the demand for recycled raw materials. In some applications such as industrial batteries, EV batteries and automotive batteries containing rare metals, the discussions are ongoing on establishing minimum mandatory levels of recycled content from 2027 for e.g., cobalt and lithium [5].

Choose clean materials by avoiding the use of hazardous substances

Hazardous substances are the substances that are toxic to human health and environment, are explosive, corrosive, flammable etc. If used at levels that exceed regulatory limits, hazardous substances may pose risks to human health and environment.

European Chemicals Agency (ECHA) administrates a so-called Candidate List of substances of very high concern for Authorization [6]. The Candidate List is a part of REACH [7], the EU regulation on chemicals, containing over 200 very hazardous substances and is constantly being updated.

Restriction of Hazardous Substances in Electrical and Electronic Equipment (RoHS) [8] is the EU Directive restricting the use of hazardous substances such as heavy metals like lead, mercury, cadmium and hexavalent chromium (chrome VI), brominated flame retardants and ortho-phthalate plasticizer in electrical and electronic equipment). It is important to comply with RoHS for each component in electric or electronic products. EU Commission is evaluating the possibility to restrict additional hazardous substances within the RoHS Directive, including potential exemptions [9].

Choose non-critical raw materials

Reliable and unhindered access to certain raw materials is a growing concern within the EU and across the globe. To address this challenge, the European Commission has created a list of critical raw materials (CRMs) for the EU, which is subject to a regular review and update. CRMs combine raw materials of high importance to the EU economy and of high risk associated with their supply, e.g., lithium, cobalt, natural graphite [2].

The latest version of the EU 2020 CRM list contains 30 materials, including metals [2], see also Appendix “EU List of critical metals and materials”. Hence, the use of alternative materials in electronics should be prioritized where possible.

Optimize material efficiency

Optimized materials efficiency through reduced material consumption and thus reduced environmental impacts, e. g., elimination of unnecessary materials, choice of lighter materials, reduction of product size or volume.

It can be relevant to consider the choice of mono-materials over mixed or multi-layer materials, or alternatively separable materials. The potential solutions to consider could be the choice of easier separable raw materials, modular product design, adjusted functionality or new recycling process among other potential solutions.

2.2 End-of-life

Product, product components and materials can be recovered in a variety of ways in the end-of-life phase. In Europe, the EU Waste Framework Directive introduces a Waste hierarchy that defines a preferred 'hierarchy' of European waste management [10].

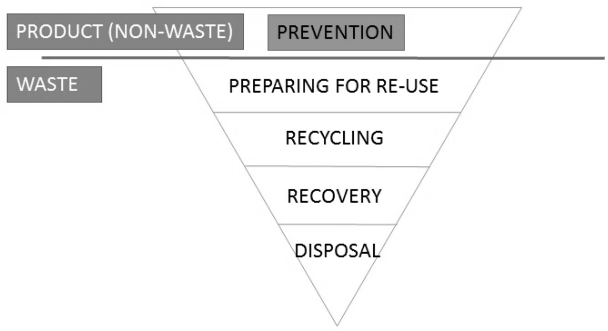


Figure 3 Waste hierarchy according to the EU Waste Framework Directive [10]. Preventing waste is the preferred option.

According to its principles, waste prevention (not creating waste in the first place) and re-use of products are the most preferred options, followed by recycling (including biological waste recycling) and then recovery of energy. Waste disposal through landfills should be the very last resort, see Figure 3.

EU Waste hierarchy principles

Priority	Principle	Explanation
1	Prevention	Taking measures before a product has become waste by generating less waste, keeping products in use longer (reuse, lifespan extension), using less hazardous substances.
2	Preparing for re-use	Checking, cleaning, repairing product or its spare parts so that they can be reused.
3	Recycling	Waste materials are reprocessed into new products, materials or substances for original or other purposes.
4	Other recovery	Incineration or incineration with energy recovery, gasification and pyrolysis which produce energy and materials from waste.
5	Disposal	Landfill

There are different collections and recycling targets for electric and electronic waste and battery waste introduced under Extended Producer Responsibility (EPR) schemes in the EU [11]:

- For industrial battery waste, the proposal for a new regulation includes requirements of collection rates of 65-75% by year 2025 and recycling requirements of used metals up to 95% depending on the metal and the ambition the new regulation will have, by weight. [12].
- For electrical and electronic equipment (EEE), the collection rate requirement is 65%, of which recovery and recycling / preparing for reuse targets vary between 55% - 85% depending on EEE application, by weight [13].

