EPoSS.
European Association on Smart Systems Integration

ECS Sustainability and Environmental Footprint

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1 Executive summary

In this White Paper, experts from the smart systems integration community of EPoSS present their views on the state-of-the-art and future technology targets in the green electronic components and systems (ECS) domain – following the EU laws and international standards set up to support the European Green Deal – and provide recommendations to European stakeholders (both public and private) regarding the next shared actions that should be taken.

1.1 Identified challenges within the green ECS domain

The global context of hazardous wastes shows that waste out of ECS – known as e-waste (also called "waste from electrical and electronic equipment", shortened to WEEE for regulatory purposes) – is expected to grow up to 9 kg per capita and a total of 74.7 Mt by 2030. Of Europe's contribution of around 12 Mt in 2019, only 42.5% was collected and recycled. The circular economy, with its 9R[1] framework and eco-design, are the main tools to reduce the environmental footprint of ECS, with life-cycle assessment as a framework for also identifying hotspots and checking results of the intended reduction. But ECS themselves can also be regarded as an enabler for a more circular economy.

The challenges for R&D and regulation for green ECS and a successful reduction of e-waste identified by the EPoSS expert group are summarised in Fig. 1.1.

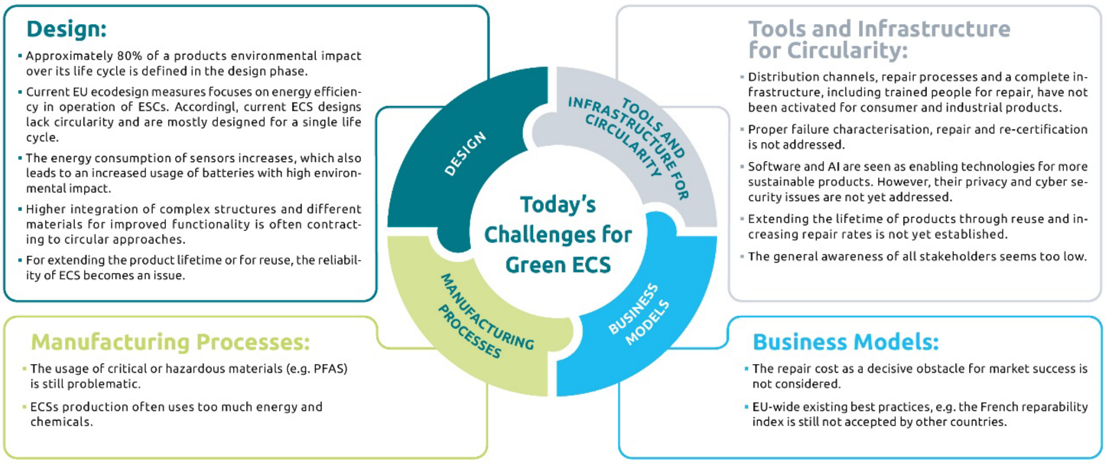

Figure 1.1 Summary of identified challenges for green ECS and successful reduction of e-waste

1.2 Overall and specific recommendations

The experts have compiled a set of overall recommendations that serve as a framework for R&D projects and regulations (see Fig. 7.1) so far not sufficiently addressed by the existing Horizon Europe and Key Digital Technologies (KDT) projects. These recommendations include establishing a collaborative platform for eco-designers, manufacturers and recyclers to coordinate and accelerate efforts, as well as create awarness for the issue. Additionally, there is a call to motivate and

[1] Refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover.

generously reward green innovations and environmentally friendly technologies, and the need to establish a transparent and up-to-date database. It is emphasised that the new EU eco-design should establish indexes with clear benchmark values for the 9Rs, and that special attention is needed to address electronic components that are only indirectly impacted by current and planned product group measures.

Furthermore, the experts identified some specific and technical actions that need to be added to the current ECS-SRIA[2] Roadmap for more sustainable ECS and a reduction of e-waste (see Fig. 1.2).

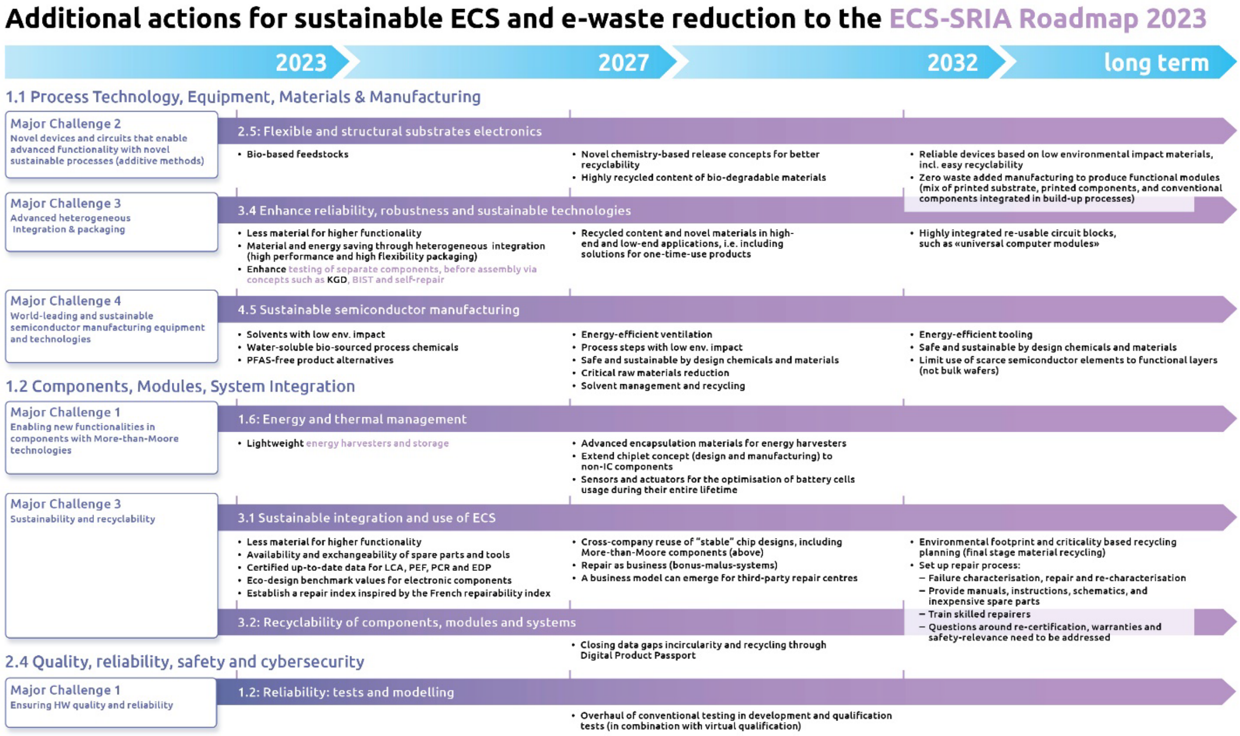

Figure 1.2 Specific and technical actions that need to be added to the current ECS-SRIA Roadmap for more sustainable ECS

The recently launched projects in Table 3.1 are developing green technologies for functional electronics and taking the first steps towards eco-designed smart electronic systems. However, there remains much opportunity for new EU initiatives in the domains of green manufacturing, recyclability, repairability and new green business models.

[2] Sixth edition of 'Electronic Components and Systems (ECS) Strategic Research and Innovation Agenda (SRIA) 2023-ECS-SRIA 2023' (see https://www.smart-systems-integration.org/publication/ecs-sria-2023).

2 Introduction

2.1 How to read this document

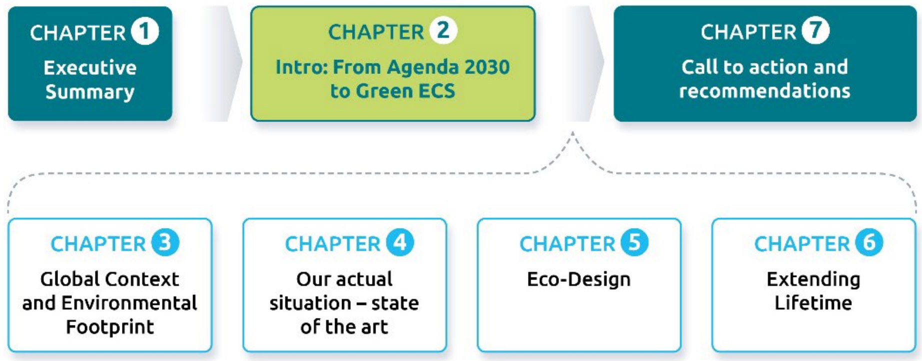

Figure 2.1 Chapter overview

Chapter 1 summarises the position of EPoSS for readers already knowledgeable on the topic. Chapter 2 introduces the topic and offers a cogent overview of the global context with an important starting point: the Agenda 2030 of the United Nations and its 17 sustainability development goals (SDGs) that this White Paper refers to.

Chapters 3–6 provides a range of detailed views and frameworks on ECS, explaining the current global context and expectations on future challenges. The content of these chapters underscores recommendations to minimise the ECS environmental footprint with faster and better results to support the EU Green Deal in an even more sustainable way.
Chapter 7 summarises all the recommendations and calls for further action for Europe.

2.2 From Agenda 2030 to Green ECS

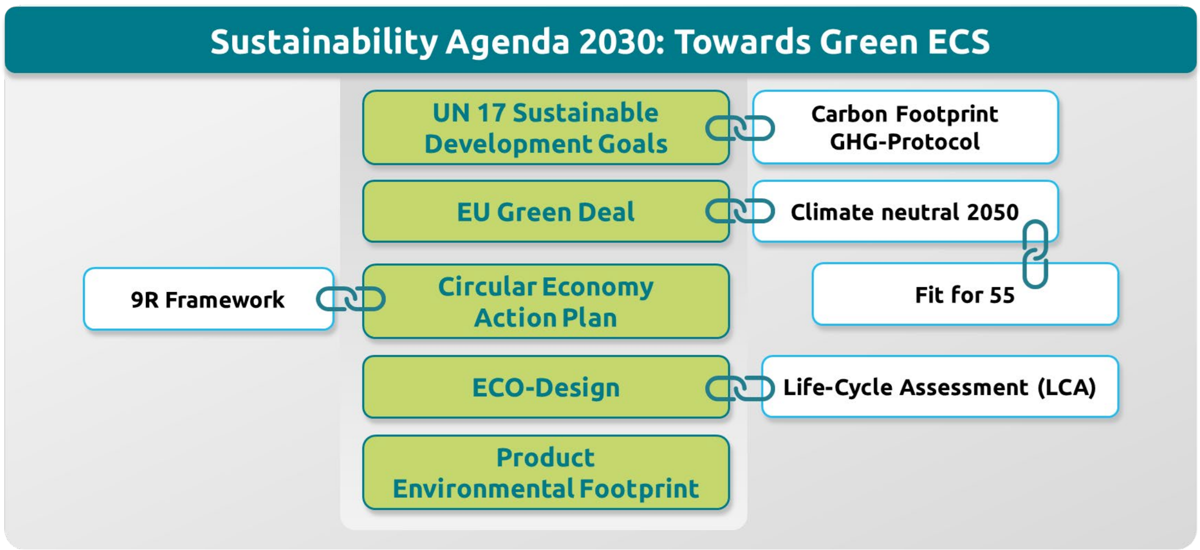

Figure 2.2 Sustainability Regulations and Standards

Agenda 2030, launched by the UN in New York in 2015, aims to target all activities of humankind, our planet Earth and the global complexity of economy, society and ecology. The EU Green Deal, as a reaction by the EU Commission to Agenda 2030, has also had a tremendous impact on national laws and regulations, as well as on new standards that will continue to affect research and technology, business and citizens over the coming decades. Climate change and greenhouse gas (GHG) emissions have implications for both humans and natural systems, and could lead to significant impacts on resource availability, economic activity and human wellbeing. There is a need for an effective and progressive response to climate action (SDG#13) on the basis of the best available scientific knowledge. Such a response will also refer back our activities on all 17 SDGs, and we will need further adaption to regulations and standards. However, we also emphasise here a more circular economy through eco-design and the 9R framework, as well as greater data analysis and comparison for GHG targets or Lifecycle Assessments (LCAs) and product environmental footprint.

How can ECS establish and strengthen sustainable and resilient value chains supporting the EU Green Deal by following EU laws and international standards? How will it be best to handle and generally regulate e-waste (WEEE) in the near future?

On one hand, ECS are essential elements to enable other sectors to mitigate climate change and reduce their environmental impact towards green ECS. For instance, SDG #7 – the supply of clean, affordable and secure energy or resource-efficient buildings, smart mobility, as well as healthy and environment-friendly food supply chains – will all rely on ECS to achieve their ambitions. **It is estimated that digital technologies have the potential to save almost 10 times more emissions than they produce by 2030.** In other words, this will enable the decoupling of economic growth from resource use, which is again a key target of the European Green Deal. However, it is important to take indirect impacts and rebound effects of ECS into account [3],[4].

On the other hand, an individual company involved in the ECS sector itself needs to use its own potential to improve the energy performance and disposability of electronic components, and to reduce their environmental footprint by means of cleaner and greener production processes, more circularity and less energy and material consumption towards green ECS.

The different technologies of these two lines of combining green and ECS were summarised by Henri Rajbenbach (European Commission) at the KDT-JU workshop in 2021 (see Table 2.1). In this White Paper, however, we will focus on green ECS technologies. Different challenges will therefore be listed and recommendations made to better achieve the targets of the EU Green Deal.

[3] Bol, D. "The Environmental Footprint of IC Production: Review, Analysis, and Lessons From Historical Trends," in IEEE Transactions on Semiconductor Manufacturing, 2023, 36(1)

[4] Raskin, J.-P., *et al.*, "Could Unsustainable Electronics Support Sustainability? ", Sustainability, **2021,** 13, 6541

Table 2.1 Green ECS and ECS for green as summarised by Henri Rajbenbach (European Commission) at the KDT-JU workshop in June 2021

Green ECS	**ECS for Green**
New materials and substrates: wide bandgap, flexible	Multi-sensing systems for environmental monitoring
Low-power computing architectures: neuromorphic, quantum	Post-Covid teleworking environments
Ultra-low power edge processing	Artificial intelligence (AI), exploiting database for good data, coming from distributed sensors, in real time
Si-photonics, spintronics	Further digitalisation of key application areas: mobility, agriculture, health, industry, energy
Fully depleted silicon on insulator (FDSOI)	Reducing industrial environmental footprint: energy efficiency, disposability of electronics
In-memory computing	

3 ECS and the global environmental context

Chapter 3 focuses on ECS in a global and European context. First, the global e-waste situation will be debriefed and its circumstances in geographical regions shared. Specific trends in the EU will also be highlighted, before the existing initiatives and legislations are presented. The circular economy model as a solution to reduce e-waste will be explained, including the definitions of LCAs, 9Rs, environmental footprint impact categories and the ECS product lifetime.

3.1 Global e-waste

E-waste is the term used for discarded electrical or electronic devices by the UN Basel Convention. The reasons for discarding devices can vary, from fully functional items that are no longer required by their owner, to damaged items that have reached the end of their useful life. The Basel Convention addresses the transboundary movement of hazardous wastes and their disposal, but also includes aspects related to the remaining value of devices due to their metal content. Today, there exists relatively good evaluation of e-waste generation worldwide. Indeed, according to the dedicated UN institute, the United Nations Institute for Training and Research (UNITAR), which regularly publishes an e-waste monitor, around 53.6 Mt of e-waste was generated in 2019[5]. This figure was calculated and based both on the production of electric and electronic devices and their expected lifetime, and waste statistics from several countries. It does not include items that were sold or donated, but does for what was passed to specialised companies for handling. It thus includes items that are still functional or have functional components that can be used as spare parts. The total amount of e-waste represents around 7.3 kg per capita globally. With the increasing place of electronic devices in our daily lives, this number has significantly grown since 2014 (44.4 Mt produced, 6.4 kg per capita) and is expected to grow further by 2030 (74.7 Mt produced, 9.0 kg per capita).

At the global scale, in 2015 the UN launched the ambitious 'Transforming Our World: The 2030 Agenda for Sustainable Development‘, which identified the 17 SDGs. Reducing e-waste is an integral part of many different SDGs. – for instance, SDG 12 focuses on “Ensuring sustainable consumption and production patterns” to define and harmonise recycling rates.

3.2 Geographic regions

It has been noted that electronic device ownership varies by income level. As a consequence, e-waste production is also dependent on household income levels, and consequently on geographic region. The most e-waste was generated in Asia, with **24.9 Mt** in 2019, due to a large population, but with only 5.6 kg per capita. **12 Mt** and **13.1 Mt**, respectively, were generated in the same period in Europe and the Americas, but with 16.2 kg and 13.3 kg per capita. Asian production and domestic consumption is expected to increase over the next decade due to economic growth across the whole region.

[5] Forti, V., Baldé, C. P., Kuehr R. and Bel, G., 'The Global E-waste Monitor 2020: Quantities, Flows, and the Circular Economy Potential‘, UNITAR, Dec. 2020 (see https://www.itu.int/en/ITU-D/Environment/Documents/Toolbox/GEM_2020_def.pdf).

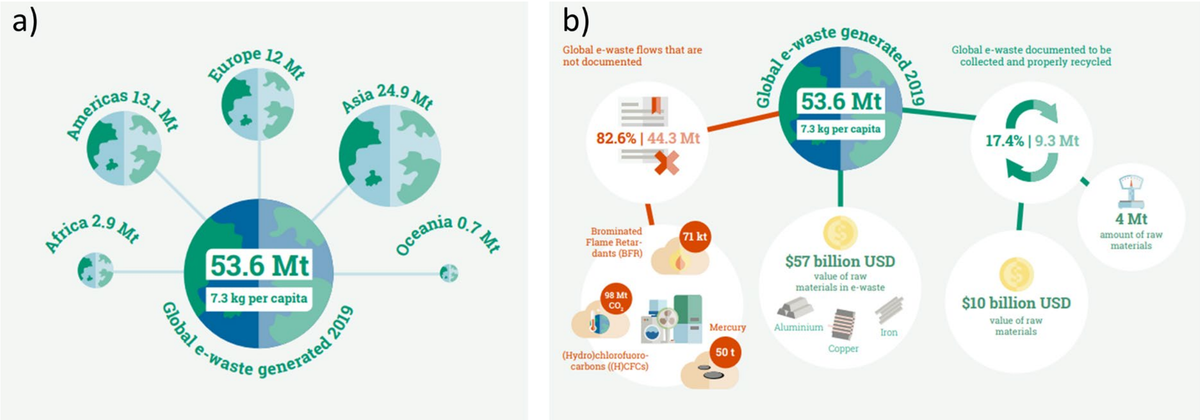

Figure 3.1 (a) Global e-waste generated in 2019; (b) Fraction recycled. Illustrations: NU/UNITAR SCYCLE – Nienke Haccoû[6]

The European Union is one of the most advanced actors in e-waste recirculation processes. Indeed, in this region 42.5% of e-waste is documented to be collected and recirculated as product or component or recycled as material, whereas this is only the case for 9.4% in Americas and 11.7% in Asia. This can be explained by the clearer European and national political support for such initiatives.

3.3 Existing initiatives

Circular economy concepts are proposed to increase the utilisation of resources and contribute to implementing sustainable industrial production practices. In general, a shift from existing linear economy business models is expected to provide advantages on many issues. Circular economy business models could also provide benefits for economies and environment by preserving the value of goods and infrastructure, reducing supply risks, boosting competitiveness and innovation, and creating job opportunities while also addressing environmental impacts of resource use and emissions.

For instance, the European Commission presented in 2020 their new **Circular Economy Action Plan** (CEAP) to limit waste generation and encourage recycling, product repair and reuse. Part of this initiative is the digital product passport, which informs end-customers and businesses about products' sustainability. In addition, the CEAP illustrates loss of value, increasing uncertainty around supply, waste and environmental degradation as negative impacts of linear economy models.

[6] ibid.

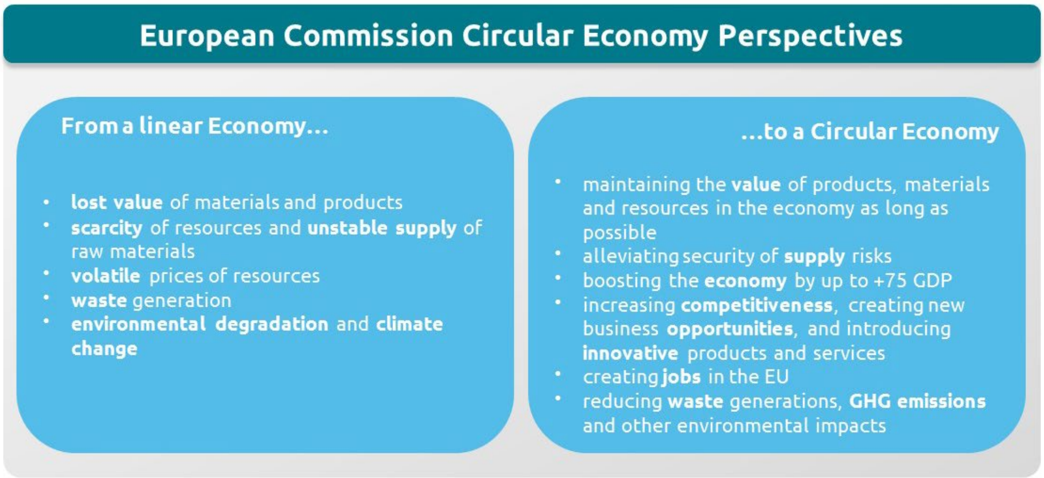

Figure 3.2 European Commission Circular Economy Perspectives (according to EU Action Plan for Circular Economy, 2016)[7]

The CEAP has been adopted as part of the Green Deal Framework, and includes electronics and information and communication technology (ICT) as a key product value chain. In particular, COM/2020/98, entitled “A New Circular Economy Action Plan for a Cleaner and More Competitive Europe”, describes several challenges for electronics and ICT. For instance, WEEE is growing annually at a rate of 2%, with the estimated recycling rate being less than 40% for electronic waste and thus considered to be low. There is also a general loss of value due to design choices when fully or partially functional products are discarded because they are not repairable, the battery cannot be replaced, the software is no longer supported, or materials incorporated in devices are not recovered.

Based on identified challenges, regulatory measures under the Ecodesign Directive are intended to establish design for energy efficiency and durability, repairability, upgradability, maintenance, reuse and recycling. Further details were indicated in the Ecodesign Working Plan 2022–2024, 2022/C 182/01, which was announced by the Commission in the *Official Journal of the European Union*.

Among its conclusions was a focus on electronics and ICT as a priority sector for implementing the ‘right to repair’, including a right to update obsolete software. Regulatory measures are also intended for mobile phone chargers and similar devices, including the introduction of a common charger (and interface), improving the durability of charging cables, and a scheme to return or sell back old mobile phones, tablets and chargers.

Many of the areas mentioned in this document are already regulated in legislation, and thus a review of existing regulations is expected. This would include EU rules on the restriction of hazardous substances in electrical and electronic equipment, and aims to provide guidance to improve coherence with relevant legislation, including the EU’s regulation on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), the Restriction of Hazardous Substances (RoHS) and Ecodesign Directives.

[7] EEA, 'Closing the loop – An EU Action Plan for the Circular Economy, 2016 (see https://www.eea.europa.eu/policy-documents/com-2015-0614-final).

In general, the concept of the circular economy (CE) builds on well-implemented strategies to prevent waste generation, and includes eco-design rules during product design phase and measures for utilising products and components after a use phase. Materials are also reclaimed from products that have reached their end of life. CE emphasises the importance of business models that foresee a shared use of goods, as well as the implementation of product service systems in which the producer retains ownership of a product and is responsible for ist maintenance and repair. The implementation requires more ICT in the form of both hardware (sensors, monitoring, control) and software, thus increasing resource demand initially, during operation and at end-of-use/end-of-life (EoL).

In many cases, CE is linked with future products, although it also involves aspects of closing product loops and material loops as important components (both for newly designed options and products that are on the market and were designed before CE was established).

On a national level, France has imposed the display of a repairability score on sold electronic components. In addition to major government initiatives, there are also several grassroots initiatives and consumer groups that are active in this area – such as HOP in France and Runder Tisch Reparatur in Germany – that critically accompany the legislative process, among other things.

3.4 Overview over current Horizon Europe and KDT projects

As shown in Table 3.1, there are currently eight Horizon Europe and two KDT projects that will help develop new technologies by the European academia and industry towards more green and sustainable electronics solutions.

Table 3.1 Overview over current Horizon Europe and KDT projects

HORIZON-CL4-2021-DIGITAL-EMERGING-01-31: Functional electronics for green and circular economy
BAMBAM – Building Active MicroLED displays by Additive Manufacturing **CircEl-Paper** – Circular Economy Applied to Electronic Printed Circuit Boards Based on Paper **ECOTRON** – How to minimise the ecological footprint for functional electronics **HyPELignum** – Exploring wooden materials in hybrid printed electronics: a holistic approach towards functional electronics with net zero carbon emissions **SusFE** – Innovative Processes and Methodologies for Next Generation Sustainable Functional Electronic Components and Systems **SUINK** – Sustainable self-charging power systems developed by inkjet printing **Sustain-a-Print** – Sustainable materials and process for green printed electronics **UNICORN** – Unveiling Innovation Potential of Circular Approaches in Automotive Electronics and Beyond
HORIZON-KDT-JU-2022-2-RIA – Focus Topic 2:Eco-designed smart electronic systems supporting the Green Deal objectives (research and innovation action, RIA)
• **EECONE** – European Ecosystem for green electronics • **SUSTRONICS** – Sustainable and green electronics for the circular economy

3.5 Reducing e-waste with a circular economy model: Quantifying environmental impacts

Established linear business models apply a make/use/dispose principle. Product EoL was not part of product development.

One approach to quantifying the use of resources, emissions and waste generation is LCA. LCA is a systematic analysis of the environmental impact of products during their entire life cycle ('from cradle to grave') – i.e. during production, the use phase and disposal of the product, as well as associated upstream and downstream processes, including the production of raw materials and supplies. The (linear) life cycle of electronic components and systems is shown in Figure 3.3 to illustrate this principle.

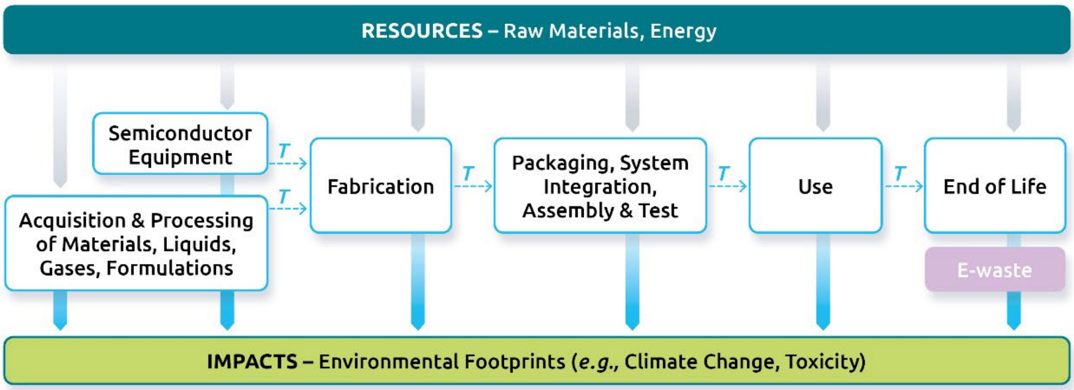

Figure 3.3 Traditional make/use/dispose life cycle for electronic components and systems (T refers to transport resources used at various stages of the life cycle)

The ISO 14040 standard on LCA defines a framework for the assessment procedure. LCA as a holistic approach predicts inclusion of several impact categories; for studies in the EU, a set of 16 impact categories are provided according to environmental footprint (see also Table 3.2). All extractions of resources from the environment (e.g. ores, crude oil) and emissions into the environment (e.g. waste, carbon dioxide) are considered as elementary flows, and included in an inventory and processed into environmental impacts in several categories.

A **circular economy model** would help reduce the environmental impact of production and consumption using a multitude of strategies, including recirculation for products and components and recycling of materials. From raw material mining, sustainable and eco-design, via production supplied with low carbon energy, to recycling: such a process should diminish the impact of electronic devices and any of their components. LCA can also be applied to evaluate the changes compared to a linear business model.

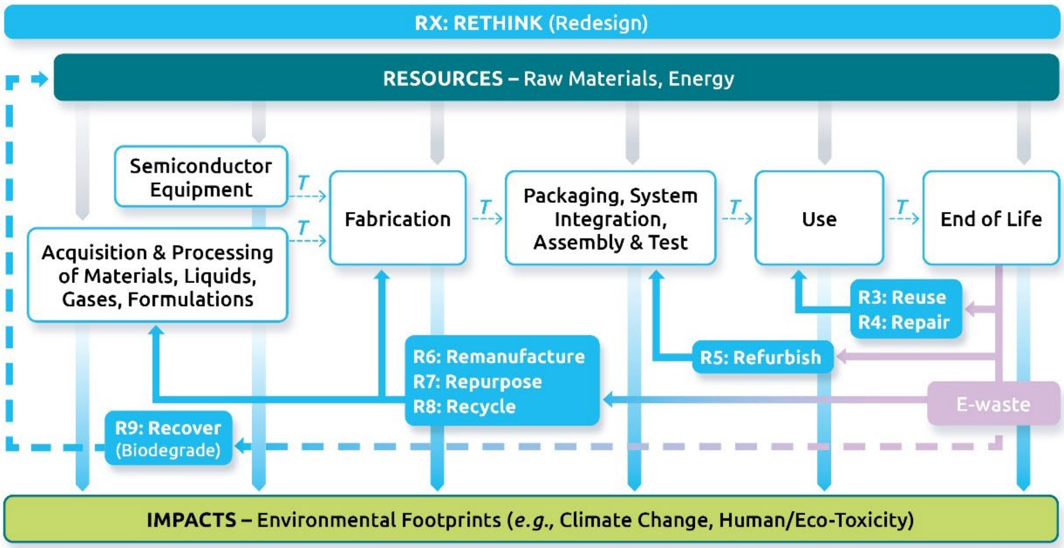

Figure 3.4 The eco-design contribution with the design for R approach in the green ECS framework

The transition from an initial make/use/dispose model will benefit from the inclusion of concrete actions. It can be described according to the 9Rs framework, which is described in Table 3.2 and categorises existing strategies to close loops and extend the lifetime of products. The framework is intended for a variety of products, and examples have been added for illustration. Note that not all strategies are applicable immediately for all industrial sectors.

Table 3.2 9R+1 strategies with description and examples from the ECS field based on the strategy presented by Potting *et al.*[8]. Reliability is seen as an important function but not as one of the Rs[9].

	Strategies	Description	Examples and clarification	Strategic domains
R0	Refuse	Phase out product/abandon function/use different product.	Telefax machines, services using physical storage such as CD or DVD.	Design: smarter product use and manufacture needs to be considered in design. For products, robustness and reliability need to be included in design decisions.
R1	Reduce Rethink	Make product use more intensive.	Shared use of washing machines and dryers.	
R2	Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials.	Using heat exchangers and similar approaches to utilise by-products. Industrial symbiosis and networks. Lean production.	
R3	Reuse	Reuse by another consumer of a discarded product that is still in good condition and fulfils its original function.	Consumer gives away or sells (old) devices that are still in working order.	Lifetime extension: Extension of the lifetime for the initial product or parts. The product is not fragmented. Products and parts that enter a second use phase need to be tested and a remaining use phase has to be determined – for example when used as spare parts. Reliability and robustness considerations are important to achieve the extended lifetime.
R4	Repair	Repair and maintenance of defective product so it can be used for its original function.	Fixing solder contacts or cracks. Can be applied for the same user or a new user. Minor changes.	
R5	Refurbish	Restore old, defective or obsolete products and bring them up to date (often by a third party).	Removing and replacing mainboards on used phones for platforms such as refurbed, Swappie and others. Substantial testing, cleaning and changes. Refurbished products are sold with a (shorter) warranty. Removed parts are used as spare parts (aftersales) or discarded.	
R6	Re-manufacture	Use of 'cores' of a discarded and defective products. Can imply that the original manufacturer is involved.	Mostly for investment goods such as machinery and engines, substantial testing, cleaning and changes. Removed parts are used as spare parts (internal, aftersales) or discarded. Google indicates that in 2016 36% of their servers in data centres were remanufactured machines.	
R7	Repurpose	Use of discarded products or its parts for a different function.	Using batteries from electric vehicles as storage options to be combined with PV panels/wind turbines for off-grid users. Only partial use of the product is implied.	
R8	Recycle	Process materials to obtain the same or different quality	Copper from cables and devices; disassemble, separate and fragment parts and products to use materials in production processes. Also includes chemical processing to obtain clean materials.	Material circularity; useful application of materials.

[8] Potting, J., Hekkert, M., Worrell, E. and Hanemaaijer, A., „Circular Economy: Measuring Innovation in Product Chains“, PBL Netherlands Environmental Assessment Agency, The Hague, 2016.

[9] Kirchherr, J., Reike, D. and Hekkert, M., "Conceptualizing the Circular Economy: An Analysis of 114 Definitions, Resources, Conservation and Recycling“, Volume 127, 2017, pp. 221–32 (see https://doi.org/10.1016/j.resconrec.2017.09.005).

R9	Recover	Using selected benefits of discarded materials: incineration of materials with energy recovery, using nutrients from food waste as compost.	Plastic incineration with coupled district heating in the Nordic countries. Benefits can be observed if the recovered materials replace other options, such as (fossil) fuels or mineral fertiliser.	

As indicated in Figure 3.4, different recirculation strategies can be combined – for example a product can be used, reused, refurbished and then recycled. Also, damaged components that are removed and replaced in a refurbishing process are potentially available for material recycling.

The following are indicators anticipated for a clear description of impact along the overall life cycle. The European Platform on Life Cycle Assessment (EPLCA) includes information on the Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF) methods as a common way of measuring environmental performance (EU Commission Recommendation 2021/2279). The PEF and OEF are the EU's recommended LCA-based methods to quantify the environmental impacts of products (goods or services) and organisations. To ensure this, the PEF guide developed by the European Commission includes several impacts categories (as listed in Table 3.3). Note that specific methods are also required, but have not been included here to improve readability.

Table 3.3 Environmental footprint profile impact categories[10]

Environmental footprint (EF) impact category[11]	**Impact category indicator**	**Unit**
Climate change, total[12]	Global warming potential (GWP100)	kg CO_{2} eq.
Ozone depletion	Ozone depletion potential (ODP)	kg CFC-11 eq.
Human toxicity, cancer	Comparative toxic unit for humans (CTU_h)	CTU_h
Human toxicity, non-cancer	Comparative toxic unit for humans (CTU_h)	CTU_h
Particulate matter	Impact on human health: Mass inhaled -> Disease incidences -> Human health impacts	kg $PM_{2.5}$ inhaled … *DALY*/ kg $PM_{2.5}$[13]
Ionising radiation, human health	Human exposure efficiency relative to U235	kBq U235 eq
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kg NMVOC eq
Acidification	Accumulated exceedance (AE)	mol H^{+} eq.
Eutrophication, terrestrial	Accumulated exceedance (AE)	mol N eq.
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq
Ecotoxicity, freshwater	Comparative toxic unit for ecosystems (CTU_e)	CTU_e
Land use	Soil quality index	Dimensionless (pt)
Water use	User deprivation potential (deprivation-weighted water consumption)	m^3 water eq. of deprived water
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq.
Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ

The results are then further processed by applying normalisation factors to estimate the quantitative share of the studied system compared to global emissions. The results are dimensionless or expressed per person. Normalisation factors are provided by the Joint Research Centre (JRC). In a second step, the normalised factors are converted with weighting factors that represent the perceived relative importance of the considered life-cycle impact categories, and which can then be aggregated to a single score value. Toxicity categories are not included in the single score results.

[10] See https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_ITequipment_Feb2020_2.pdf (Table 3.5, p 23).

[11] „Commission Recommendation on the Use of the Environmental Footprint Methods to Measure and Communicate the Life-cycle Environmental Performance of Products and Organisations, C (2021) 9332 final.

[12] The indicator "Climate change, total" is a combination of three sub-indicators: climate change – change fossil; climate change – change biogenic; and climate change – land use and land use change.

[13] Disability-adjusted life years (DALY).

This approach is mandatory in EF calculations, and normalisation and weighting factors are provided and updated via the EPLCA.

Lifetime of ECS products

The lifetime of an ECS can be extended by implementing strategies that aim for continued use of a product or component; in the 9R framework, these are R3 (reuse) to R7 (repurpose). The 9R framework indicates that more value can be captured by reusing products and components, and the strategies are in descending order to express this; recycling and recovering are strategies to keep materials, but do not contribute to extending the lifetime of products.

ECS as an enabler for a circular economy

While the main focus of this section has been on the negative environmental impacts of ECS and approaches to mitigate them[14], digital technologies also have the potential to improve traceability and transparency during product lifetime, allowing manufacturers to monitor, control, analyse and optimise materials‘ quality and products‘ performance. This is a requirement for implementing and managing digital product passports for products along their life cycle. They could also enhance end-of-life management practices, predictive and condition-based maintenance, extending product lifetime or enabling new business models such as product/service systems.

[14] See EEEEE, "Vision Paper on the Role and Impact of 'Functional Electronics‘ on the Transition Towards a Circular Economy“, May 2020 (https://5e-project.eu/wp-content/uploads/2020/10/Vision-Paper_Functional-electronics-for-a-circular-economy.pdf).

4 Today‘s situation: From cradle to gate, and improvements

This chapter will summarise the current status of the achieved level of greenness in ECS by differentiating through the lens of different technologies – i.e. production processes, components, but also software aspects and reliability methods.

4.1 Challenges of today´s ECS

Many uses of electronic components and systems contribute to environmental improvement and sustainable development, such as through improvements in ICT-based communication enabling virtual meetings, thus reducing the need for air/road travel. However, the overall electronics market is far from being a benign environmental influence. The main reasons for this ambivalent track record are:

- with digitalisation, the total amount of ECS is rising rapidly and spreading into even more application areas;
- ECS use an extreme range of elements and materials, incorporating many critical materials (even if often in small amounts per function);
- processing of advanced ECS is energy- and chemical-intensive, and in particular cleanroom processing of semiconductors;
- during the recycling of materials, only a small proportion of metals are effectively recovered, but not all the critical materials or the environmental footprint of the semiconductors;
- for many product types and in many regions there is no recycling, making electronic waste one of the fastest growing and most problematic waste streams globally;
- electronic waste is often shipped from one continent to another for reuse/repair/recovery, which also leads to an additional increase in environmental footprint since the receiving countries usually have no infrastructure for treating what is left after recovery, while toxic substances are also released or generated through uncontrolled incineration.

Structure to analyse the current situation, ongoing improvements and radical improvement options

Developers of products and systems need to be much more empowered to choose the right type of electronics, and even the right amount of 'electronification‘ for their intended solution.

This requires four pillars to ensure widespread industrial change:

(1) Ability to design right (see Chapter 5)

(2) Accessability to much broader 'green‘ technology options

(3) Anticipate and integrate other players at the 'system‘ level (i.e. outside the linear build/sell/use/discard view of manufacturing)

(4) Develop and implement product- and system-level safeguards against uncontrolled and harmful waste streams.