If electronics are integrated into other products, the regulations above apply as well. However, in practice integrated electronics may end up being collected or sorted by users into another product category and respective EPR (e. g. packaging, vehicle, construction waste etc), which have other collection and recycling rate requirements. For instance, considering smart and intelligent packaging application with integrated electronics, the material recycling target is 85% for paper-based packaging, by weight [14].

2.2.1 From 4R to 9R

It can be stated that the current EU legislation has strong focus on recycling. Circular economy however opens up novel possibilities for many more different circular business models of reuse and recycling than today´s linear economy.

If the EU Waste Hierarchy can be interpreted as a 4R framework (Reduce (i. e. prevention of waste), Reuse, Recycle and Recover, while Disposal not being a part of the circular economy), the full-scale circular economy could be further elaborated into 9R framework [15], see Figure 4.

Below is the summary of the 9R circular strategies which can minimize the production of waste as illustrated in Figure 4. The circular strategies are found along the whole life cycle of a product, follow an order of priority from R0 to R9 and are divided into three levels of circularity [16].

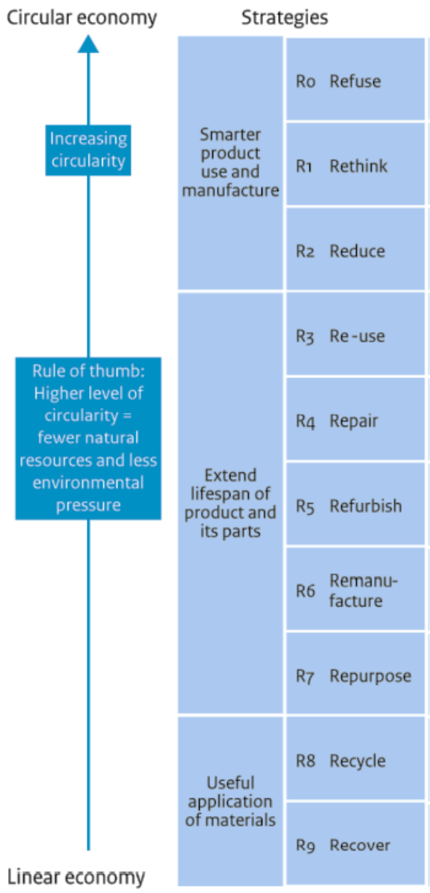


Figure 4 The 9R framework - circular strategies within the production chain, in order of priority from R0 to R9 [16].

Smarter product use and manufacturing

Circular strategies R0 – R2:

- **R0 Refuse:** Make product redundant by abandoning its function or by offering the same function with a radically different product.
- **R1 Rethink:** Make product use more intensive (e. g. through sharing products, or by putting multi-functional products on the market).
- **R2 Reduce:** Increase efficiency in product manufacturing or use, by consuming fewer resources and materials.

Extend lifespan of product and its parts

Circular strategies R3 – R7:

- **R3 Reuse:** Reuse by another consumer of discarded product which is still in good condition and fulfills its original function.
- **R4 Repair:** Repair and maintenance of defective product so it can be used with its original function.

- **R5 Refurbish:** Restore an old product and bring it up to date.
- **R6 Remanufacture:** Use parts of discarded product in a new product with the same function.
- **R7 Repurpose:** Use discarded product or its parts in a new product with a different function.

Useful application of materials

Circular strategies R8 – R9:

- **R8 Recycle:** Process materials to obtain the same (high grade) or lower (low grade) quality.
- **R9 Recover:** Incineration of materials with energy recovery.

2.3 Summary of sustainable material choices

Materials with low sustainability impact along the whole life cycle

To summarize, a lower sustainability impact, and in particular lower carbon footprint, can be achieved by applying the abovementioned strategies or combinations thereof:

- Choice of renewable and/or recycled materials, including:
    - Choice of renewable energy in materials production
    - Less energy intensive material production
    - Locally produced materials, thus requiring less transportation
- Choice of clean materials, by reducing or avoiding hazardous substances
- Choice of non-critical materials
- Optimize material efficiency e .g., by weight (lightweight), size, volume, choice of mono- or separable materials.
- Avoidance or reduction of waste (by considering EU Waste Hierarchy principles, alternatively the whole range of 9R circular strategies, from R0 Refuse to R9 Recover, whereas R0 Refuse is the most circular strategy).