The technology options to improve the current situation, which are the basis of this chapter, cover:

- Reducing the 'cradle to the gate‘ (the path from the extraction of the raw material to the factory gate) environmental footprint through use of:
  - intrinsically **greener materials** (lower environmental footprint for extraction/production);

  - **improving processing** by drastically reducing environmental footprint (water use, global warming potential, chemical footprint).
- Reducing the 'gate to the grave' environmental footprint through use of:
  - smart, miniaturised and versatile **integration technologies** at the component and module level to reduce energy usage during operating lifetime;
  - increasing lifetime by repair (see Chapter 6);
  - **improved reliability.**

Improving the efficiency of conventional electronic systems – e.g. greater computational power per watt, smaller chip size per functionality delivered, or lower losses of power electronics – is a necessary and sustained contribution to greening electronics, but should be regarded as an intrinsic extension of the current way of doing business. **'Green ECS' focuses on what needs to be done and can be achieved through new technology options on top of the popular energy-efficiency trends.**

Changing the paradigms of the current design and development chain towards holistic eco-design and upgrading business models towards a circular economy will be covered separately (Chapters 5 and 6), although of course ultimately all approaches are interconnected.

4.2 Materials

This section will highlight known, as well as new, materials, their important role for energy-efficient electronic components, and thus also edge computing and complements thematically with an outlook on life-cycle assessment for materials and related processes in general.

Energy-efficient ECS will play a key role in the building process – e.g. of edge-computing devices, especially regarding the 'backpack' of materials. On the one hand, industry uses extremely pure and precious metals and materials, while on the other the total amount of such materials in products is comparably low. Decision processes are currently driven by cost (during manufacturing and sometimes also in the application phase), but will presumably change in the near future. It is assumed that one day energy consumption will no longer correlate with CO_2 production due to the increasing decarbonisation of industries and societies, while shortages of critical and rare materials will become an increasing issue, and the focus will therefore be on building up a circular economy to maintain the material supply chain.

4.2.1 Materials: Sourcing, replacement of toxic or critical raw materials

As shown in Figure 3.4, the full 'cradle-to-gate' life cycle – from environmentally sound raw material sourcing through transportation to cleanroom fabrication – should be considered to minimise environmental footprint impacts. The electronics sector depends on silicon and a range of critical raw materials (CRMs) including cobalt, germanium, indium, platinum group metals (PGMs), natural graphite, rare earth elements (REEs), and tungsten[15,16]. The criticality assessment is based on the supply risk (SR) and economic importance (EI). Critical raw materials are more and more used in various components, but always in small quantities per application, which makes their recycling

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[15] European Commission, "Study on the EU's List of Critical Raw Materials (2020)", September (https://ec.europa.eu/docsroom/documents/42883/attachments/1/translations/en/renditions/native).

[16] European Commission, "Critical Raw Materials for Strategic Technologies and Sectors in the EU - A Foresight Study', 2020 (https://ec.europa.eu/docsroom/documents/42882, accessed 08/12/2022).

challenging. Future materials selection strategies should consider environmental footprint impacts (GHG emissions, toxicity, etc), as well as cost, performance and security of supply. In addition, novel chemistry-based release concepts for the improved recyclability of components and materials are being researched.

The EU is also currently considering a ban on an entire group of problematic industrial chemicals. Per- and polyfluorinated alkyl (PFA) compounds, of which there are several thousand, could be banned completely. PFAs are also used in ECS, and therefore ECS-based industry and academia is desperately searching for more environmentally friendly chemicals as an alternative to this group of PFAs. Similarly, alternative chemistries are also being researched for GHG Protocol-related gases (such as NF_3, PFC).

4.2.2 Materials: Incorporating high recycled content, bio-based and/or bio-degradable materials

Conventional electronic devices are primarily integrated on fossil-based polymeric and composite substrates, such as polyimide and FR4, respectively. Flexible printed circuits offer several advantages compared to rigid circuits, including reduced package dimensions, reduced weight, and optimisation of component real state[17], as well as the use of printing-based manufacturing. Currently, printed electronics are based mostly on polymeric substrates, such as polyethylene terephthalate (PET) and polyethylene naphthalate (PEN). At present, the main sources of climate impacts and sustainability challenges in printed electronics technologies relate to the use of fossil-based substrate materials and also metals.[18,19]

The use of lower environmental impact flexible substrates based on recycled, bio-based and bio-degradable materials will bring new opportunities. The main bio-based materials towards flexible electronics are polylactic acid (PLA), silk fibroin and cellulose-based materials, such as paper products[20,21], while several different bio-plastic substrate alternatives are also being developed (see Figure 4.1). Bio-plastics could present some limitations in terms of thermal or moisture resistance as well as price, although the price is expected to decrease as markets evolve. Using paper as a substrate for printed electronics has obvious advantages – such as low cost, flexibility, biodegradability, compostability and ease of disposal through fibre recycling or incineration – but ist high roughness and absorbency, poor barrier properties and sensitivity to elevated moisture levels

[17] Gagliardi, M., "Global Markets for Roll-to-roll Technologies for Flexible Devices“, 2016 (see www.bccresearch.com).

[18] Liu, J., Yang, C., Wu, H., Lin, Z., Zhang, Z., Wang, R. and Wong C. P., “Future Paper Based Printed Circuit Boards for Green Electronics: Fabrication and Lifecycle Assessment”, *Energy & Environmental Science,* 7(11), 2014, pp. 3674–82.

[19] Espinosa, N. García-Valverde, R., Urbina, A., Lenzmann, F., Manceau, M., Angmo, D. and Krebs, F. C., “Life Cycle Assessment of ITO-free Flexible Polymer Solar Cells Prepared by Roll-to-roll Coating and Printing”, *Solar Energy Materials and Solar Cells*, 97, 2012, pp. 3–13.

[20] Irimia-Vladua, M., Głowackib, E. D., Vossb, G., Bauera, S. and Serdar Sariciftcib, N., "Green and Biodegradable Electronics“, *Materials Today,* July–August 2012, 15(7–8), p. 7.

[21] Sun, Q., Qian, B., Uto, K., Chen, J., Liu, X. and Minari, T., "Electronic Biomaterials Towards Flexible Sensors: A Review“, *Biosens. Bioelectron.* 2018, 18.

can create challenges[22,23]. Use of bio-based substrate materials is in line with EU's bioeconomy strategy[24], which aims to strengthen the connection between economy, society and the environment.

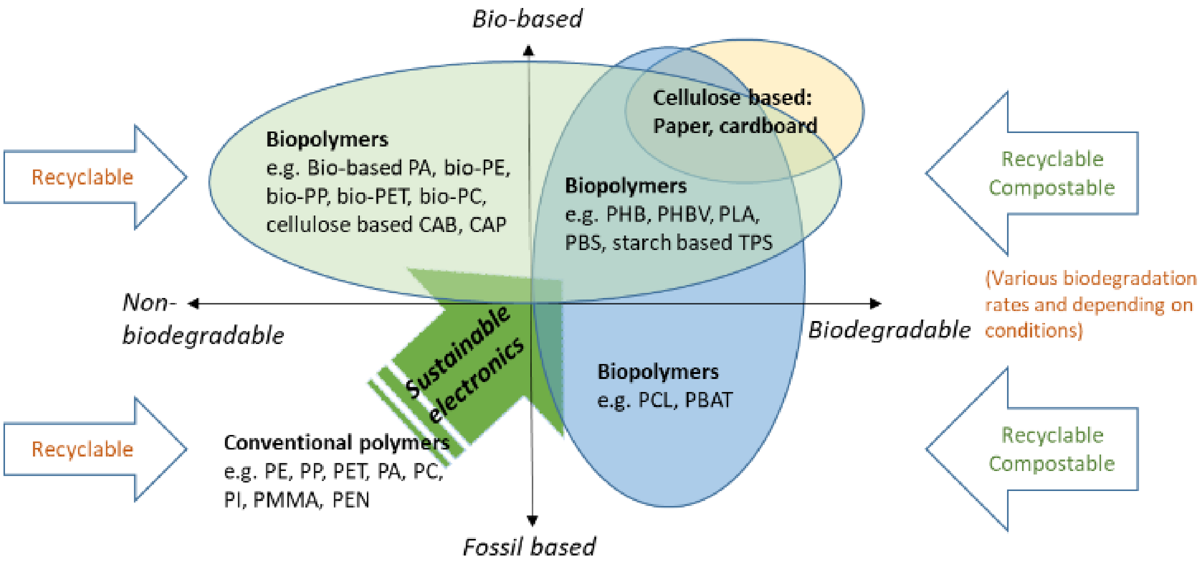

Figure 4.1 Bio-based substrate alternatives.Illustration by VTT, Finland

Biodegradation in electronics is a specific area focused on areas such as biomedical applications placed inside the body, drug delivery or therapeutics, as well as environmental sensing and monitoring applications. Biodegradation of materials and components is also important in applications that most probably, or by design, end up in nature at the end of their lifetime. Research efforts and applications in these areas are increasing and enabled by, for example, novel biodegradable substrate materials[25,26]. VTT and collaborators have integrated environmentally friendly smart label solutions for intelligent packaging by utilising printed electronics, bio-based materials and eco-design concepts (see Figure 4.2).

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[22] Jansson, E., Lyytikäinen, J., Tanninen, P., Eiroma, K., Leminen, V., Immonen, K. and Hakola, L., "Suitability of Paper-based Substrates for Printed Electronics", *Materials,* 2022, 15, 957 (https://doi.org/10.3390/ma15030957).

[23] Immonen, K., Lyytikäinen, J., Keränen, J., Eiroma, K., Suhonen, M., Vikman, M., Leminen, V., Välimäki, M. and Hakola, L., "Potential of Commercial Wood-based Materials as PCB Substrate Materials", 2022, 15(7), p. 2679 (https://doi.org/10.3390/ma15072679).

[25] Feig, V. R., Tran, H. and Bao, Z., "Biodegradable Polymeric Materials in Degradable Electronic Devices", *ASC Cent. Sci.,* 2018, 4, pp. 337–48.

[26] Li, L., Wang, D., Kong, Y. L., "Recent Progress on Biodegradable Materials and Transient Electronics", *Bioactive Materials,* 2018, 3, pp. 322–33.

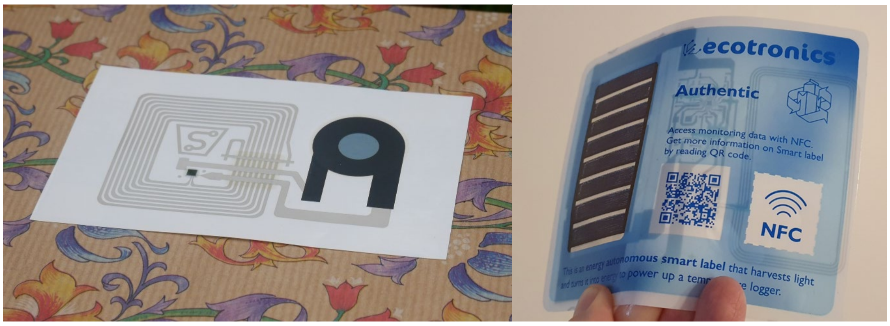

Figure 4.2 Anti-counterfeit label and energy autonomous temperature logger based on sustainability approach. Both have been awarded 'Best publicly funded project demonstrator' in OE-A Competition 2021 and 2022, respectively. Images: VTT, Finland

Silver, the current 'standard' for conductive material in printed electronics, has high environmental impact due to its mining process as a side-product from other mines, among other reasons, while its high cost is also an economic issue. Replacement of silver with other metals, such as copper or aluminium, could lower the environmental impact, but an even better option would be to use carbon-based materials, or replace at least part of the metals with carbon.

Another sustainability issue for metal inks is sintering at high temperature – since many biopolymer and paper-based substrates are heat-sensitive materials, this high energy-demanding process step can be avoided. Sustainability can also be increased by formulating the ink base from renewable materials, and by using low or no volatile organic compounds.

4.3 Processes

This section will highlight the necessary improvements in processes to reduce environmental footprint. It is divided into two parts to address the main electronic process lines separately: the classical cleanroom-based wafer-scale processes; and the emerging additive manufacturing processes, such as printed electronic processes.

4.3.1 Processes: Pathways to reduced environmental footprint of cleanrooms

Sustainability in cleanroom semiconductor wafer fabrication is a significant challenge due to rigorous multi-step workflows and strict procedures. Many solvents, cleaning materials and water are used only once, which creates a huge amount of waste, and cleaning products must be constantly re-stocked. Complex machinery at clean rooms also has a devastating energy demand, and air flow is crucial – such as the use of ventilation, air conditioning and heating. In addition, many processes require the use of different (and sometimes hazardous) gases. Cleanrooms are extremely energy-hungry.

In standby mode, cleanroom operations consume 60% of the total energy used during fabrication[27]. As the impact of the semiconductor industry on water scarcity in Taiwan has shown, water is not an unlimited resource. Some cleanrooms already optimise water usage by recycling and reusing. For energy optimisation, several options are in operation: optimised maintenance settings, automatically powering down equipment, optimised lighting, use of energy efficient tools, optimised air recyclers, filters, cooling and heating, and the use of renewable energy sources. More sustainable and

[27] J. Lopes Barbosa *et al.*, *Journal of Cleaner Production,* 2023 (to be published).

environmentally friendly solvents and gas usage will further reduce the environmental impact of cleanrooms. For the photolithography process, water-soluble bio-sourced resists are already being tested and are promising candidates[28].

Unfortunately, for most of the real-time operating systems (RTOs) and semiconductor industries the motivation for greener cleanroom operations still comes from the high energy prices, and are therefore more financially driven than by lowering the environmental footprint in general! Also, there is still scope for the cleanroom tooling industry to develop a more sustainable set of tools[29].

4.3.2 Processes: Additive manufacturing, printing (S2S and R2R)

Sustainable production can be achieved by efficient energy and material use, as well as by replacing fossil-based feedstock with, for example, bio-based feedstock, thereby enabling more sustainable electronics – and, in the future, also e-waste – with a reduced environmental footprint. Printing-based additive, high throughput methods offer the electronics industry the possibility to achieve these goals. These sustainable production methods are already mentioned in the ECS-SRIA Roadmap. It is estimated that additive manufacturing processes such as printing, powered by electricity generated from renewable energy, uses one-tenth of the materials of traditional factory production, resulting in a clear reduction in CO_2 emissions and use of the earth's resources[30]. With additive methods, energy consumption during manufacturing can be up to five times less than with conventional methods[31]. Furthermore, the use of environmentally hazardous etching chemicals can be avoided. Additive manufacturing processes also enable more lightweight products (less materials used), less energy consumption (high integration of functionalities), the possibility of new types of functionalities (attached to non-conventional platforms such as packaging and textiles), and the ability to more easily disintegrate and recycle materials and components (less materials, bio-based options).

Additive and sustainable manufacturing enable totally new electronic devices that can be integrated to multiple products for multiple domains, such as disposable tests for diagnostics and point-of-care, Internet of things (IoT) solutions for smart and intelligent packaging, condition monitoring of production and supply chain, structural electronics in automotive and other fields, environmental monitoring, precision agriculture, and wearable solutions[32]. Sustainable technical solutions also offer

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[28] Servin, I. *et al.*, "Water-soluble Bio-sourced Resists for DUV Lithography in a 200/300 mm Pilot Line Environment", *Micro and Nano Engineering,* 2023 (https://doi.org/10.1016/j.mne.2023.100202); Servin, I. *et al.*, "Chitosan as a Water-based Photoresist for DUV Lithography", *Proc. Of SPIE 2023 Proceedings Volume 12498, Advances in Patterning Materials and Processes XL;* 1249818, 2023 (https://doi.org/10.1117/12.2658423).

[29] Barbiroglio, E., "No Water No Microchips: What is Happening in Taiwan?", *Forbes*, May 31, 2021 (https://www.forbes.com/sites/emanuelabarbiroglio/2021/05/31/no-water-no-microchips-what-is-happening-in-taiwan/?sh=143d52a722af).

[30] Rifkin, J., "Beyond Obama's Plan: A New Economic Vision for Addressing Climate Change", *Huffington Post*, blog, June 2, 2014 (https://www.huffpost.com/entry/obamas-climate-change-plan_b_5427656).

[31] Nassajfar, M. N., Deviatkin, I., Leminen, V. and Horttanainen, M., "Alternative Materials for Printed Circuit Board Production: An Environmental Perspective", *Sustainability*, 2021, 13(21), (https://doi.org/10.3390/su132112126).

[32] Hakola, L., Jansson, E., Futsch, R., Happonen, T., Thenot, V., Depres, G., Rougier, A. and Smolander, M., "Sustainable Roll-to-roll Manufactured Multi-layer Smart Label", *Int J Adv Manuf Technol,* 117, 2021, pp. 2921–34 (https://doi.org/10.1007/s00170-021-07640-z).

sustainability opportunities for the product use phase, such as reduction of food waste, faster diagnosis and increased productivity.

4.3.3 Processes: structural electronics

Structural electronics (SE) involves the printing of functional electronic circuitries across irregular-shaped architectures. In-mold structural electronics (IMSE) brings the electronics even more compact form by integrating printed circuitry and discrete electronic components within injection-molded plastics, creating a seamless structure.

IMSE-based solutions are single piece, electronically active parts that replace multi-part structures and their labour-intensive electro-mechanical assembly. Many IMSE use cases are for human/machine interface (HMI) control panels and functional/styling illumination solutions. In these, IMSE adds touch controls, lighting, antennas, sensors and control circuitry, along with digital interfaces, into the 3D cosmetic surface structure of a seamless, lightweight part that delivers cosmetics, mechanical structure and electronic functions enabling the programming and digitalisation of plastic. Due to their design, IMSE solutions can add electronic functions in locations prohibitive for traditional electronics, and enable design innovation that can differentiate customers' products.

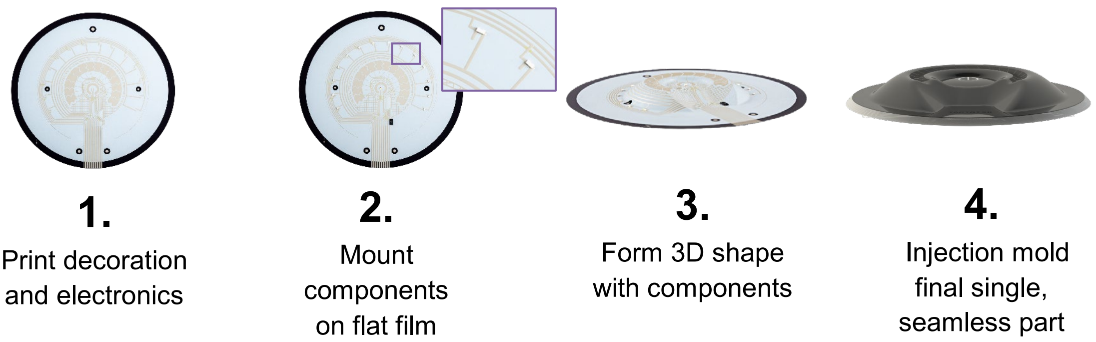

Figure 4.3 IMSE process steps by TactoTek

Injection-molded structural electronics IMSE® is the most advanced in-mold electronics platform in the world, producing up to a 60% reduction in carbon footprint compared to conventional electronics:

- IMSE designs are developed with simulation-driven processes requiring less materials and energy;
- significantly less plastics are used;
- the IMSE system-in-package (SiP) printed circuit board (PCB) is approximately one-tenth the size of conventional electronics, significantly reducing CO_2 emissions and other waste streams since PCBs are the most carbon-intensive part in electronics production;
- IMSE parts are single piece solutions, which means there are fewer parts to be designed, tooled, produced and delivered to an integrator, enabling a more sustainable supply chain;
- IMSE is realised by efficient additive manufacturing and minimal manual assembly;
- IMSE use cases are not limited to any specific sector but can be used in any kind of electronic device where a human/machine interface is needed.

4.4 Components

4.4.1 Components: Sensors

The development of sensing elements with a low environmental footprint impact throughout their life cycle is a key challenge to deliver sustainable edge sensors and networks for IoT applications. This is particularly true for short-lifetime sensors (e.g. for wearables or intelligent packaging) or hard-to-retrieve sensors (e.g. for environmental monitoring). EPOSS members have developed new low-footprint sensor elements to address this challenge (Figure 4.4), while Tyndall have developed 3D, porous, laser-induced graphene-like carbon (LIG) sensing elements from biopolymers (chitosan[33], see Figure 4.4a) and renewable natural materials such as cork[34]. Recent demonstrations include electrochemical detection of glucose using wearable chitosan-based laser graphene sensors (Figure 4b) and chemi-resistive sensing of volatile organic compound vapours (VOCs, Figure 4c). Through the H2020 APACHE project, Tyndall and FORTH have also developed LIG-based humidity sensors on polyimide for wireless monitoring of cultural heritage objects, including museum storage containers and artworks[35,36].Figure 4d shows an example of a frame-mounted, wireless edge node that is currently monitoring Andy Warhol's Flowers painting in the Guggenheim museum in Venice. Within the PLANtAR project, Fraunhofer ENAS have developed low-footprint, wood-based sensor systems for *in situ* environmental monitoring (Figure 4e).

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[33] Larrigy, C., *et al.*, "Porous 3D Graphene from Sustainable Materials: Laser Graphitization of Chitosan", *Advanced Materials Technologies,* 8(4), 2023, p. 2201228.

[34] Silvestre, S. L., *et al.*, "Cork derived Laser-induced Graphene for Sustainable Green Electronics", *Flex Print Electron,* 7, 2022, 035021.

[35] Gawade, D. R., *et al.*, "A Smart Archive Box for Museum Artifact Monitoring Using Battery-less Temperature and Humidity Sensing", *Sensors,* 21(14), 2021, p. 4903.

[36] Paterakis, G., *et al.*, "Highly Sensitive and Ultra-responsive Humidity Sensors Based on Graphene Oxide Active Layers and High Surface Area Laser-induced Graphene Electrodes", *Nanomaterials,* 12(15), 2022 (https://www.mdpi.com/2079-4991/12/15/2684).

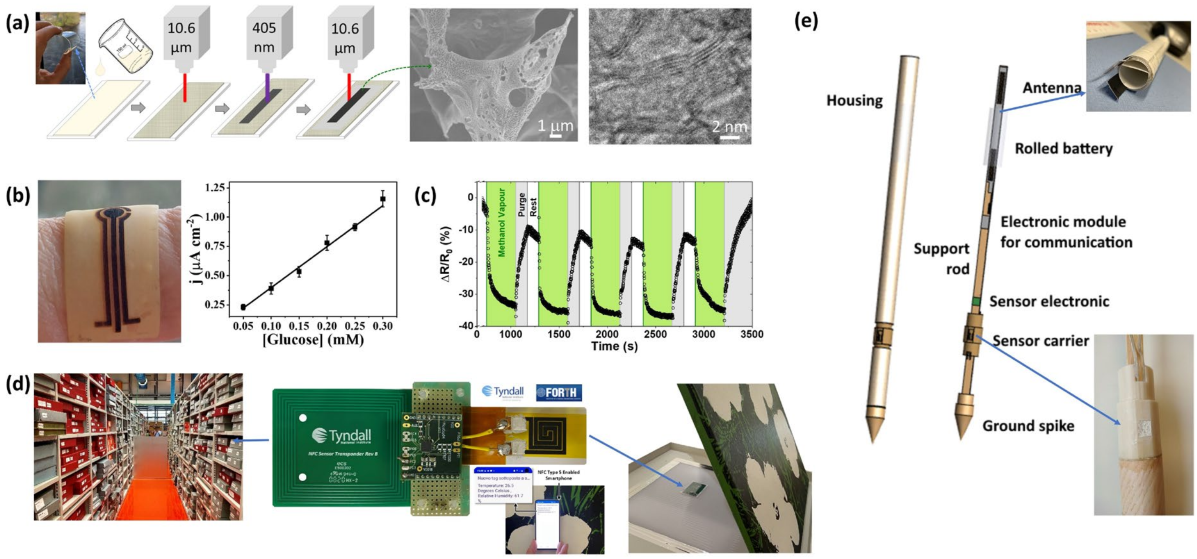

Figure 4.4 (a) Porous, 3D laser-induced graphene-like carbon from chitosan biopolymers; (b) wearable chitosan LIG sensor for electrochemical detection of glucose[37]; (c) two-terminal chemi-resistive detection of methanol vapour (1300 ppm) using mm-sc (image: Tyndall National Institute); (d) edge node for wireless humidity and temperature monitoring[38]; and (e) wood-based sensing platform for environmental monitoring[39]

Edge computing is essential to decrease the amount of data to be transmitted, and thereby reducing the environmental footprint for IoT applications. Sensors and actuators are key components for edge technology systems to gather data from the environment and act locally. Together with electronic components for data processing and decision-making, they enable portable mobile systems to perform local measurements – leading to a higher information density and decisions with a better precision and quality. To achieve these goals, integration and miniaturisation are key competences for sensors and actuators. A decrease in size and weight enhances the power and energy efficiency of portable systems. However, the impact of the production of the edge devices should not be overlooked and must be taken into account e.g. by LCA to verify that the impact of the reduced energy consumption exceeds the productions impact[40.]

4.4.2 Components: Energy harvesting

To truly benefit society, scientific and technological innovations are needed in the medium and long term to address the challenge of sustainably powering hundreds of billions of IoT edge devices. Currently, typical wireless edge sensor devices have a battery life of between two and five years. The remaining useful life of the sensor is usually well over 10 years, which necessitates multiple battery replacements. This in turn leads to maintenance and often device downtime. In addition, ecological problems arise in connection with the manufacture and disposal of so many batteries every single day. In some cases, effective battery life can be extended using energy harvesting techniques, thus reducing the use of scarce materials (R1).

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[37] Hamidi, H., *et al.*, "Laser induced Graphene (LIG) Biosensors Derived from Chitosan: Towards Sustainable and Green Electronics", 2023 (http://dx.doi.org/10.2139/ssrn.4425608).

[38] Gawade, D. R., *et al.*, "A Smart Archive Box for Museum Artifact Monitoring Using Battery-less Temperature and Humidity Sensing", *Sensors,* 21(14), 2021, p. 4903.

[39] PLANtAR project

[40] Bol, D., *et al.*, "Assessing the embodied carbon footprint of IoT edge devices with a bottom-up life-cycle approach ", *Journal of Cleaner Production,* 322, 2021.

Energy harvesting technologies can be broken down into converting energy from an available source into useful power (i.e. appropriate voltage, current to drive an edge sensor device). Therefore, ultra-efficient power management integrated circuits (PMICs) are crucial. Potential sources for micropower include:

- electromagnetic radiation (light or transmitted radio-frequency, RF, power) harvesting through photovoltaic cells or wireless power harvesting, respectively;
- mechanical energy (electromagnetic vibrational, piezoelectric or triboelectric harvesters);
- heat (thermoelectric generators, TEGs).

Figure 4.5a shows the typical power consumption for IoT edge devices during operation, communication, standby and sleep modes (following the EnABLES position paper)[41], together with standard power generation values in the energy harvesting 'sweet spot' (100 nW – 0.5 mW).

Thin-film amorphous Si-based solar cells are an excellent technology for integration in small-scale energy scavengers for consumer applications for several reasons: (1) they can be fabricated on a wide range of different substrates (e.g. glass, plastics, polymers, foils, and even paper); (2) their useful aesthetics making them very suitable for product integration; (3) high power output under indoor lighting and low illumination conditions allows the use of a very thin (< 1 µm) layer stack for energy conversion; and (4) the application of a wide range of colours. For instance, these solar cell devices can be integrated in watch dials, wristbands, wearables, calculators, cell phones and biomedical devices.

To date, prototypes developed at CSEM have been successfully integrated in backpacks and wristbands for watches, as well as directly in watch dials. The latter have even been successfully integrated in a commercial product that has made it to market: solar watch dials developed at CSEM power the Tissot T-Touch Connect Solar watch. Another example is WITNESS, which is powered by a flexible, adhesive PV-cell, with a camera with an autonomous image logger that can record pictures based on scene activity detection. It is deployed in the field like a sticker, and can wirelessly transmit information (Figure 4.5b).

While wireless power transfer is technically feasible, challenges for IoT edge devices include the need for large antenna surfaces to harvest the RF energy, which could impose space constraints; and/or the need for small separations between the transmitter (energy source) and the edge device to minimise losses.

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[41] EnABLES European Infrastructure Powering the Internet of Things Research Infrastructure Position Paper (https://www.enables-project.eu/wp-content/uploads/2021/02/EnABLES_ResearchInfrastructure_PositionPaper.pdf).

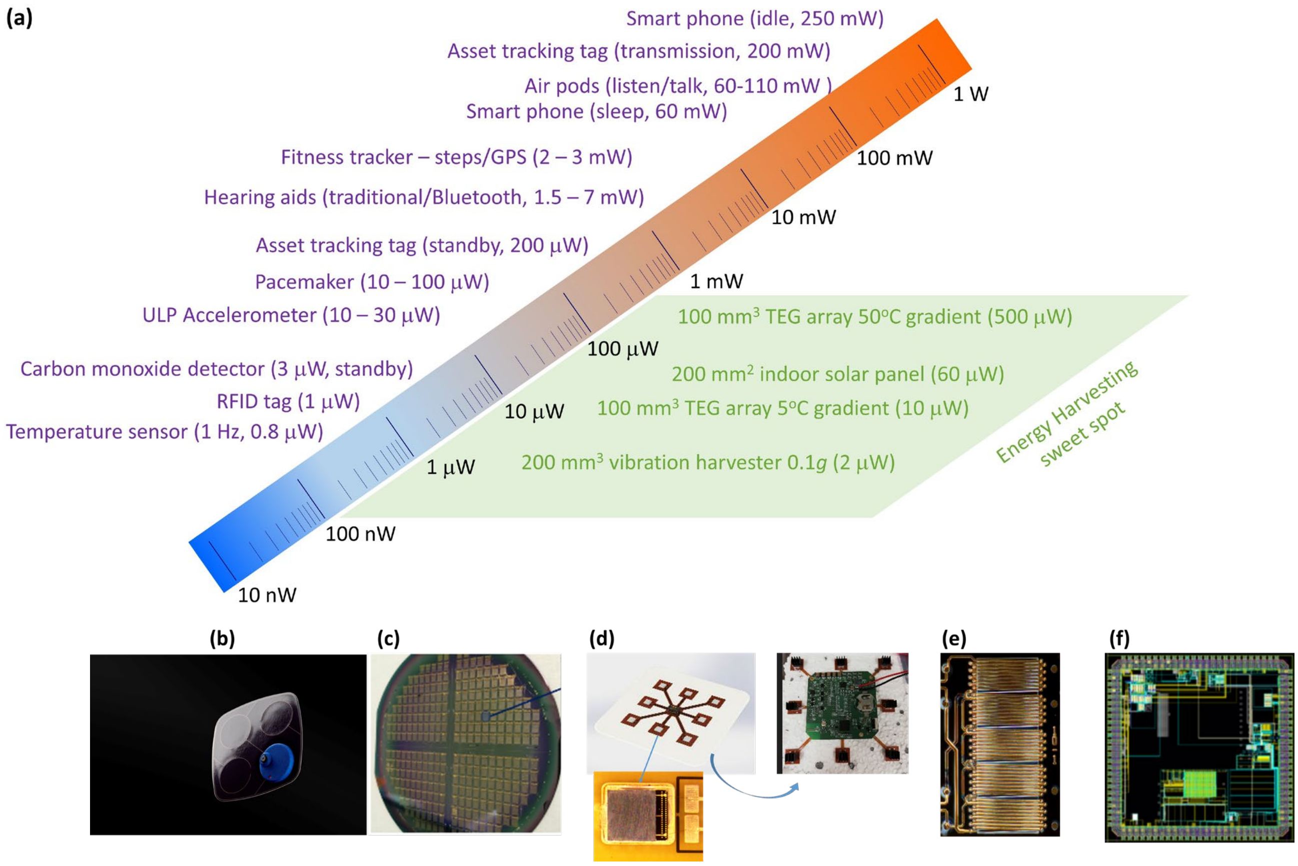

Figure 4.5 (a) Typical power consumption for IoT edge devices during operation, communication, standby and sleep modes. The shaded region shows the "sweet spot" for energy harvesting (100 nW – 0.5 mW). Image: Tyndall National Institute; (b) WITNESS powered by CSEM's flexible solar cells. Image: CSEM, Antal Thoma; (c) wafer-scale thermoelectric generators (TEGs) fabricated at Tyndall; (d) SmartVista wearable smart patch powered by eight commercial TEGs; (e) silicon-integrated transformer for 'cold start' micropower management; and (f) power management integrated circuit. (a), (c)–(f) EnABLES position paper[42]

Although electromagnetic energy harvesters can scavenge energy from vibrations, scalable routes for small form-factor devices compatible with edge IoT or consumer electronic devices are needed. Piezoelectric generators convert strain/pressure to energy, but pose problems such as the replacement of toxic materials (e.g. lead) and their reliability. Triboelectric harvesters operate through contact electrification from mechanical friction, but again scalable device fabrication routes are required and reliability remains an issue (e.g. sensitivity to humidity).

TEGs (see Figure 5) harvest energy due to thermal gradients (Seebeck Effect). While TEG-based harvesters can work well with large temperature gradients (e.g. heat from large motors in industrial settings), the small temperature differences associated with wearable devices presents a challenge. Again, scalable integration routes are needed. Life-cycle assessment shows that state-of-the-art WPT sensors have a 5-10 times higher environmental impacts compared to battery-powered ones and to-date the use of WPT should be limited to applications where conventional battery-powered systems cannot be used[43].

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[42] ibid.

[43] M. Gonzalez et al., "Technical and Ecological Limits of 2.45-GHz Wireless Power Transfer for Battery-Less Sensors," in IEEE Internet of Things Journal, 2023, 10(17), pp. 15431-15442

Ultra-low-power chips are necessary to reduce the energy consumption of such IoT devices. These chips consist of basic components, the memory elements for storing the data at extremely low voltage and the functional blocks, i.e. a processor (RISC-V), a Bluetooth radio module for the wireless connection and converters for converting the real, analogue signals into digital values. By using adaptive body biasing techniques, the system can function in an optimised way in all modes (active, stand-by, off) and the power loss can be minimised. Meanwhile it has to be made sure that the reduction of energy consumption due to the device exceeds its embodied footprint over its whole life cycle[44].

4.4.3 Components: Pushing efficiency in all power conversion stages

Holistic system-level approaches are important to ensure ultra-efficient energy harvesting and power conversion to prolong battery lifetime for edge IoT devices. Harvesting ambient energy to on-chip or in-package storage devices, and subsequent conversion to usable voltage and/or current levels for the IoT device load, presents many challenges in simulating and developing ultra-efficient PMICs (see Figure 4.5f). According to the EnABLES position paper, these include[45]:

- impedance-matching techniques to maximise energy transfer;
- novel power architectures to efficiently convert energy (often at very low voltages and power levels) to usable levels, ideally with multi-source capability for different types of harvested energy;
- self-start circuits to ensure device autonomy and ultra-low (nW) quiescent power consumption;
- digital mode control to be able to dynamically configure operation modes for sensors, MCUs (microcontrollers) and transceivers to minimise their power consumption and only activate as needed.

4.5 System integration

4.5.1 Integration: Less material for higher functionality

One ongoing trend to reduce the material footprint of electronics is to achieve higher functionality while at the same time reducing the amount of material invested (or wasted in the production). For semiconductor devices, this is exemplified by Moore's law, where despite the increased processing expenditure per wafer the environmental impact per transistor function has decreased for decades. The principle can be extended to other functions or larger components, such as smaller IC packaging footprint, smaller switching power supplies using higher frequencies, or flex–rigid substrates partially replacing additional cables and connectors. Smaller dimensions of printed circuit board features can reduce the size of the PCB and the number of layers needed. In a way, this is a standard evolution of electronics due to performance and cost requirements, but for the right applications it can be pushed further as a green design principle.

The higher functionality and reduced size and weight of the electronics may contribute to longer product use and second-hand marketing of such products. However, this is not automatically the case, and there could be a rebound effect whereby the more material efficient solution will enable

[44] Bol, D., *et al.*, "Assessing the embodied carbon footprint of IoT edge devices with a bottom-up life-cycle approach ", *Journal of Cleaner Production,* 322, 2021

[45] ibid.

many more electronic applications, thus leading to a greater number of electronic products and more waste in the end.

With regard to material recycling, the material mix tends to move towards more complex structures, particularly when bulk plastics are reduced. The remainder of highly mixed metals, including precious and trace metals, may be harder to recover. However, overall the pace of integration of electronics is positive for the environment and must be maintained through additional technological innovation and new and better exchange between players, or eco-design beyond company boundaries.

4.5.2 Integration: Smarter thermal, electrical, optical, fluidic integration

Bringing the non-electric functionalities of electronic packages and modules into a common design and optimisation flow can lead to new product architectures or technology mixes, which can reduce the important material overheads of conventional designs further. Integrated heat management (reducing heatsinks and necessary fans) – where possible bringing fluidic cooling as close to the chip as possible, but also using heat pipes and new thermal materials to push the boundaries of passive cooling – can reduce the materials needed, and lower operating temperatures. Optical links on the package and board level can not only be more energy efficient in the future where very high data frequencies are required, but also save space and material compared to conventional copper connections. Optics for sensing and microfluidics such as in medical point of care (POC) applications show the type of integration gain possible. Initial examples are in place, but need to be made available to larger markets and more types of companies, including small and middle-sized enterprises (SMEs). System integration planning and new design approaches are key to leveraging this for greener electronic systems.

As an extension of the first point above, some integration trends could lead to more reliable operation and longer use times. The material mix should be optimised towards recycling compatible metals streams, such as copper (with precious metals), aluminium or iron/steel.

4.5.3 Integration: Heterogenous packaging for highest integration with least material use

Combining ICs of different semiconductors and from different size nodes can be environmentally beneficial compared to producing very large system-on-chip (SoC) solutions to be produced in one silicon foundry. As technologies for integrating more than one chip into IC packages have evolved and diversified, it is also possible to integrate sensors, micro-electromechanical systems (MEMS) or optical chips in the same package. This leads to closely integrated function blocks, which may not even be feasible on silicon SoC since the process flows of the different devices (in the cleanroom front end) are not compatible. Stacking and thinning of multiple chips (these can all be silicon) reduces package size further, leading to minimised system dimensions. Figure 4.6 shows an example with multiple silicon chips in one IC package. Thin components (both chips and passive components) can also be integrated in the PCB substrate (embedding), which can save material and space for some applications.

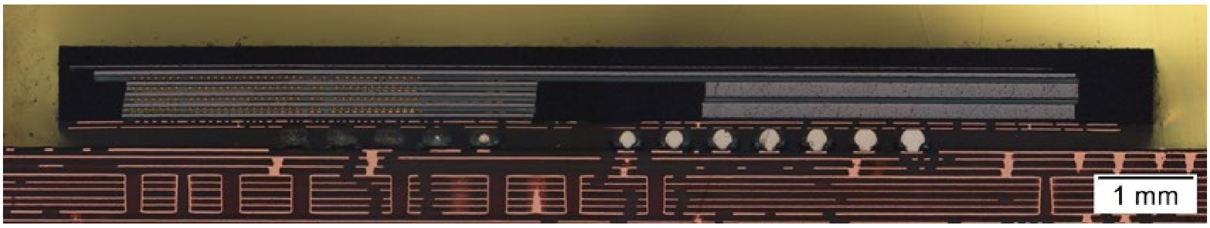

Figure 4.6 Cross-section of a commercial component including various semiconductor chips. Image and preparation: Fraunhofer IZM[46,47]

As with the above sections on integration, these technologies are already being developed and used in industry. However, selecting the right miniaturisation approach for a specific application should in the future be done for environmental benefit, not just cost and performance. New variants of such technologies need to be pushed to market readiness, and to be easily available to many more companies.

4.5.4 Integration: Chiplets and new highly customised IC packaging

While multi-chip modules and packages have been around for some time – either incorporating heterogenous integration or just silicon – chiplets propose a new design philosophy, where not all chips are developed by one company (or under contract for one company). This non-contractual ecosystem of chip developers and manufacturers should lead to a new balance of efficiencies. In particular, reuse of 'stable' chip designs from older manufacturing nodes would become widespread, and the optimisation effort for designing and redesigning for the most advanced technology node would be concentrated where it delivers the highest benefit. Here, benefit does not only mean cost, performance and area, but also environmentally optimised results.