It is though important to remember that optimizing one phase of a products' life cycle should not lead to sub-optimization elsewhere in the life cycle since sustainability of a product is determined over its entire life cycle. Hence, it is important to highlight that the strategies can be sought along the whole life cycle, thus enhancing the overall of green electronics.

3 Green electronics – a future scenario analysis

3.1 Introduction to scenario analysis

The scenario analysis exercise was performed within the DCC because projecting possible trends and developments onto the future may evolve the area of green electronics in different directions. Four future scenarios have been set up within the timeframe of 2022 - 2045, based on the foresight work with future e-waste [17] and probable societal interventions [18].

The interventions that the future scenarios are built upon are the following:

- *Extent of stakeholder pressure (high/low):*
    - Regulatory interventions
    - Behavioral/consumer changes

- *Extent of value-creating innovation (high/low):*
    - Technical improvements and disruptions within and outside the electronics value chain
    - Strategic interventions from businesses, e.g., business models, material and format changes

After defining the scenario interventions as above, four future scenarios were formed, see Figure 5.

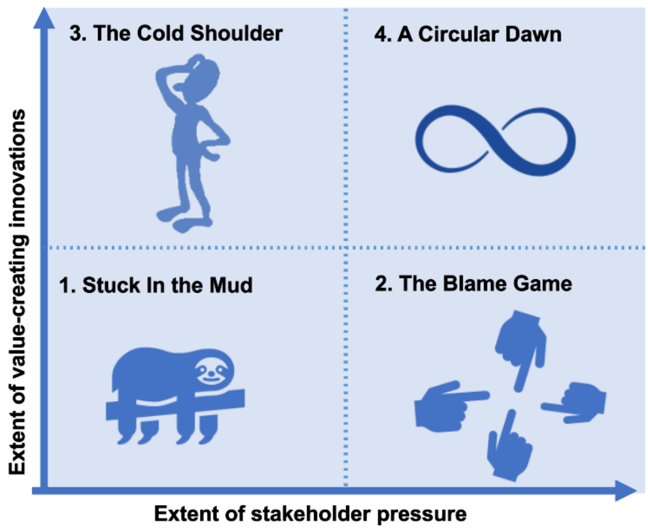


Figure 5 Four future scenarios based on two interventions: extent of value-creating innovation and extent of stakeholder pressure.

1. *Stuck in the mud*
   A business-as-usual scenario, where the year 2045 is more or less the same as year 2022.

2. *The blame game*
   Where the society has high expectations on circular economy, but governments, industry and end-users blame each other for not doing enough or not doing it in a right way.

3. *The cold shoulder*
   While proactive businesses are driving the change towards circular economy, the circular business models fail due to reluctance from end-users and lack of massive action towards overarching policy from law makers.

4. *A circular dawn*
   Where the circular economy has become a new normal and the whole society is thriving in a resource-efficient, circular and biobased economy.

Each scenario were guided by the following scenario factors:

- Policy
- Technology
- Business and End user
- Impact

The *Policy* factor is formed from the perspective of EU directives and other important strategic initiatives:

- While the WEEE [19] and Batteries directives focus on requirements of collection and recycling targets and also mandate producers to be in charge of WEEE and batteries in end-of-life, the RoHS [9] directive regulates the use of hazardous chemicals in manufacturing of electronics.
- Action Plan for the Circular Economy addresses the efficient resource use.
- UN's global Agenda 2030 [20] includes a goal of ensuring sustainable production and consumption (SDG 12 [21]).

The *Technology* factor is described from the perspective of new materials, sector-based growth and innovation:

- Growing use of clean technologies[1] requires electronic products such as solar panels and batteries.
- Electronics are increasingly used in buildings, transport systems, as wearables, integrated electronics etc. resulting in so called "cross-over products".
- More complex electronic products to achieve multiple functionalities.
- More energy efficient technologies replacing old items.

The *Business and End user* factor is represented by business models and end user behavior:

- Nowadays, linear business models are prevailing in electronics production, consumption and also recycling, mainly being based on economic incentives and not necessary considering the lifecycle impacts as well as design for end-of-life.

[1] *Clean technology* is broadly defined as any process, product, or service that reduces negative environmental impacts: through environmental protection activities, through the sustainable use of natural resources, or through the use of goods that have been specifically modified or adapted to be significantly less energy or resource intensive than the industry standard.