As a side-effect, the chiplet paradigm, but also new packaging principles such as panel-level packaging, could give access to complex multi-chip designs to smaller companies through principles of multi-project manufacturing (analogous to multi-project wafers in the semiconductor fabs). This would allow more (smaller) companies to customise their designs for highest efficiency, and benefit from the lower environmental footprint of the latest flexible manufacturing developments.

From a distance, the reuse of chiplets sounds like an enabler for repair down to the chip level – i.e. replacing a faulty chip or even upgrading with a pin-compatible substitute. However, after assembly and packaging of the chiplets, the individual chiplets are not accessible and current approaches do not support re-opening of packages and then changing any of the chip interconnects. Once packaged, a chiplet solution is basically a monolithic module.

Nevertheless, as some interface functions realised by specific chiplets could remain stable over generations of the subsystem, interchangeable modules could be developed across company boundaries. This type of 'encapsulated compute module' could pave the road to reuse those parts of electronics that generally accrue the highest upstream environmental footprint: memory, computing and communication. If reuse on a module level becomes feasible through this path, then repair would also benefit, despite the use of the highest level integration technologies.

[46] Proske, M., *et al*., "Life Cycle Assessment of the Fairphone 3", Technical Report, July 2020.

[47] Billaud, M., *et al.,* "ICs as Drivers of ICT Carbon Footprint: An Approach to More Accurate Die Size Assessment", CARE Innovation 2023.

Reusable modules in this sense might be further off in the future, but the concepts of chiplets and customised high-end IC packages are directly related to the European Chips Act. There is a need in research and in industry to predict the environmental benefits of targeting chiplet designs, and using chiplets manufactured in Europe where possible.

4.6 Methods for sustainable monitoring

4.6.1 Reliability of electronic components and systems

The reliability of a product refers to its ability or the probability to perform as specified when used for designed purposes and under defined conditions. When the performace has left the specified range, the lifetime of the product has ended. It is considered to be no longer functional and needs to be repaired or replaced. Therefore, increasing the reliability of ECS directly improves the sustainability of the end-product. It is obvious that a longer fault-free life leads to fewer repairs and replacements of electronics, and in the end reduces e-waste. The resources spent on development and production are therefore used more intensively, yet the positive impact and close interaction between reliability and sustainability are even more diverse and complex. In fact, every aspect of current research in reliability methodology also makes a strong contribution to improved sustainability and reduced environmental footprint of the electronics. This interrelation is explained below for each of the main aspects.

Over the past decade, reliability research in electronics has developed along two branches. Traditionally, reliability assessments have focused on determining the total lifetime through end-of-life testing and analysis. More recently, estimation of the remaining useful life (RUL) during use of the electronics in the final application has likewise gained great interest.

End-of-life assessment

Derived from the actual loading scenarios compiled to mission profiles, tests have been developed that accelerate the major degradation mechanisms without changing their nature. WIth their use, the optimum design can be identified in a fraction of the actual lifetime – e.g. in tests of three months comparing to 10 to 15 years of field use. Statistical evaluation of some 10 to 30 samples yields the characteristic lifetime and its deviation, which is the basis for the release of new products into production and for sale. Currently, these qualification campaigns use tests that expose the samples to characteristic loads such as temperature change or vibration or various atmospheres (e.g. dry and humid). In real use, however, all these loading conditions occur simultaneously and interact with each other. New testing strategies are currently under development that combine loads to capture the actual field use situation more realistically. This research aims to increase the reliability of future electronic components and systems, especially for applications in harsh environments and safety-relevant parts. It thus contributes to the increase in sustainability of the new products, such as electric vehicles and advanced driver assistant systems currently being developed by/for the automotive industry.

If physical reliability tests are replaced by validated simulations, the assessment time can again be reduced substantially – e.g. down to a few days for a full optimisation study considering many design variants. Usually, these simulations are performed before the fabrication of the first physical samples of the new products. That means the design for reliability (DfR) based on these numerical simulations avoids the manufacture of many samples in several design options as well as their physical tests. This reduces the environmental footprint of the development significantly. In addition, the short time required for virtual testing makes room for including even more design options and load cases than would have been affordable based on physical testing. Hence, virtual prototyping using validated models enables much more comprehensive evaluations. It also has great potential to accommodate the steep increase in complexity of electronics in high-reliability applications that is expected over the coming years. Virtual prototyping can reduce the risk of failure for new products efficiently and safely – i.e. it increases the lifetime of the products and hence improves the sustainability of the new solutions.

Remaining useful life estimation

With the advent of applications such as autonomous driving, fully automated industrial workshops, and bidirectional, multi-modal and decentralised energy infrastructure, the safety relevance of the electronic systems is increased massively. Unexpected failures of the electronics during operation could have severe or even catastrophic consequences, and hence must be prevented. The current safety approaches, which rely on redundancy and fallback solutions alone, are insufficient. The latter degrades the performance or even leads to a complete cessation of the operation. This is safe but unwanted, and often unacceptable. Redundancies avoid this but at the expense of requiring additional resources. Multiple parts need to be fabricated and installed, which add mass and energy consumption to the application, enlarging the ecological footprint. Often, they still do not provide the required safety level. If one of two parts malfunctions, it is not always clear which is correct, and hence the redundancy ratio must even be increased to three parts so that the majority stay correct in case of the first failure. Nevertheless, it is never known for how long the redundant parts will survive the failure of the original part, and the safety level has therefore already decreased substantially after the first failure.

An additional approach has been introduced to mitigate these concerns, one based on self-monitoring and continuous assessment of the state of health of the original parts. In case of differences between the expected and the actual behaviour due to degradation, the RUL can be estimated based on the data gathered. In addition, appropriate measures can be taken if necessary.

In recent years, the methods for estimating the RUL of individual electronic parts under practical use conditions have become the second branch of research in reliability methodology. This looks for early warning indicators that change their status when degradation has passed a critical threshold, as well as searching for characteristic data trends whose extrapolation can also estimate the RUL. Both paths – i.e. the physics of failure (PoF) and degradations-based methods, as well as the data-driven (DD) estimates – can even be combined with the hybrid approach to prognostic health management (PHM) that prevents unexpected failures without necessitating redundancy. This has a great effect on the economy as well as the ecology of the new solutions. PHM makes the systems safe in a very smart, affordabl, and sustainable way as it reduces the need of redundant parts.

Digital twins and compact digital twins

In both branches of the reliability methodology, EoL assessment and RUL estimation, numerical modelling is speeding up the analysis. It can further be improved by automation, which advances the simulation schemes into digital twins that can perform the complete DfR optimisation of the new products without manual interference. After defining the experiments (DoE), they assess the EoL estimates of each leg and identify the optimum design variant. This increased efficiency strengthens the acceptance of virtual prototyping in the industrial practice, and hence lets the ecologic benefits grow by fabricating even less physical samples and avoiding even more time and energy consuming tests. These automatic schemes can also generate comprehensive sets of data that estimate the EoL expectancy of the electronics products under all the various operational and environmental conditions for which they are specified.

Based on this training data, behavioural models can be established by advanced response surface or other AI methods (e.g. neural networks). These models constitute compact versions of the digital twins. Compared to the full versions, they require much less computational resources and can provide the EoL estimates in a small fraction of the time – e.g. 1,000 to 10,000 times faster. Moreover, these behavioural compact digital twins can be shared with partners along the value chain since they do not reveal the valuable IP of the originator, such as the internal geometry, the material data, or any other modelling details. Yet, they provide all information needed for the virtual DfR at the next level of integration, often enabling it altogether.

In the branch of RUL estimation, compact digital twins are also very beneficial. Here, they can improve the PHM substantially. When small enough to be implemented directly in the electronic system to be monitored, they can continuously provide estimates about the expected behaviour of the critical parts in this system. Deviations from actual behaviour may have been caused either by degradation, which can lead to failure, or model inaccuracy. These two types of deviations show characteristic patterns so that an AI routine can easily trigger the appropriate response. In the first case, a RUL assessment, corrective actions, and a notice of necessary maintenance would be made. Corrective actions can include dynamic performance adjustments, by means of which the RUL is increased such that the completion of the current mission is guaranteed. It can even leave the end-user sufficient time to have the necessary maintenance of components and consumables performed at a convenient time so that no part needs to be replaced too early and the system availability using the original parts is maximised. In the other case – i.e. if the deviation is caused by model inaccuracy – a feedback note is sent to the component manufacturer. Obviously, the experienced load case was not considered well enough in the simulations that provide the training data, and which are used for the product DfR. Thus, the feedback from the field helps to improve these models so that the next products will be even more reliable.

For feedback, the AI routines used to create the compact digital twin also enable compliance with the General Data Protection Regulation. Instead of the full use case information that would enable profiling of the end-user, the manufacturer receives only the corrected set of neural network weighting factors that extend its scope to the additional use case as well. This example of federated learning has been adopted from the biomedical domain, where patient data must be protected while diagnostic results are transmitted. On that basis, these new AI methods improve the reliability and the safety of the future electronics components without requiring all the many redundant parts that would otherwise be mandatory – so that the use of the new AI methods also improves the sustainability of the future product solutions substantially.

4.6.2 Software and AI for sustainability

This section describes the key role played by the software in the ECS and its capacity to provide key features for sustainable ICT, including in the domains of IoT, Industry 4.0, edge computing, digital twins, etc, which rely on properties that go beyond the pure hardware capabilities, to be managed over the entire life cycle.

Software is an enabling technology, which allows for flexibility, reconfiguration, lifetime extension, usefulness, security, reliability, and eventually the management of the hardware (optimisation, graceful degradation, power management and adaptation to application and environmental changes, etc). AI brings new capabilities and represents a breakthrough in digitalisation, but it is also considered a threat in many respects. In this regard, sustainability requires at a minimum to be able to understand the operations of AI and to secure its operation to build intelligent yet trustworthy systems.

The hardware provides a pool of resources, including energy, bandwidth, storage and processing capabilities. These resources are defined by their design and operational characteristics, in particular their capacity or amount, their reliance on other resources and their respective usage (e.g. power consumption). Software can make great use of this information to optimise their usage and extend drastically the lifetime (over a battery charge by consuming less energy or over their operational life by software fixes and upgrades), availability, trust, performance and usefulness of the devices. Software allows for reconfiguration of systems or individual components and adaptations of changing conditions in the environment and in the application specification and constraints. Thus, choosing the right resource for the right task at the right moment is an optimisation role typically delegated to the software for its greater flexibility over time, whereas providing the best trade-off in terms of power consumption, recyclability, miniaturisation, cost, etc, is defined at the hardware design time.

The environmental footprint of devices and applications is heavily reduced by the minimisation of data displacement, which means a more powerful local processing of the acquired data, savings on the communication bandwidth and energy. Furthermore, latency is reduced drastically and robustness is increased because actions can be taken independently from any external resources or infrastructure. Combined with energy harvesting and compliance to the Gene's Law on energy efficiency, the end-device becomes completely autonomous.

Sustainability involves all the processes for keeping the existing deployed elements of the systems operational, safe and secure, such as software update and upgrade. Security mechanisms and security material protection are the basic building blocks on which the update/upgrade processes rely. Autonomy of the functional operation near the physical process is another dimension of sustainability, most importantly for guaranteeing (fallback) operations even in the absence of external resources such as the Cloud, and for reducing the latency and power consumption (saving on the exchange of data). This effectively combines with the energy-wise autonomy.

Distribution of processes, including AI such as machine learning and inferences processes, creates islands of intelligence, which also need to be managed and updated, calling for their monitoring and evolution (e.g. through firmware update).

Software is a key enabler for the successful operations of AI applications when it comes to data filtering and validation to allow for the scalability of AI, which goes hand in hand with explainable or interpretable AI to be fully reliant on these technologies. The impact of poor data quality on organisations has risen to about USD10 million per year[48].

Security relies on a combination of hardware and software to offer protection during communications, credential management, storage, against side channel attacks and even after post-compromise or after decommissioning.

Software is at the heart of all this, in particular in communication, data processing and orchestration, among many other functions. New trends are reinforcing the above points: greater autonomy, smarter behaviour, right time, right location, self-upgrading and self healing, self assessment (for security), mission management, supply chain transparency, controlled degradation, zero-trust, explainable and interpretable AI, even more integration and More-than-Moore approaches, etc.

- Gathering data at large and deeply in the processes and participating entities also allows for implementing the LCA and full-blown traceability, and is a key component in the integration glue of the ECS. It also supports the supply chain and optimising their operations and outcome and, most importantly, for the decision support (potentially AI-based) in the process of rational environmental policy implementation and enforcement. In that context, the software components undertake a huge role, while counting, as much as possible, for a marginal use of resources.
- The software brings flexibility in ECS by implementing complex logics, allowing systems to adapt, by specification, to various situations expected at the design phase. The software has also to be robust and secure, through updates, automatic reconfiguration, networking and collaboration across entities, bug fixes, vulnerability patches, etc, to adapt to unexpected events such as environmental, operational and functional changes over time, as well as anomalies and attacks. Beyond resource consciousness, the software must recognise the possible evolution of the hardware platform, compensating for hardware inflexibility, its faults and the degradation of future zero environmental impact hardware, which will 'disappear‘ in its operational enviroment, while ensuring the best possible resource usage and most reliable and secure operations, even after decommissioning or failure.
- Software implements the logic of processes and applications, and ECS have recently witnessed the advent of intelligent platforms running groundbreaking software able to predict events and even elaborate complex statements based on large learning sets. Beyond the apparent magic, such evolution brings trustworthiness of such systems and their outcomes at the forefront of requirements from many perspectives (intellectual, societal, ethical, operational, governmental, etc).
- For a sustainable interconnected ecosystem of ECS, the software must be secure, reliable and constantly automatically and autonomously adapted.

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[48] “Poor-quality Data Imposes Costs and Risks on Business says New Forbes Insights Report”, *Forbes*, May 31, 2017 (https://www.forbes.com/sites/forbespr/2017/05/31/poor-quality-data-imposes-costs-and-risks-on-businesses-says-new-forbes-insights-report/?sh=4eb96655452b).

For more about the sustainability of edge computing and AI, we recommend the 2021 EPoSS White Paper “AI at the Edge”[49].

[49] https://www.smart-systems-integration.org/system/files/document/EPoSS-White-Paper-AI print.pdf.

5 Green ECS by design

The design phase of ECS is essential for a circular transition since circularity decisions, such as those concerning the type of materials, assembly methods and expected lifespan, significantly influence the impacts of the system during its lifetime. It is estimated that approximately 80% of the sustainability performance of a product over its life cycle is defined in the early stages of the product design and development process[50]. However, ECS design is far from being circular and most of the current ECS have been designed for a single life cycle. Contrary to green design, which focuses on improving specific aspects of a product in terms of their environmental impact, the aim of the eco-design of ECS is a life-cycle-oriented minimisation of their environmental impacts that takes into account the opportunites for circular economy.

This chapter will describe the necessary actions to put in place to facilitate green electronics at the design phase largely from a techncial viewpoint. Section 5.1 explains the underlying policies and regulations driving eco-design; section 5.2 presents some eco-design tools; section 5.3 reviews the approaches for the eco-design of the ECS; section 5.4 presents the challenges and opportunities; while Section 5.5 provides an outline of the main guidelines for the eco-design of ECS, with the end-objective of allowing a circular economy of electronics.

5.1 Relevant current and proposed eco-design directives: EU regulations for ECS

The EU Ecodesign Directive is a set of regulations that aim to improve the environmental performance of energy-related products, including electronics. The directive applies to a wide range of electronic products, namely electronic displays, set-top boxes, computers, video (game consoles), external power supplies, device (networked) standby, imaging equipment, servers, and digital storage.

The directive sets energy-efficiency requirements for electronic products, such as standby and idle power consumption and energy-efficiency ratings. The requirements aim to reduce the amount of energy consumed by electronic devices, thereby reducing the carbon footprint associated with their use. The directive also aims to encourage the design of electronic products that are easier to repair and recycle. This includes the use of standardised components, modular design, and the provision of repair and maintenance information. The goal is to extend the life of electronic products and reduce the amount of waste generated by their disposal. In addition, the eco-design directive imposes restrictions on the use of certain chemicals in electronic products, such as lead, mercury and cadmium. These chemicals are hazardous to human health and the environment, and their use is therefore limited or prohibited. The directive also requires electronic products to be labelled with information on energy efficiency and other environmental attributes. This includes the provision of energy consumption information and an energy-efficiency rating, as well as information on product repairability and recyclability.

[50] Kamp Albæk, J., *et al.*, "Circularity Evaluation of Alternative Concepts During Early Product Design and Development“, *Sustainability*, 12(22), 2020.

Directive 2009/125/EC[51] is the key piece of legislation related to the EU Ecodesign Directive. It sets out the framework for establishing eco-design requirements for energy-related products, including electronics. This directive aims to reduce the environmental impact of products throughout their entire life cycle, from raw materials extraction to disposal. Under this directive, manufacturers of energy-related products are required to design their products to meet specific environmental criteria, such as energy efficiency, water consumption, and the use of hazardous substances. The directive also establishes a set of procedures for developing and implementing eco-design requirements, including stakeholder consultation and impact assessments. Currently, there are eco-design measures in place for 31 product groups based on the 2009/125/EC directive, primarily aimed at reducing energy consumption[52].

Directive 2009/125/EC replaced the earlier Directive 2005/32/EC[53], which established a framework for setting eco-design requirements for energy-using products, including electronics. This directive focused on improving the environmental performance of products, particularly their energy efficiency. It required manufacturers to meet minimum energy-efficiency requirements and mandated the use of energy labels to help consumers make informed purchasing decisions. Directives 2009/125/EC and 2005/32/EC have both played an important role in shaping the EU's approach to eco-design and promoting sustainable electronics, and have helped reduce energy consumption, promote the use of safer and more environmentally friendly materials, and encourage the design of products that are easier to repair and recycle.

In terms of the impact of the directives and their associated regulations, the EU’s eco-design impact accounting annual report for 2021[54] highlighted the various electronic categories and the anticipated effect of the legislation by 2030, but focuses on the reduction of energy consumption, GHG emissions and consumer expense. Acording to the report, in 2021 alone the current eco-design measures saved EUR 120 billion in energy expenditure for EU consumers, and led to a 10% lower annual energy consumption by the products covered. Table 5.1 gives an overview of the expected yearly reduced electricity consumption and GHG emission by 2030 for different products with the respective regulation. All product group-specific regulations are pursuant to the framework directive 2009/125/EC.

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[51] Directive 2009/125/EC on ecodesign for energy-related products: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0125.

[52] Overview of existing EU Ecodesign, Energy Labelling and Tyre Labelling measures (May 2023): https://commission.europa.eu/system/files/2023-05/Summary%20overview%20of%20ED-EL%20measures%20v3%20-%20for%20web%20-May%202023.pdf.

[53] Directive 2005/32/EC on the ecodesign of energy-using products: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32005L0032.

[54] European Commission, Directorate-General for Energy, "Ecodesign Impact Accounting Annual Report 2021: Overview and Status Report“, 2022 (https://data.europa.eu/doi/10.2833/38763).

Table 5.1 Expected yearly reduced electricity consumption and GHG emission by 2030[55]

	Reduced electricity consumption by 2030 per year	Reduced GHG emissions by 2030 per year	Product group regulation
Electronic displays	51TWh	7MtCO_2eq	2019/2021[56] and 2019/2013[57]
Set-top boxes	3.8TWh	0.5 MtCO_2eq	07/2009[58] and 1275/2008[59]
Computers	Less volume of high energy consuming desktops to low energy demanding laptops		617/2013[60]
Video (game consoles)	4.1TWh	0.6 MtCO_2eq	1275/2008
External power supplies	5.4TWh	0.8 MtCO_2eq	2019/1782[61]
Device (networked) standby	16.1 TWh per year	2.3 MtCO_2eq per year	1275/2008
Imaging equipment	6.9TWh per year	1 MtCO_2eq per year	1275/2008
Servers and digital storage products	3 TWh per annum		2019/424[62] 2009/125/EC

As part of the Ecodesign Working Plan 2022–2024 (see Section 3.3), the European Commission published a new "Ecodesign for Sustainable Products Regulation" 2022/0095 (COD)[63] on March 30, 2022, which is currently (June 2023) being discussed in the European council. The new regulation seeks to establish a framework for setting eco-design requirements for sustainable products, and will repeal Directive 2009/125/EC.

[55] ibid.

[56] EU Regulation 2019/2021 on energy labelling and ecodesign requirements for electronic displays: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32019L2021.

[57] EU Regulation 2019/2013 on energy labelling of electronic displays: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R2013.

[58] EU Regulation 107/2009 on ecodesign requirements for simple set-top boxes: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009R0107.

[59] EU Regulation 1275/2008 on ecodesign requirements for standby and off-mode electric power consumption of electrical and electronic household and office equipment: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008R1275.

[60] EU Regulation 617/2013 on ecodesign requirements for computers and computer servers: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013R0617.

[61] EU Regulation 2019/1782 on ecodesign requirements for external power supplies: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R1782.

[62] EU Regulation 2019/424 on ecodesign requirements for servers and data storage products: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0125.

[63] COM/2022/142 final "Proposal for a Regulation of the European Parliament and the Council Establishing a Framework for Setting Ecodesign Requirements for Sustainable Products and Repealing Directive 2009/125/EC" (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0142).

The new regulation aims to expand the scope of the product catalogue beyond energy-related products while at the same time incorporating a broader range of circularity aspects for all product groups. These include:

- product durability, reusability, upgradability and repairability;
- presence of substances that inhibit circularity;
- energy and resource efficiency;
- recycled content;
- remanufacturing and recycling;
- carbon and environmental footprints;
- information requirements, including a digital product passport;
- products' expected generation of waste materials.

As soon as the European Council and Parliament adopt the new regulation, delegated acts for specific product groups will have to be drafted and adopted by the European Commission.

5.2 Eco-design tools for ECS

Environmental assessments are being conducted using various tools. The first set of tools used are general LCA tools such as GABI, OpenLCA and SimaPro. These provide the possibility to undertake an extensive study of the environmental footprint but are limited by the lack of critical data and the long duration needed to gather information.

The resource-intensiveness of standard LCA tools has led to the development of generic modules built on the LCA tools[64]. One example is the EDEP where the LCA software GABI is used to create a parametrised and moduled interface for specifically analysing electronic products. Here, basic components in an electronic system are generalised into modules. As a result, instead of attending to each component, the practitioner simply has to categorise the modules and adjust the relevant parameters.

Furthermore, there are eco-design tools that are specifically designed to ascertain that products and processes are compatible with current directives. GreenDataManager (GDM) is one such tool[65], and it has several in-built regulations to cross-check the compatibility of a products/process with current regulations.

In addition, there are several eco-design tools and screening LCA tools that are less time- and data-intensive than standard LCA softwares. Some are developed by LCA software providers (ECO-it by Pre), while others are from independent environmental groups/companies (Ecodesign PILOT, Ecolizer 2.0., EcoDesignStudio). There are also tools produced by technological companies for internal and external use such as SOLIDWORKS Sustainability by Dassault Systems.

In conclusion, there are a series of challenges when it comes to assessing the environmental footprint of ECS, such as acquiring quality data and standardising the assessment process. Despite

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[64] Baumann, M., Held, M., Herrmann, C., Saraev, A., Riese, O. and Steininger, H., "Ecodesign Tool for SMEs in the Electronics Sector“, IEEE, September 2012, in Electronics Goes Green 2012+ (pp. 1–8).

[65] https://www.greensofttech.com/greendata-manager-gdm-software/.

such issues, several eco-design tools are being used, including general LCA tools, generic modules built on LCA tools, and eco-design tools specifically designed for regulatory compliance. While each of these has its advantages and limitations, their use is essential in mitigating the environmental impact of electronic products throughout their entire life cycle.

5.3 The Design for R concept for the eco-design of ECS

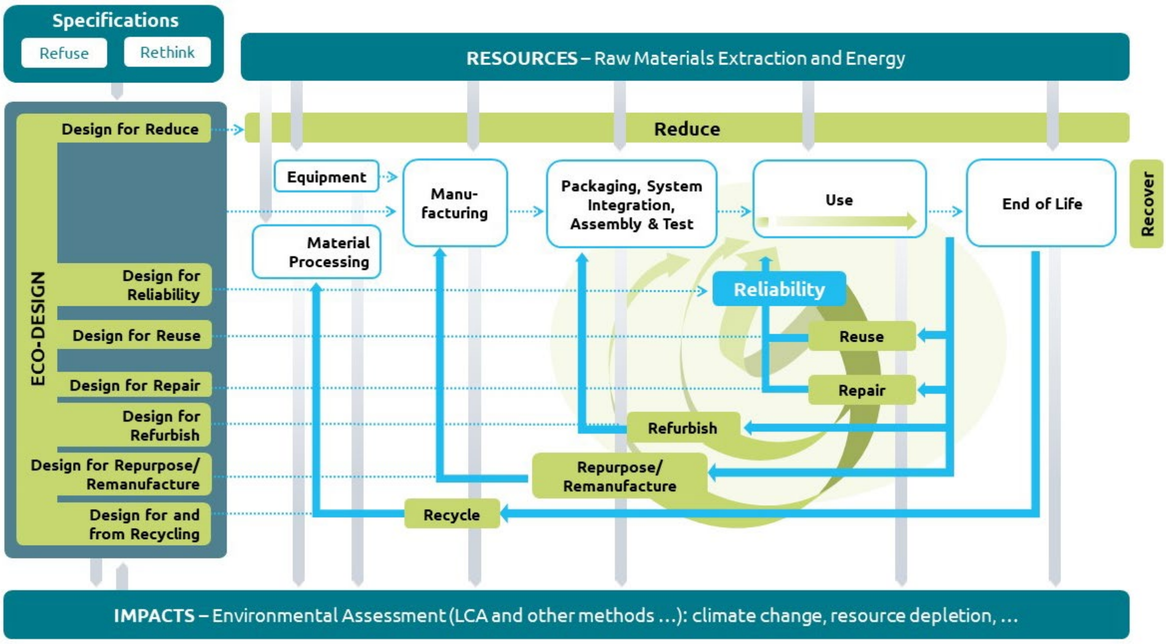

Figure 5.1 Design for R concept applied to ECS circular economy (B. Robin, CEA)

Various studies have explored how design can contribute to circular economy through the adoption of Design for X (Excellence) approaches[66]. Most ‘Design for’ approaches, as well as most of the R frameworks[67], target products, services or product-service systems without focusing on ECS in particular. To make the circular economy of ECS an implementable reality and not a theoretical dream, in this section we propose practical leads for the eco-design of electronics.

By considering the Rs introduced in the 9R framework (see Figure 5.1), we propose a Design for R approach that we consider the most inclusive and adapted to ECS. We take into account most of the Rs of the framework that can be assessed in the design phase, and also introduce the 'reliability‘ property, introduced in the 9R framework in Chapter 3 and fundamental in the design phase to guarantee the lifetime of the systems. The order of the Rs is carried out based on their position in the framework and then adding a final R for reliability. The priority of the actions can greatly vary among systems and can be guided by performing LCA. The life-cycle phases and parts of the systems contributing most to the environmental impacts should be identified during the design through LCA

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[66] C. Sassanelli *et al.*, "Addressing Circular Economy Through Design for X Approaches: A Systematic Literature Review“, *Computers in Industry,* 120, September, 2020 (https://www.sciencedirect.com/science/article/pii/S0166361519311455).

[67] Kirchherr, J., Reike, D. and Hekkert, M., "Conceptualizing the Circular Economy: An Analysis of 114 Definitions“, *Resources, Conservation and Recyling*, 127, December 2017, pp. 221–32 (https://www.sciencedirect.com/science/article/pii/S0921344917302835).

before and while applying the Design for R concept. For example, for personal computing devices (mobile phones, wearable devices, tablets, laptops, desktop PCs, etc), most carbon emissions come from design and manufacturing integrated circuits rather than hardware use and energy consumption[68], so the Design for R should be applied as a priority to this part of the ECS.

Design for 'reduce‘

The 'reduce‘ strategy aims at increasing efficiency in ECS manufacture or use by consuming fewer resources and materials. Broadly, carbon emissions of ECS have two sources: hardware manufacturing and infrastructure; and operational energy consumption. Addressing both emissions requires fundamentally rethinking designs across the entire computing stack. Since the first direct detrimental impact of ECS arise from their production, it is necessary to design systems by reducing the pressure on the usage of resources. Besides the reduction of resources, the reduction of energy is the second lever through the design of energy-efficient systems.

Design for 'reuse‘

The 'reuse‘ of an ECS can be intended as product reuse or component reuse. The reuse of systems or parts of a system is generally positive for the environment as it reduces or replaces the use of another resource. Reuse is environmentally and economically more interesting than recovery of materials.

Product reuse is the second-hand trading of products for use as originally designed, and there is no need for new part manufacturing. The required energy or cost for recovery can be less. The concept of component reuse stems from the fact that many components have a design life that exceeds the life expectancy of the product itself. The objective of component reuse is to allow parts from a non-repairable system to become spare parts for maintenance or used in a different system. In component reuse, parts from a specific product are not kept with the product but instead are collected by part type, cleaned and inspected for possible reuse. When all the components of an ECS are replaced, we say the system has been remanufactured.

The possibility of reuse can be planified from the design phase. The design for reuse first requires modularity in terms of hardware and software. Second, during the lifetime of the system, we need methodologies to assess the remaining life and reuse potential of used components69. Such methodologies must be integrated in the design of the system. It is important to note that, when determining a component’s reuse potential, two factors must be taken into account: the remaining physical life of a system (i.e. how long an item will continue to perform its intended functions within a specified usage environment); and the technological life, which relates to the changes in technology and the consequent market demand.

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[68] U. Gupta, et al., "Chasing Carbon: The Elusive Environmental Footprint of Computing“, IEEE Micro, 42(4), 2022 (https://dl.acm.org/doi/10.1109/MM.2022.3163226).

[69] Rugrungruang, F., Kaebernick, H. and Kara, S., "An Integrated Methodology for Assessing Physical and Technological Life of Products for Reuse“, *International Journal of Sustainable Manufacturing,* 1(4), 2009, pp. 463–90.

Design for 'repair'

Since a direct detrimental impact of ECS arise from the end of life, it is mandatory to extend the lifetime of the systems. Besides the design of reliable systems, another action towards lifetime extension is through repair, and hence ECS must be designed to be repairable. (see Chapter 6).

Design for 'refurbish'/'remanufacture'/'repurpose'

The objective of refurbish, remanufacture and repurpose strategies is to allow a second life for a system or part of it. The functions necessary for a refurbish, remanufacture or repurpose of a system must be planified from the design phase to allow partial diagnosis, retesting and recharacterisation of the system or part of it. Moreover, the design must make sure that the unused parts will be securely isolated and not create problems for the remaining ones.

Design for and from 'recycling'

The recycle phase dismantles the system, separates it into materials and provides recovery treatments. From the economic and environmental perspectives, efficient recycling is of great importance since ECS are rich in base and precious metals[70].

ECS design must explicitly take into account the recyclability of the system. From a materials perspective, measures are needed to improve on recyclability. In addition to the use of recyclable materials, the ability to break connections between materials that are not compatible in recycling processes is crucial[71]. A concept younger than the design 'for' is the design 'from' recycling, which plays a key role in closing the material loops within a circular economy[72].

Design for 'reliability'

Innovation by design is currently conducted with an almost exclusive focus on performance. Reliability becomes a mandatory constraint only for safety-critical applications. For sustainability, design for reliability must be conducted for every ECS, safety-critical or not, with the objective of guaranteeing and extending the lifetime of the system. This constitutes a response to the Circular Economy Action Plan[73] approved by the European Commission in 2015, to increase the value of products by promoting their use for longer durations and to minimise the amount of waste generated. Lifetime optimisation and extension by design for reliability is generally positive for the environment, whereas obsolescence or induction of new ECS are obviously detrimental. Clearly, reliability approaches can hinder technical obsolescence due to physical constraints such as ageing, but cannot solve obsolescence caused by the changes in a product's value. Hence, design for reliability can optimise and extend the physical lifetime of ECS, helping to reduce e-waste, but cannot impact the value lifetime. Design for reliability also allows other means for lifetime extension (repair, reuse, refurbish, addressed above) as reliable components can be reused or refurbished, reducing the necessity for repair.

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[70] Kaya, M., *Electronic Waste and Printed Circuit Board Recycling Technologies* (Springer International Publishing, 2019).

[71] Balkenende, A. R. and Bakker, C. A., 'Developments and Challenges in Design for Sustainability of Electronics", *Transdisciplinary Lifecycle Analysis of Systems*, Conference Paper, 2015.

[72] Berwald, A. *et al.*, "Design for Circularity Guidelines for the EEE Sector", *Sustainability,* 13(7), 2021.

[73] European Commission, "Closing the :oop – An EU Action Plan for the Circular Economy", COM/2015/0614, 2015.

Nevertheless, the environmental impacts of the reliability techniques introduced in the design must be evaluated, leading to a new, more holistic approach by design, called 'eco-reliability'[74].Tools to design eco-reliable ECS are thus required, going beyond the evaluation of the environmental impacts achieved through LCA.

5.4 Challenges

The Ecodesign-Directive (Directive 2009/125/EC)[75] was largely directed at reducing the energy consumption of electronic (consumer) products, and required consideration of the energy efficiency of freezer, washings machines, etc, already at the design stage. Since its publication in 2009, however, maximising resource-efficiency (especially of physically scarce and economically critical materials) and minimising other environmental impacts such as plastic waste or toxic waste, have increasingly come into focus. As a result, eco-design targets have multiplied, and a delicate balance weighing the overall cost to the environment is required to assist decision-making. These targets are intimately linked to the 10R (Table 3.1).

The most important targets in ecodesign are to: (1) decrease energy use in operation and production (decarbonisation); (2) improve resource efficiency, particularly regarding scarce, economically critical or socially unsustainable raw materials (greener production); (3) increase the lifetime via enhancing performance, reliability and robustness (lifetime optimisation); and (4) enable repairing, reusing, remanufacturing, refurbishing, and recycling (circularity). Crucially, several targets in ecodesign transcend the technical domain and are reliant on social and economic factors, such as design, marketing strategies, planned obsolescence, and consumer enthusiasm for recycling.

5.4.1 Challenges in decarbonisation and green production

The electronics industry, and in particular chip manufacturing, has a massive environmental footprint: its requirement for tools and cleanroom conditions results in a large carbon footprint (it could consume up to 20% of the global electricity demand by 2030[76]); its use of specific etching gases employs toxic and ozone-layer depleting materials; and the focus on subtractive manufacturing creates an excessive amount of chemical use and wastage[77].

There are many proposed solutions and improvements, such as focusing on novel materials and technologies (e.g. additive technologies, emerging flexible materials for PCBs and integrated circuits; or comparing different component attachment materials). Others include the implementation of ecological assessments in the production methodologies, such as: comparison of wet and dry etching methods with a view to reducing chemical waste and cutting costs; and sustainability benchmarking

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[74] Middendorf, A., *et al.*, "Eco-reliability as a New Approach of Multi-criteria Optimisation", Electronics Goes Green, Conference Paper, 2012.

[75] Directive 2009/125/EC on ecodesign for energy-related products: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0125.

[76] Gupta, U., *et al.*, "Chasing Carbon: The Elusive Environmental Footprint of Computing", arXiv, 2020 (http://arxiv.org/abs/2011.02839).

[77] Belton, P., "The Computer Chip Industry has a Dirty Climate Secret", *The Guardian*, September 18 2021 (https://www.theguardian.com/environment/2021/sep/18/semiconductor-silicon-chips-carbon-footprint-climate).

of different materials and manufacturing processes[78]. However, a change to an already implemented line is complex and costly. At the same time, a relation of energy usage in production versus performance does exist – for instance, in the production of high-cost cleanroom microelectronics compared to low-cost, lower-performance printed electronics, which are often still at the research stage. The challenge in eco-design is to achieve a reduction in environmental footprint of production while not sacrificing too much performance. As longer-lasting devices score more favourably on LCA than devices based on less-lasting but more sustainable materials and production pathways, a careful assessment of the effectiveness of the proposed changes is required.

5.4.2 Challenges in lifetime optimisation

Lifetime optimisation relates to the decrease in environmental footprint during operation as well as the prolongation of the lifetime of the component. Lifetime prolongation is subject to opposing forces: on one hand, the desire of the consumer for a long-lasting product; on the other hand, the quick saturation of the market with no potential for growth in sales. Many lifetime optimisation decisions come down to consolidation. When it comes to computing performance from an operations point of view, it is usually more efficient to consolidate computer resources into large-scale data centres, where the overhead cost (energy losses) of power conversion and cooling per computation can be kept much lower. Moreover, data needs to be transferred from the source to a central location, requiring energy usage in the transmission links. To optimise energy use from a system perspective, it is advantageous know where the decision of computation takes place – e.g. close to the data source or in a central data centre, or at a networked edge compute node.

A recent example are telecom infrastructure installations that traditionally have been powered up 24/7, but where customers now demand energy-saving features and periodic power-off. This will decrease the environmental footprint of the installation during operation, but also introduces increased power cycling that could negatively affect the long-term reliability of the installation. This calls for renewed reliability assessment of already deployed installations and a modified assessment of new product generations.

5.4.3 Challenges in material circularity

Material circularity encompasses remanufacturing, repurposing and, if those are not possible, recycling. A common route for end-of-life of electronic waste is to wind up in a developing country, where formal and informal recycling is carried out, resulting in great damage to the environment and human health. However, with the growing drive for resource self-sufficiency, materials recovery from e-waste is becoming a growth industry in EU countries. However, due to the various environmental and health concerns associated with the processing, tight regulations exist and can hamper growth.

For metals, both criticality and recyclability need to be considered in eco-design frameworks[79], in addition to effects on human and environmental health. Much of their environmental impact arises at the sourcing stage due to the requirement for energy-intensive processes often employing harsh

[78] IDTechEx, "Sustainable Electronics Manufacturing 2023–2033“, 2022 (https://www.idtechex.com/en/research-report/sustainable-electronics-manufacturing-2023-2033/902).

[79] Sheng, F., *et al.*, "Evaluation on End-of-life LEDs by Understanding the Criticality and Recyclability for Metals Recycling“, *Journal of Cleaner Production,* 182, 2018, pp. 624–33 (https://doi.org/10.1016/j.jclepro.2018.01.260).

chemicals[80]. Copper, for example, has less adverse effects due to its high chemical reactivity, which makes it easy to recycle, and hence more than 80% of produced copper stays in the system. However, it is also prone to oxidation and unsuitable for applications where precious metals are required. In particular, the introduction of new functionalities reliant on rare earth materials needs to include eco-design aspects already at the research stage. For plastics, it is advantageous to consider novel bioplastics that can be produced from sustainable sources rather than relying on petroleum – however, these are also required to undergo a full LCA estimation before their consideration as they can produce surprising results.

Recycling relies on mechanical, chemical and biological processes that allow them to separate and recover various metals from non-metallic material used (various plastic components). Also, the nature of plastic components, as well as the easy separability of the non-metallic components, improves their amenability to recycling. In particular, the dissolution of plastic under benign conditions and the modularity of various components can aid the process. The treatment conditions required for recycling of all variable materials, as well as its carbon cost, need to feed into the LCAs guiding eco-design. However, this data is usually not easily available, particularly for companies working in the manufacturing sector[81].