Manufacturers fulfill the required minimum of legislation requirements, while the majority does not operate beyond compliance.

- End users play an important role in consumption patterns and waste management of electronics. Different types of environmental awareness are growing among end users such as possibilities of repair, ethically produced electronics etc.

The *Impact* factor is elaborated from the perspective of resource use, environmental damage and toxicity.

- Since electronics are becoming more advanced, more complex in composition and used in increasing volumes, the environmental impact may increase accordingly in mining or cultivating the raw materials and production of electronics.
- Toxic chemicals used in manufacturing processes, may have large environmental impact.
- Material recycling practices are rudimentary due to lack of infrastructure and also lack of policies that promote recovery of all valuable resources.

3.2 Scenario analysis

The current version of the sustainability guidelines elaborates on two future scenarios of green electronics development: *Scenario 1 Stuck in the mud* and *Scenario 4 Circular Dawn*. The two scenarios were selected, among the 4 identified in Figure 6, for further analysis since they represent two extremes of the possible future for green electronics: one passive future scenario where the development in the society is, in relation to sustainability/circularity, slow and one active future scenario where high circularity potential in the society is achieved. Below is the description of the respective scenarios followed by the speculations on the contribution of the DCC green electronics.

3.2.1 Scenario Stuck in the mud

This is the business-as-usual scenario where Linear Economy (produce-use-waste economic model) still prevails. The year 2045 is more or less the same as 2022 due to a number of distractions and changes of priorities (e.g., pandemics, climate change, changing geopolitics). The scenario results in not only growing consumption of electronics but also high generation of electronic waste.

Policy The regulations stay more or less the same as of today. No significant advances in policies lead to lack of stricter incentives for product design towards a circular economy. Current policies have set targets for collection and recycling, but these are not strictly implemented (e.g., not enough enforcement of them). Manufacturers comply only with minimum legislative requirements with one exception due to high prioritization of human health issues in the EU: the RoHs Directive [9], that manufacturers conform with to a higher extent, leading to less hazardous chemicals used in production processes.

Technology Technological innovations continue to take place but without enough radical breakthroughs towards integrating a sustainable lifecycle perspective. Products are designed for functionality and economy of

	scale, without prioritizing design for recycling. Complexity of products consisting of many combined materials together with low concentrations of valuable substances in the materials makes the economy of recycling not feasible, which in turn results in loss of valuable materials.
Business and End user	Tougher economic situation does not allow for much-needed investments in R&D to enable more climate sustainable and circular solutions. The production, consumption and recycling are entirely based on economic incentives. Only a limited number of profitable circular business models in terms of reuse, take-back schemes and design for recycling is in place. End-users have poor consciousness of the environmental issues along the whole lifecycle and do not push manufacturers towards sustainable products. End-users are not willing to accept the change towards sustainable consumption patterns and eco-conscious end-users fail to act due to practical obstacles.
Impact	Growing negative environmental impact from electronics due to increased utilization of critical raw materials and fossil-based materials coupled with higher demand for electronics. The latter due to rapid digitalization of society (e.g., Internet of Things, 5G network). It is estimated that e-waste will grow from ca 42 million tonnes to 75 million tonnes by 2030 and 111 million tons by 2050 [17]. Hazardous chemicals are still used in manufacturing processes as no replacements have been found.

3.2.2 DCC green electronics in the scenario Stuck in the mud

In this business-as-usual scenario, the functionality of the DCC green electronics continues to develop at a gradual pace in order to meet the necessary product requirements. Since the energy density of green electronics is still limited, the first applications are B2B, where electronics size is not a critical parameter. Consequently, the DCC green electronics are found in large-scale applications like residential solar, wind and solar grid batteries. The market share of electronics in large-scale energy storage applications is emerging. The overall demand for green electronics is in its infancy.

DCC green electronics consist of biobased, non-hazardous materials. The minimum biobased content is 50% and may reach up to 80%.

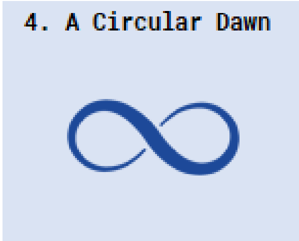
While functionality is a prioritized parameter, the circularity potential is not fully discovered yet. The world is divided, and recycling infrastructure is heterogeneous. As a result, the metal components in the DCC green electronics made of aluminum, silver and copper are recycled, but the material value of the renewable materials (more sustainable materials by origin) is considered low in the recycling systems. Hence, the renewable materials will mostly be incinerated with recovery of energy value. When incinerated, the biobased materials containing carbon will release biogenic carbon dioxide emissions to the atmosphere. In the incineration process, lignocellulosic components may cause SO_x emissions (e.g., formation of small particles in the atmosphere, acid rains, decrease growth of trees and plants), which need to be controlled at incineration plants in order not to affect both health and the environment.