5.4.4 Challenges in design tools

Finding suitable eco-design tools that assess the environmental impacts of electronic components and systems across their entire life cycle is a challenging task[82]. The challenges stem from various causes. One factor is the amount and depth of data required to assess the environmental footprint. Electronic products contain a range of materials, including rare earth metals, whose mining, purification and production is not reported and documented in a transparent way. Furthermore, data regarding the production of the ECS themselves is often shrouded in secrecy due to the intense competition in the industry. Data from the use phase is relatively easier to access, but the speed at which new devices and systems reach the market makes it necessary to collect and analyse consumer behaviour continuously. Getting information on the end-of-life of the ECS is a difficult task due to the low amount of e-waste collected[83].

The second challenge is the mismatch between the high speed of the industry and the time-intensive nature of eco-designing. The designs and the LCAs should be done continuously to keep up with the pace of the ECS industry.

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[80] Nuss, P. and Eckelman, M. J., "Life Cycle Assessment of Metals: A Scientific Synthesis“, PLOS ONE, 9(7), 2014 (https://doi.org/10.1371/journal.pone.0101298).

[81] Hagelüken, C. and Goldmann, D., "Recycling and Circular Economy – Towards a Closed Loop for Metals in Emerging Clean Technologies“, *Mineral Economics,* 35(3), 2022, pp. 539–62 (https://doi.org/10.1007/s13563-022-00319-1).

[82] Unger, N., Schneider, F. and Salhofer, S., "A Review of Ecodesign and Environmental Assessment Tools and their Appropriateness for Electrical and Electronic Equipment“, *Progress in Industrial Ecology, an International Journal,* 5(1–2), 2008, pp. 13–29.

[83] Shahabuddin, M., *et al.*, "A Review of the Recent Development, Challenges, and Opportunities of Electronic Waste (e-waste)“, *International Journal of Environmental Science and Technology,* 1–8, 2022.

The third challenge is the lack of a standard in assessing ECS. Apart from the specific requirements of the Ecodesign Directive, there are no standards for the impact categories, normalisations and weighing that have to be done in assessing environmental impacts of ECS. As a result, multiple tools and scopes are utilised by various stakeholders thereby making comparisons between different assessments results hardly appropriate.

5.4.5 Challenges in decision-making

The usefulness of eco-design frameworks and decision trees is largely dependent on complete and correct datasets encompassing the whole product life cycle. In particular, where confidential manufacturing processes and trade secrets are concerned, a distinct problem is an unwillingness to share component materials and manufacturing process details. This is exacerbated when complex value chains are involved. Lack of disclosure hampers efforts for LCA, and thus moving forward in eco-design. Potential solutions could revolve around incentivisation initiatives, including PEF pilots[84], the Safe and Sustainable by Design (SSbD) initiative85 or the Environmental Product Declaration (EPD)[86]. This incentivisation could be regulation- or market-directed by disclosure to regulatory agencies or disclosure to consumer. Another likely useful workaround could be frameworks for LCA that do not disclose product data, or the embedding of internal LCA in all larger companies.

One example for this are integrated circuits. New materials and designs are continuously being developed, which makes it difficult to have a common standard for chip manufacturing[87]. At a global scale, there is much competition in integrated circuits production and new technologies are continuously emerging[88]. Furthermore, the high starting investment requirements has meant only a few companies are able to produce the complex processors needed in modern smartphones and computers. The global distribution of these few companies makes the industry susceptible to the varying political climate, which in turn limits collaboration[89]. Addressing these challenges requires a highly adaptive, proactive and not reactive, mechanism since the speed of the technology will bring

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84 European Commission, "Environment Footprint Methods“, ‘Single Market for Green Products – The Product Environmental Footprint Pilots – Environment‘ (https://ec.europa.eu/environment/eussd/smgp/ef_pilots.htm).

85 Caldeira, P., *et al.*, "Safe and Sustainable by Design Chemicals and Materials Review of Safety and Sustainability Dimensions, Aspects, Methods, Indicators, and Tools“, JRC Publications Repository, 2022 (https://publications.jrc.ec.europa.eu/repository/handle/JRC127109).

86 ‘EPD International (https://www.environdec.com/home).

87 Leiserson, C. E., *et al.*, "There’s Plenty of Room at the Top: What will Drive Computer Performance after Moore’s Law?", *Science,* 368.6495, 2020.

88 Dyatkin, B., "While Transistors Slim Down, Microchip Manufacturing Challenges Expand", *MRS Bulletin,* 46, 2021, pp. 16–18.

89 Capri, A., "Strategic US–China decoupling in the Tech Sector", Hinrich Foundation, 2020 (https://www.hinrichfoundation.com/research/wp/tech/us-china-decoupling-tech).

setbacks to iterative solution-finding processes[90]. Green designs should be embedded from the get-go of the chip manufacturing process on different levels.

Legislation and standardisation of sustainability requirements can enforce a limit on the environmental footprint from chip production[91]. For this purpose, a program operator comprising of relevant companies, governmental agencies and sustainability practitioners should be set up to prepare product category rules (PCRs) and outline specifications that must be adhered to in the chip production process. These specifications can relate to, for example, establishing a reasonable functional unit for comparing chips, limits on emissions from production, usage of scarce and toxic materials in a chip, and requirements on the reusability/recyclability of the chip.

In addition, the use of adaptive eco-design tools right from the inception phase of a chip can ensure the chips produced have an inherent green dimension[92]. There is currently quite a number of established LCA software tools, but the use and availability of eco-design tools is not as widespread. Furthermore, current developments in AI and machine learning should be utilised to exploit the abundant data collected in the performance of chips to design more efficient, safe and error-free devices.

Another aspect would be an increase in active investment in green technology research, as this can lead to the discovery of materials and processes that are more sustainable[93]. Beyond the speed and complexity sought for new generation chips, increased attention to their sustainability is needed. Companies should dedicate a certain portion of their research activities to purely green initiatives that aim to flag environmental hotspots in the life cycle of the chips, and identify product stages that require improvements. Finally, a focus on sufficiency is required. The complexity of a device should be matched by the functionality, efficiency and sufficiency in the entire life cycle of the device. Complexity of a chip comes with a higher environmental footprint, and so the choice of which chip to use for which device should be driven by the concept of sufficiency. From the customer perspective as well, they should be encouraged to buy products that are sufficient for the purposes they need. Furthermore, upgrading/downgrading products by exchanging integrated circuits or electronic parts should be facilitated by using a modular design; to make this feasible, interface standards will need to be further developed.

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[90] Unger, N., Schneider, F. and Salhofer, S., "A Review of Ecodesign and Environmental Assessment Tools and their Appropriateness for Electrical and Electronic Equipment“, *Progress in Industrial Ecology, an International Journal,* 5(1–2), pp. 13–29.

[91] Kuo, T.-C., Kuo, C.-Y. and Chen, L.-W., "Assessing Environmental Impacts of Nanoscale Semi-conductor Manufacturing from the Life Cycle Assessment Perspective", *Resources, Conservation and Recycling*, 182, 2022, 106289.

[92] Corsi, I., *et al.,* "Environmental Safety of Nanotechnologies: The Eco-design of Manufactured Nanomaterials for Environmental Remediation", *Science of The Total Environment,* 864, 2023, 161181.

[93] Tavakoli, M., *et al.,* "3R Electronics: Scalable Fabrication of Resilient, Repairable, and Recyclable Soft-Matter Electronics", *Advanced Materials,* 34(31), 2022, 2203266.

5.4.6 Trade-offs between the 10Rs and the functionality of green ECS

The robustness and reliability of both large and small consumer electronics are the crucial technical factors leading to longer lifetimes, a highly desirable attribute in electronics. Recyclability and reusability, referring to the reuse of components, relies highly on the ease of separation of components and materials. This is often in conflict with the smaller material requirements and more cost-effective, reliable, high performing, and robust high-density packaging of electronic components. Furthermore, the use of recycled materials – such as dictated by new directives and the Green Deal – requires that the quality and reliability can be maintained and verified. Thus, to allow a fit-for-purpose eco-design framework, sustainable material sources need to be advanced, characterised and verified for use. At the same time, a rating of recycled and sustainable materials should be developed to feed into LCA and inform eco-design.

Reuse of components typically requires de-soldering and re-soldering, which in turn needs verification of quality and reliability by a specified procedure and rating system. For example, the RUL of a component or subsystem would be a useful rating parameter. Between performance and energy use a direct relationship often exists, such as in the production of high-cost cleanroom microelectronics versus low-cost, lower performance printed electronics. A further example is the use of lead solder, a highly toxic material that, despite decades of research, is still unmatched in reliability[94]. Moreover, the environmental impact of lead-free substitutes of various purposes outweighs the impacts of the toxic effects of lead in production – an example where the RoHS is not working in favour of eco-design[95,96,97].

When it comes to computer performance from an operations point of view, it is usually more efficient to consolidate computer resources into large-scale datacentres where the overhead cost (energy losses) of power conversion and cooling per computation can be kept much lower. On the other hand, data needs to be transferred from the source to a central location, requiring energy usage in the transmission links. To optimise energy use from a system perspective, it is advantageous if the decision of where a computation take place is close to the data source or in a central data centre, or at a networked edge compute node.

5.4.7 Business opportunities using eco-design

Benefits to companies arise as they conform to pressure from regulatory standards and market demands, by continuously moving towards electronics with a lower environmental impact. However, often efforts are made to redirect the pressure by influencing regulation and consumer opinion rather than achieving meaningful change by implementing eco-design strategies. Nevertheless, once commitments are made and work programmes established, this challenge can also be converted into opportunities. Crucially, circularity extends the value chain and adds the opportunity for various

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[94] Lee, N.-C., "Getting Ready for Lead-free Solders*", *Soldering & Surface Mount Technology*, 9(2), 1997, pp. 65–69 (https://doi.org/10.1108/09540919710800656).

[95] Schileo, G. and Grancini, G., "Lead or No Lead? Availability, Toxicity, Sustainability and Environmental Impact of Lead-free Perovskite Solar Cells", *Journal of Materials Chemistry C*, 9(1), 2021, pp. 67–76 (https://doi.org/10.1039/D0TC04552G).

[96] Jiang, *et al*., "Reliability Issues of Lead-free Solder Joints in Electronic Devices", *Science and Technology of Advanced Materials,* 20(1), 2019, pp. 876–901.

[97] Andrae, A., "Does the Restriction of Hazardous Substances (RoHS) Directive Help Reduce Environmental Impacts?", 6, 2020, pp. 24–37 (https://doi.org/10.30634/2414-2077.2020.06.03).

business models to profit from both lifetime optimisation and material circularity. These business models include service models, or other models relying on the return of devices, in combination with modular eco-design[98].

Opportunities in lifetime utilisation improvement: The service model

The service model is one of the most used models taking advantage of providing more sustainable solutions and common improvements for IT equipment, where technology is provided and charged for by use. Another example is the Phillips lighting supply to Washington Metropolitan Area Transit Authority[99]. This results in an optimisation focus for the lifetime of the product rather than optimised performance at point of sale, as well as improved customer/supplier communication and more efficient reclaim and recycling of products at EoL. This model is becoming increasingly popular for private/public partnerships[100], but requires tight contract models to clearly establish financial and environmental benefits for all partners that regulate who pays for upkeep, upgrades, and what happens by the end of contract[101]. Further, and particularly if sensitive areas are targeted, the collaboration needs to be centred on a clearly defined value framework.

Opportunities in material circularity

Exploiting material circularity economically means that companies benefit from the reuse of all or parts of electronics that allow the same or a different application. An example is the refurbishing of mobile phones or computer equipment by the original manufacturers or a third partner, which take the opportunity of appealing to a lower-cost market. Selling refurbished articles can have benefits beyond the initially perceived financial incentive of acquiring a lower cost, broken device, and reselling it a higher price point: for manufacturers (e.g. Microsoft), it also allows them to increase their market share and lock in a target demographic, such as young customers, who might follow up on the refurbished device by purchasing new.

Another opportunity, beyond consumer electronics, arises in ICT equipment. The ECS economic model is still primarily linear at this point, without much circularity. Internal initiatives exist to extend the service life or to enable a second life by the following EoL practices: (1) repairing failing equipment; (2) rationally refreshing or upgrading ICT equipment with next-generation ECS; (3) directing the discarded pieces of equipment to brokers or resellers for second-life usage, usually in developing countries; and (4) recycling some material in the so-called "urban mining" paradigm. In several practical examples, the scientific literature has shown that it is possible to integrate

[98] Balkenende, A. R. and Bakker, C. A., "Developments and Challenges in Design for Sustainability of Electronics", *Transdisciplinary Lifecycle Analysis of Systems,* 2015, pp. 3–13 (https://doi.org/10.3233/978-1-61499-544-9-3).

[99] "Philips Lighting to Handle Major LED Project for Washington, DC Transit Authority', *LEDs Magazine*, 2013 (https://www.ledsmagazine.com/home/article/16700863/philips-lighting-to-handle-major-led-project-for-washington-dc-transit-authority).

[100] Casprini, E. and Palumbo, R., "Reaping the Benefits of Digital Transformation through Public-Private Partnership: A Service Ecosystem View Applied to Healthcare", *Global Public Policy and Governance,* 2(4), 2022, pp. 453–76 (https://doi.org/10.1007/s43508-022-00056-9).

[101] Seiden, D., "DC Metro Must Pay Philips for Lighting Upgrade Work (Corrected)", September 10, 2020 (https://news.bloomberglaw.com/federal-contracting/philips-owed-payments-under-dc-metro-lighting-upgrade-project).

environmental impact indicators in the design-making process of EoL management practices[102], but also that the minimisation of different indicators (e.g. resource consumption, GHG emissions and waste generation) can be in contrast with each other[103,104,105].Consequently, proper LCA is required to scientifically and systematically evaluate the impacts for decision-making with respect to refresh, repair, refurbishment, reuse, repurpose and recycle at the end of first life.

For consumer electronics such as smartphones or tablets, this requires modular design to enable replacement of inner modules rather than the full motherboard, relying on the 10R evaluation of current-generation customer premise equipment (CPE). Smartphones could also be repurposed into CPE through the addition of a low-impact generic USB interface module with an experimental demonstrator. This would enable a second life for smartphones and decrease the demand for CPE in the context of resource scarcity.

This changing perspective necessitates appropriate consideration of end-of-life management of various equipment, and in particular to anchor the decision-making process for service life extension and second-life enablement into an LCA framework with concurrent minimisation of multiple indicators of the environmental impact. This should include resource and energy consumption, GHG emissions and e-waste generation (through eco-toxicity, for example).

On the other hand, the prospect and opportunities of e-waste are great if they are recycled properly. E-waste contains precious metals that can be recovered using the urban mining of e-waste: for instance, one metric ton of PCB boards can produce 1.5kg of gold and 210kg of copper[106]. The concentration of precious metals is far higher than that in the ores used for primary mining . Recovering these precious metals can generate significant profits if appropriate business models are applied. The money value of materials in e-waste generated worldwide is three times more than the total economic value of the world's silver mining[107]. Relying solely on mechanical processing causes up to 20% of metals, mostly precious, to remain within composite materials such as PCBs; pyrometallurgical, hydrometallurgical, or biohydrometallurgical processes largely increase this efficiency. However, these are complex polluting processes commonly prohibited within the EU. Unfortunately, often the expertise and infrastructure for their proper implementation is lacking in the developing countries where the e-waste ultimately ends up[108].

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[102] Bashroush, R., "A Comprehensive Reasoning Framework for Hardware Refresh in Data Centers“, *IEEE Transactions on Sustainable Computing,* 3(4), 2018, pp. 209–20.

[103] Jattke, M., Bieser, J., Blumer, Y., Itten, R. and Stucki, M., “Environmental Implications of Service Life Extension of Mobile Devices”, *Proc. Electronics Goes Green*, 2020.

[104] Gurita, N., Fröhling, M. and Bongaerts, J.,“Assessing Potentials for Mobile/smartphone reuse/remanufacture and Recycling in Germany for a Closed Loop of Secondary Precious and Critical Metals”, *Journal of Remanufacturing,* 8(1)(1–2), 2018, pp. 1–22.

[105] Bashroush, R., Rteil, N., Kenny, R. and Wynne, A., "Optimizing Server Refresh Cycles: The Case for Circular Economy with an Aging Moore‘s Law“, *IEEE Transactions on Sustainable Computing*, 7(1), 2020, pp. 189–200.

[106] Bazargan, A., K. F. Lam and Mckay, G., "Challenges and Opportunities in E-waste Management“, in Li, Y. C. and Wang, B. L. (Eds), *E-Waste: Management, Types and Challenges* (Nova Science Publishers, pp. 39–66).

[107] World Economic Forum, "A New Circular Vision for Electronics: Time for a Global Reboot“, January 2019 (https://www3.weforum.org/docs/WEF_A_New_Circular_Vision_for_Electronics.pdf).

108 Abdelbasir, S. M., et al., "Status of Electronic Waste Recycling Techniques: A Review“, Environmental Science and Pollution Research, 25(17), 2018, pp. 16533–47 (https://doi.org/10.1007/s11356-018-2136-6).

To improve recycling outputs at the design stage, there are opportunities to be found in the implementation of eco-design guided by modularity to allow easy separation of parts from each other, also called 'green modularisation'[109]. This will allow for more targeted recycling and even the inclusion of biodegradable materials, for example. For this to present a business opportunity, eco-design alone is not sufficient: return of EoL products needs to also be supported – such as practised by Xerox, who are preventing tens of thousands of metric tons of waste from entering landfill every year. Post-return, the producer also needs to profit from remanufacturing, repurposing or reprocessing to gain a financial advantage. However, methodologies for green modularisation design are complex to implement and evaluate, and require observation over multi-year periods with adequate EoL reporting. Nonetheless, paired with appropriate LCA and evaluation procedures, they present a viable future direction for sustainable electronics.

Based on the challenges addressed in the sections above, we willl continue by expressing a set of eco-design guidelines that can support electronics design considerations to reflect the eco-system of the product.

5.5 Guidelines

While ECS can be a key lever in moves towards sustainability since they could ease energy efficiency and dematerialisation, their environmental footprint must be mastered starting from the design phase. Based on the Design for R and a review of works proposing design guidelines[110], we identify the following main guidelines to drive the eco-design of ECS towards circular economy, in which ECS life is extended enabling multiple product life cycles.

- **Knowledge of environmental impacts and choice of materials**

The first step to mastering the environmental footprint of ECS is through the knowledge of the impacts from the design phase. LCA, as standardised by ISO 14040, is the most advanced approach for environmental assessment, taking into account all life-cycle phases from raw material mining to end-of-life. In the design process, it must be conducted from the early stages and for every design choice. This allows it to address the design for circularity guidelines identified in Berwald *et al*.[111]: avoidance of hazardous substances; enabling easy access and removal of hazardous or polluting parts; use of recyclable materials; use of material combinations and connections allowing easy liberation; and use of recycled materials.

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[109] Sonego, M., Echeveste, M. E. S. and Debarba, H. G., "The Role of Modularity in Sustainable Design: A Systematic Review“, *Journal of Cleaner Production,* 176, 2018, pp. 196–209 (https://doi.org/10.1016/j.jclepro.2017.12.106).

[110] Bovea, M. D. and Pérez-Belis, V., "Identifying Design Guidelines to Meet the Circular Economy Principles: A Case Study on Electric and Electronic Equipment“, *Journal of Environmental Management,* 228, 2018, pp. 483–94.

[111] Berwald, A. *et al.*, "Design for Circularity Guidelines for the EEE Sector“, *Sustainability,* 13(7), 2021.

- **Eco-reliability**

A good ECS design needs to consider both environmental assessment and reliability as early as possible in the design process[112]. A multi-objective design must be investigated with a clearly defined lifetime and environmental strategy. In this context, eco-reliability becomes a guideline for eco-design, defining the cause-and-effect relations of environmental and reliability aspects.

- **Modularity**

Modularity ensures that ECS are conceptualised and designed in such a manner that, at the end of the life cycle, they can be easily dismantled and their components reused, recycled or upcycled. Moreover, to increase the number of reusable components and reduce the input of new resources, it is necessary to dedicate efforts towards the standardisation of the system's parts in the design stage.