End-users are not fully aware of the environmental challenges along the whole lifecycle of electronics and do not push businesses and policymakers towards green electronics.

End-users are neither willing to switch to more sustainable consumption patterns, services and products like green electronics. Only a few forerunning businesses succeed in finding profitable circular business models of reuse and recycling of green electronics in niched applications and for B Corporations[2].

3.2.3 Scenario Circular Dawn

Sweden has reached its carbon neutrality in year 2045 and EU has five years left until the target fulfillment. The transition to a resource-efficient, circular and biobased economy is the key in reaching the ambitious climate objectives. In practice, this is enabled by re-thinking production and consumption practices and innovations. All stakeholders are committed to consider a lifecycle approach, from raw materials selection to end-of-life management.



Policy Governments enforced more stringent environmental legislation, being supported by businesses and driven by consumers. The focus lies on renewable energy and less-intensive raw materials, production and consumption. Reuse of products and components prior to recycling is encouraged. End-of-life management is facilitated by design guidelines for recycling. All lifecycle stages of electronics are being addressed and aligned for retention of product or material value - there is no waste, only resources.

Technology The society is thriving with plenty of innovative technologies and initiatives. Information technologies such as 5G and IoT enable and accelerate the circular economy rapidly. Investments into circular business models of recycling and reuse explode with the aim to retain value of products and product components as long as possible in value cycles. While products are circular by design (e. g., last longer, modular, spare parts available, recyclable), innovative recycling technologies allow for easy product disassembly and subsequent recycling of components.

Business and End user Businesses drive the change towards circular production and consumption practices, benefiting from profitable circular business models. A shift in responsibility, from Extended Producer Responsibility (EPR) for electronics and batteries to so-called Producer Lifecycle Ownership (when the producer retains the ownership over products, thus becoming the raw material supplier for their new products) takes-off by businesses. Hence, end-users consume more products as services (PaaS), instead of owning them. Electronics are either used in stand-alone equipment or are integrated into products (e. g., in buildings, wearables). End-users are incentivized to reuse products, as well as collect and sort waste.

[2] B Corporations are benefit corporations or companies that create positive impact on society, employees, the community and the environment in addition to earning profit.

Impact	A combination of product and product component reuse, material recycling and responsible sourcing of virgin raw materials ensures good practices despite rapid growth in electronics consumption. Hazardous chemicals in production processes are replaced with more environmentally-sound alternatives to a high extent. Economic values are being aligned with environmental values in the electronics lifecycle.

3.2.4 DCC green electronics in the scenario Circular Dawn

A circular approach to everything produced and consumed have shifted the development and manufacturing of electronics towards environmentally sound materials and processes by the use, for example, of renewable or recycled resources and by implementing circularity in the end-of-life.

In this truly circular scenario, the DCC green electronics have fulfilled their functionality in terms of energy density. The functionality is achieved due to rapid development in the area. The DCC green electronics can now be found in a variety of applications such as wearables, electronics integrated in textiles, buildings, clean technologies (e.g., photovoltaic panels, large batteries). They are complementing other more conventional energy storage solutions.

DCC green electronics solely consist of renewable, non-critical and non-hazardous materials. While products continue to miniaturize and become sophisticated in material composition to fulfill their function and quality, these are designed in a modular approach and allow for disassembly and subsequent recycling in the end-of-life (design for assembly and disassembly). Bioderived graphene processing have gone down in cost considerably and now end up in conductivities (compare with Moores law) adequate to replace metal-based ink in certain applications, e.g., current collectors in energy storage, electrically driven sensors and actuators, and low demanding circuit components.

Businesses are also flourishing due to profitability of the circular business models of reuse, i. e. not only recycling. The stand-alone or integrated DCC green electronics are rented by function, including maintenance services. After their useful service life, electronics are returned to their producers for further reuse, upcycling or downcycling. Hence, the value is found in material flows along the whole life cycle, starting from the choice of materials with less environmental impact to cycling the products, product component or materials into new material loops.

There are new material flows at recycling stations that enable maximum value recovery of green electronics. Automated and tailor-made separation and sorting technologies support value recovery. Low carbon footprint impact is achieved through green electronics. All low demanding electronics are now green and the total market for electronics have expanded considerably. Electronics applications have expanded hugely within construction, interior design, packaging, textiles medical technology and health, energy grid, and farming.

4 DCC sustainability checklist

The DCC has an important role to play in transforming electronics in the circular bioeconomy. Biobased materials such as cellulose are abundant renewable raw materials and can replace raw materials with high sustainability burden.

As a guide to reaching the future scenario *Circular Dawn,* follow the steps in the DCC sustainability checklist below. By doing so, the choices of renewable raw materials in the development of the DCC electronics can be evaluated and optimized from a life cycle perspective, thus preventing potential sub-optimisations somewhere else in the life cycle of electronics.

4.1 Define product and function

1. Specify the product and its function:

Product name	Function (product requirements)
E. g., Battery for window alarm	Stationary smash window alarm, charged once a year, 15-year-life (corresponding to 15 charging cycles), indoor, status communication once a month and alarm signal if window smashed.

2. Provide the list of materials (with their respective quantities) present in the product:

Function	Material	Mass proportion (kg)	Percent proportion (%)
E. g., Casing	Paper	0,1	5%
Total:			

4.2 Evaluate product

In the product evaluation step, answer the checklist questions below:

Table 2 Sustainability checklist with focus on raw material and end-of-life life cycle phases of a product

Sustainability parameters	Supporting questions	Answers
	Raw materials:	
EU Critical Raw Material list	Are there any materials that are listed on the EU Critical Raw Material list [2]? See the list in the Appendix section.	
Hazardous substance	Are there any of the materials listed on the ECHA list of Hazardous substances [6]? Check also whether your material contains any hazardous substances, e.g. in pastes, solvents, additives.	
Renewable materials	What materials are originating from renewable sources (both organic/bio-based and inorganic)?	
	What materials are non-renewable, i.e., fossil-based or mined?	
Recycled materials	Is it possible to replace materials originating from virgin, renewable sources with recycled materials, fully or partially?	
	Is it possible to replace virgin fossil-based and mined materials with recycled materials, fully or partially?	

Sustainability parameters	Supporting questions	Answers
List of materials	How many materials and substances do you use?	
	Define the respective proportions of the above	
Using less material	How well are you aware of how much of the material you need to achieve the required functionality?	
End-of-life:		
Reuse	When approaching end of life, is there a clear indicator that the product is not performing according to its function?	
	When approaching the end-of-life, is it possible to reuse, repair, refurbish, remanufacture or repurpose the product or product components to prolong their life?	
Recycling	Check if the product will be: 1) collected, 2) sorted and 3) materials in the product recycled in the recycling infrastructure. In the recycling process, is it possible to process materials to obtain the same (high grade) or lower (low grade) materials quality?	
	If the product will end up outside the recycling infrastructure, how it will be handled then? E.g., incinerated.	
Holistic aspects		
Legislation - Recycling targets and other legal requirements	Check the collection, reuse and/or recycling targets in the WEEE directive, the Battery Directive, the Packaging and Packaging Waste Directive – how does your product support recycling targets in the intended product application? Check also other relevant legal requirements, e.g., RoHS directive on hazardous substances etc.	

4.3 Reflect and Optimize

Based on the answers from the sustainability checklist above, weight the pros and cons and start iterating on optimization options for your product, with both functionality and sustainability in mind.

Reflect and optimize with the below recommendations and questions as inspiration:

- Functionality is the key to success – but with the intended use in mind:
    - Is it possible to use a less conductive material for the intended use, if that would make the end product (more) recyclable?
    - Is it possible to use less material and still obtain the intended functionality?
    - Is it possible to replace the material with a material of lower impact while keeping the functionality on the acceptable level?

- An electrical product requires materials with different capabilities, so the product will probably consist of a mix of different material. Can the materials used consist of different forms of the same starting material, which would make recycling of the product easier?

- Metals have high electric conductivity, but once used, consider how pure the metal must be to provide the property you are looking for. Recycled metal may be less pure (alloyed with other metals) than the virgin metal but may work in your application.

- There are already today procedures for retrieving metals from waste, but when the metals are in low concentrations, they may be lost in other waste flows. If you use metals – can they be easily separated from the rest, thus making it likely they will be recovered by recycling or reuse?

- Avoid materials on the EU List of critical metals and materials. Of the materials used today in DCC, natural graphite is on the list [2].

- Avoid hazardous substances that are listed on the ECHA-list [6].

- Out of 9 different R-strategies (see Figure 4), what is your main strategy of going forward, and why? Consider also a possibility of combining different R-strategies together in order to maximize circularity of your product, components or materials.

5 References

[1] DCC Website, https://digitalcellulosecenter.se/.

[2] EU list of critical raw material updated every three years, https://ec.europa.eu/growth/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en.

[3] Review of critical metal dynamics to 2050 for 48 elements – ScienceDirect, https://www.sciencedirect.com/science/article/pii/S0921344919305750.

[4] Design Council, EU - https://joint-research-centre.ec.europa.eu/scientific-activities/sustainable-product-policy_en.

[5] European Commission, New regulatory framework for batteries, Setting sustainability requirements, https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/689337/EPRS_BRI(2021)689337_EN.pdf, accessed at 2021-12-16.

[6] European Chemical Agency – list of substances of very high concern. It is continuously updated. https://echa.europa.eu/candidate-list-table.

[7] REACH, https://echa.europa.eu/sv/regulations/reach/legislation.

[8] European Commission, DIRECTIVE 2011/65/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment, 2011, https://eur-lex.europa.eu/legal-content/EN/T.

[9] RoHS exemptions, https://rohs.exemptions.oeko.info/index.php?id=288.

[10] Waste hierarchy, EU Waste Framework Directive, https://ec.europa.eu/environment/topics/waste-and-recycling/waste-framework-directive_en.

[11] DIRECTIVE 2006/66/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC, accessed at 2021-12-11.

[12] Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020.

[13] DIRECTIVE 2012/19/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, of 4 July 2012, on waste electrical and electronic equipment (WEEE).

[14] European Parliament and Council Directive 64/62/EC of 20 December 1994 on packaging and packaging waste. Link: https://www.compostnetwork.info/wordpress/wp-content/uploads/CELEX_01994L0062-20180704_EN_TXT.pdf.

[15] Conceptualizing the circular economy: An analysis of 114 definitions, Julian Kirchherr* , Denise Reike, Marko Hekkert, https://www.researchgate.net/publication/320074659_Conceptualizing_the_Circular_Economy_An_Analysis_of_114_Definitions.

[16] 9 R Framework https://www.researchgate.net/publication/320074659_Conceptualizing_the_Circular_Economy_An_Analysis_of_114_Definitions/figures?lo=1.

[17] Future E-waste Scenarios; Parajuly, K.; Kuehr, R.; Awasthi, A. K.; Fitzpatrick, C.; Lepawsky, J.; Smith E.; Widmer, R.; Zeng, X. (2019). StEP (Bonn), UNU ViE-SCYCLE (Bonn) & UNEP IETC (Osaka).

[18] RISE, Intressentföreningen Packforsk, Rethinking the packaging system – Innovation manifesto, 2020..

[19] European Commission, Summary document of the Waste electrical and electronic equipment rates and targets, https://ec.europa.eu/eurostat/documents/342366/351758/Target-Rates-WEEE/b92a549c-7230-47ba-8525-b4eec7c78979, accessed at 2022-03-01..

[20] United Nations, https://sdgs.un.org/2030agenda , accessed at 2022-03-01.

[21] United Nations, https://sdgs.un.org/goals/goal12, accessed at 2022-03-01.

6 Appendix

6.1 EU List of critical metals and materials

Every third year, the EU lists critical raw materials is being updated. The latest version of the list is from year 2020.

Table 3 Table 3 EU list of critical raw materials, the up-to-date version from year 2020 (new as compared to 2017 **in bold**).

Antimony	Hafnium	Phosphorus
Baryte	Heavy Rare Earth Elements	Scandium
Beryllium	Light Rare Earth Elements	Silicon metal
Bismuth	Indium	Tantalum
Borate	Magnesium	Tungsten
Cobalt	Natural graphite	Vanadium
Coking coal	Natural rubber	**Bauxite**
Fluorspar	Niobium	**Lithium**
Gallium	Platinum Group Metals	**Titanium**
Germanium	Phosphate rock	**Strontium**

More information on the list and how the critical raw materials were selected, see: https://ec.europa.eu/growth/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en