- **Evolution**

To extend the lifetime of ECS, their potential for evolution must be taken into account from the design phase. The recommendation ist o exploit the reconfiguration capacities of reconfigurable hardware, such as field-programmable gate arrays (FPGAs), to reduce the functional obsolescence of electronic products[113]. Another means of evolution is the design of generic rather than functional-specific architectures for ECS.

- **End-of-life anticipation**

When adopting the life-cycle approach in the design of ECS, the EoL stage considerations must be integrated in the design stage. An end-of-life index is proposed to encompass every aspect of the end-of-life, with the final objective of alleviating the problem of e-waste[114].

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[112] Middendorf, A., *et al.*, "Eco-reliability as a New Approach of Multi-criteria Optimisation", Electronics Goes Green, Conference Paper, 2012.

[113] Bossuet, L., "Sustainable Electronics: On the Trail of Reconfigurable Computing", *Sustainable Computing: Informatics and Systems*, 4(3), 2014, pp. 196–202.

[114] Lee, H. M. *et al.*, "A Framework for Assessing Product End-of-life Performance: Reviewing the State of the Art and Proposing an Innovative Approach Using an End-of-life Index", *Journal of Cleaner Production,* 2014.

6 Extending product lifetime

6.1 Introduction

The largest emission of CO_2 during the life cycle of electronic products usually comes during production. Thus, a major lever for CO_2 reduction is to extend the lifetime of products through repair and reuse.

Section 6.2 described that, in Europe, the majority of the population (77%) would rather repair than replace broken products. Moreover, repairing uses up to 100% of the materials used for the product, as opposed to recycling, which only captures a certain percentage of the product and still produces e-waste.

Section 6.3 pointed out that an important factor in increasing repair rates is attractive business models for industry. Various distribution channels need to be activated for consumer and industrial products to enhance attractiveness to the stakeholders – including producers, repair centres, consumers and commercial customers.

As described in section 6.4, to ensure an increase in the repair rate, various steps of the repair process need to be considered, such as failure characterisation, repair and re-characterisation. For these steps, manuals, instructions, schematics and inexpensive spare parts must be provided, skilled repairers must be trained, and products must be designed for easy diagnostics and repairability. Questions around re-certification, warranties and safety-relevance also need to be addressed.

In section 6.5 actions for target groups and best practices were summarised. For instance, an EU-wide repair index inspired by the French repairability index needs to be introduced. In particular, the availability of inexpensive spare parts must be ensured. Generally, repair cost is a decisive obstacle to repair, but unfortunately this aspect is not considered in current EU proposals. Other measures can increase the repair rate, such as raising customer awareness, tax incentives for repair shops, repair vouchers and the creation of an appropriate legal framework.

6.2 State of the art, expected changes

6.2.1 Vision

EPoSS‘ vision is as follows: “EPoSS is the European Association leading the development and integration of intelligent and green Smart Systems technologies and solutions for a sustainable society”. One of its main goals regarding sustainable society is to support the avoidance of e-waste through smart systems. The extension of the product lifetime plays a decisive role in this. Our vision is to quintuple the lifetime of products, as well as individual parts and components, which will lead to a reduction of e-waste by 20%.

There are several levers to extend lifetime, especially in the field of repair and reuse (see Figure 6.1).

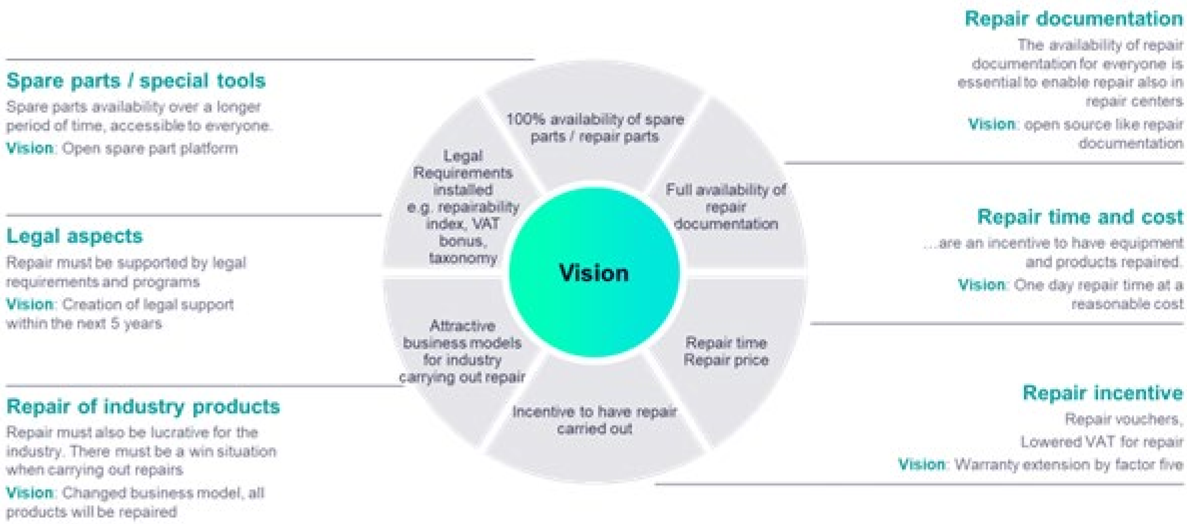

Figure 6.1 Vision for extending product lifetime of ESC to support the avoidance of e-waste

6.2.2 State of the art of product lifetime

Today electrical and electronic equipment (EEE) is ubiquitous. In 2019, about 53.6 Mt of e-waste were produced worldwide, equal to 7.3kg per capita[115]. By 2030, the amount of e-waste is expected to reach 74.7Mt, 9qkg per capita[116]. E-waste consumes the world’s resources and has an impact on people’s life. Hence, the key objective is to reduce the generation of e-waste. In 2015, the United Nations and all member states adopted the 2030 Agenda for Sustainable Development and it 17 SDGs, some of which relate to e-waste. The reasons for the increase of e-waste include: known megatrends such as urbanisation, industrialisation, short life cycles and very few repair options.

A large share of e-waste comes from consumer products, but reducing e-waste is as important for industrial products as for all other electronics equipment. Generally, people are interested in reducing e-waste according to a Eurobarometer survey, and 77% of EU citizens would rather repair their appliances than replace them[117]. The most promising measure to reduce e-waste is therefore repair.

According to one European report[118], there are already several studies and initiatives that support repairability:

- ADEME report on "benchmark international du secteur de la réparation";
- Austrian standard ONR 192102:2014;
- Benelux study on "Repairability criteria for energy related products";

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[115] Forti, V., Baldé, C. P., Kuehr, R. and Bel, G., "The Global E-waste Monitor 2020: Quantities, Flows and the Circular Economy Potential“, United Nations University (UNU)/United Nations Institute for Training and Research (UNITAR) – co-hosted SCYCLE Programme, International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Rotterdam.

[116] ibid.

[117] HOP, "Durable and Repairable Products: 20 Steps to a Sustainable Europe“, White Paper, 2020.

[118] Cordella, M., Alfieri, F. and Sanfelix, J., "Analysis and Development of a Scoring System for Repair and Upgrade of Products – Final Report“, EUR 29711 EN, Publications Office of the European Union, 2019 (doi:10.2760/725068, JRC114337).

- DEFRA study on "The Effectiveness of Providing Environmental Sustainability Information on Products in Influencing Purchasing Behaviours";
- DG ENV "Study on Socio-economic Impact of Increased Repairability";
- DG JUST "Behavioural Study on Consumers´ Engagement in the Circular Economy";
- Design for Repairability tool;
- Ease of Disassembly Metric;
- Groupe SEB´s "Product 10Y Repairable" label;
- i-Fixit scoring system;
- Labo Fnac's "indice de réparabilité";
- prEN 45554 – general methods for the assessment of the ability to repair, reuse and upgrade energy-related products;
- Some initiatives "Runder Tisch Reparatur/ Roundtable repair" in Germany, etc.

As mentioned, a good approach for creating awareness about repairability is the French repairability index. Since 2021, every new product in the categories of smartphones, laptops, television sets, washing machines and lawnmowers must be evaluated for repairability. The main impact factors are documentation, disassembly, availability of spare parts, price of spare parts and other product-specific aspects. However, although repair processes are already in place, they are not yet sufficient.

According to Rudolf *et al.* (2022)[119], the main stakeholders in terms of repairability are:

- recyclers;
- manufacturers;
- consumers;
- logistics;
- governments;
- spare part providers; and
- repairers.

Current repair rates are rather low – for different consumer products such as mobile phones, the repair rates are between 8% and 22%[120]. Unfortunately, there are some barriers that need to be overcome to increase repair rates. There are still open questions on, for example, documentation, warranty, liability, compatibility, obsolescence, safety, and material mixtures and material labels. The most resource-effective strategy for products is to maximise the iruseful lifetime. This means long-term upgradeability and repairability. Such an extended lifetime shifts products from a status as an 'object' to a much more appreciated status level. Upgradeability is an important feature to implement technical progress, updated regulations and potential higher energy savings.

The focus of education and training of engineers is still on production skills. However, repair will become much more important in future and repair rates must be increased. New job opportunities will be created, which will require new job descriptions, such as as repair technicians. These new

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[119] Rudolf, S., *et al.,* "Extending the Life Cycle of EEE—Findings from a Repair Study in Germany: Repair Challenges and Recommendations for Action", *Sustainability,* 14, 2022, 2993 (https://doi.org/10.3390/su14052993).

[120] Laitala, K., *et al.*,"Increasing Repair of Household Appliances, Mobile Phones and Clothing: Experiences from Consumers and the Repair Industry", *Journal of Cleaner Production,* 282, 2021 (https://doi.org/10.1016/j.jclepro.2020.125349).

roles and business models will grow rapidly, and the consumer electronics repair and maintenance global market is expected to reach USD9.6 billion by 2026[121].

6.2.3 Expected changes

The main goal is to increase useful lifetime with repair as much as possible. To improve the repair rate and extend the useful life of electronics, several changes are needed, including:

- introduction of a simple indicator such as a repairability index;
- new design guidelines for repair;
- (financial) attractive benefits for repair (manufacturer and customer), such as VAT bonus, tax incentives;
- a repair chapter in the sustainability reporting;
- availability of affordable spare parts;
- rules and methodology for re-characterisation and warranty regulations;
- new repair processes.

6.3 Value chain, repair, flow, business models, skills

Repair processing and repair logistics depend on several influencing factors. Commercial products and industrial products must be differentiated using different sales channels. For all the different distribution/retention models, there are also different take-back, scrapping and repair models. For each variant, the repair can be carried out either by the manufacturer themselves, by an authorised repair centre or by independently acting repair shops. Also, there are differences between aspects such as where to return the goods, who selects the repair centre and the warranty conditions of the repaired goods. A particularly important element is the continued certification given to the product (safety, security, national conformity, etc). However, the most important aspect of all repair business models is the question of how to make repair attractive to stakeholders.

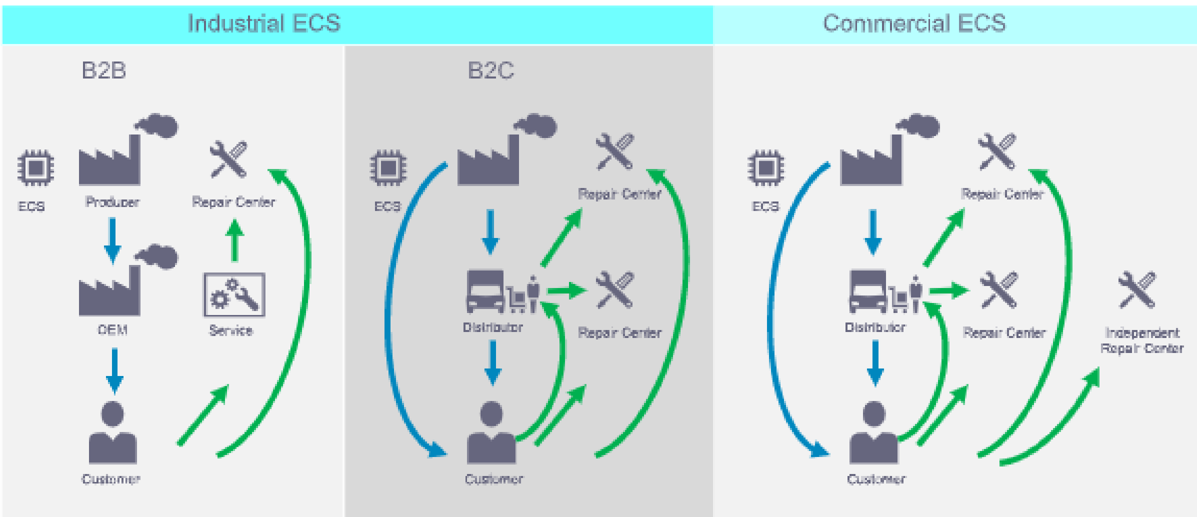

Figure 6.2 Material flow for repair (delivery – returned goods) by different business models

[121] https://www.businesswire.com/news/home/20220225005230/en/The-Consumer-Electronics-Repair-and-Maintenance-Global-Market-is-Expected-to-Reach-9.6-Billion-by-2026-ResearchAndMarkets.com.

Figure 6.2 shows the structure according to which the different business models can be viewed. First of all, industrial ECS need to be treated differently than commercial ECS. Within the industrial ECS, there are two variants regarding the supply chain: delivery to original equipment manufacturer (OEM); and delivery to end-customers directly or through distributors.

With the different business-to-business (B2B) and business-to-consumer (B2C) business models, as well as in commercial electronics, the paths of returned goods also differ.

6.3.1 B2B: Business-to-business

The manufacturer of ECS delivers to the OEM, who integrates the electronic systems into machines and then delivers them to the end-customer. The manufacturer usually operates their own repair centre or uses repair centres with which they have a contractual relationship. The OEM provides a service for the machines it builds, which carries out the repair and recommissioning in the event of failure of the machines. Failed ECS at the end-customer's site either reach the manufacturer's repair centre via the OEM service or are sent back directly from the customer to the manufacturer for repair. The manufacturer of the electronic systems operates its repair centre according to purely economic aspects. They will only repair returned goods if it is foreseeable that the repair is more cost-effective than delivery of a newly produced part, or if they are forced to do so by law. The lever to increase the repair rate is on the side of the manufacturers or the legislator, respectively.

For industrial electronics, another aspect must be taken into account: certificates that are linked to the repaired product. These certificates are only continued if the products are repaired professionally, qualified, and also certified.

6.3.2 B2C: Business-to-consumer

The return route for returned goods is much more complex if they are delivered to the end-customer directly or via distributors. The customer who has purchased directly from the manufacturer will also send defective goods for repair to the manufacturer (e.g. online business). In this case, any repair will be carried out by a repair centre either operated or contracted by the manufacturer. In the case of sale via a distributor, the customer will send defective devices to the distributor, who will then take over the repair organisation. The repair is then carried out via the manufacturer's repair centre or through a repair centre with which the distributor has a contractual relationship. Alternatively, the customer will carry out the processing directly with the repair centre named by the distributor. The problem of the certificates described in B2B also applies here. Thus, the repair centre selected by the distributor must be qualified and certified.

With the B2C business model, there are two main levers to improve the repair rate:

- increasing the attractiveness for the manufacturer to repair instead of supplying new parts; and
- ensuring repairability for the repair centres (Design for Repair, make spare parts available, provide technical documentation, etc).

6.3.3 Commercial electronic systems

- In the case of commercial ECS, the distribution and return routes are similar to those for the B2C model. Here, however, independent repair centres come into play, which are commissioned directly by customers (mainly after the warranty expires). The most important levers to increase the repair rate are identical to the levers above: increase attractiveness for the manufacturer to repair instead of supplying new parts and ensure repairability for the repair centres (Design for Repair, make spare parts available, provide technical documentation, etc).

6.4 Characterisation, repair, and re-characterisation: Drivers and barriers

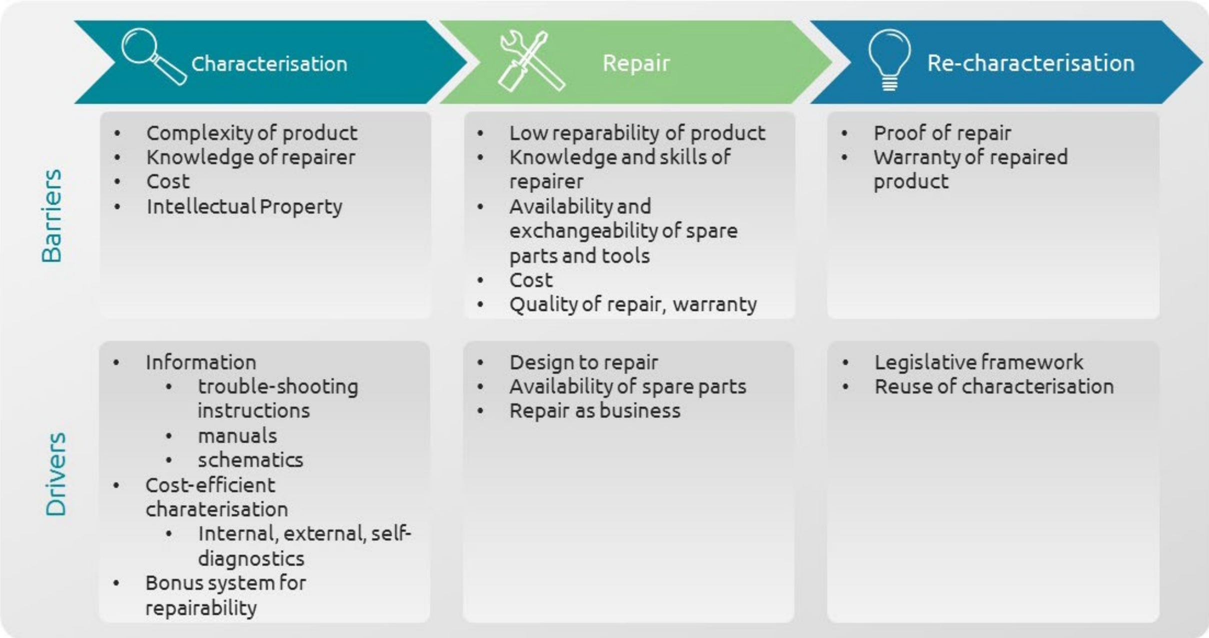

Figure 6.3 Drivers and barriers for repair

Repair is the key to extending product life, with malfunctioning products being brought to a working state. However, various laws are barriers to repair, including intellectual property (IP) law, copyrights, patents, trademarks, contracts, chemical substances, tax, and consumer law[122].

The repair flow according to Figure 6.3 can be divided into three steps:

- failure characterisation;
- repair; and
- re-characterisation

6.4.1 Failure characterisation

With characterisation, malfunctioning parts are localised and identified. Depending on the distribution/retention model, the barriers and drivers of characterisation will vary. Common barriers include increasing product complexity and integration – for example, more functions of a product, while reducing its size, makes it difficult to localise and identify the malfunction, and therefore information must be available. Depending on the business

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[122] Svensson-Hoglund, S., *et al.*, "Barriers, Enablers and Market Governance: A Review of the Policy Landscape for Repair of Consumer Electronics in the EU and the U.S.", *Journal of Cleaner Production,* 288, March 2021, 125488 (https://doi.org/10.1016/j.jclepro.2020.125488).

model, this information must be provided for repair centres of the producer, certified repair shops and the public. This can include troubleshooting instructions, manuals and schematics. On the repairer side, training is needed to identify and fix broken parts.

Another barrier is the cost factor. A first, inexpensive characterisation is important to lower the entry hurdle. Design-to-repair should consider self-diagnostics and predictive maintenance within the product, as well as external diagnostics by the producer and any repairer to drive repairability. These design-to-repair efforts should be awarded and recognised, including visibility to customers and consumers. Publicly available information about repair raises awareness and helps users to evaluate the feasibility of repair.

6.4.2 Repair

With the repair, non-functional parts are exchanged or brought back into a working state. Barriers arise from the increasing integration, miniaturisation, new technologies and faster innovation cycles. For example, new tools are used, there are non-standard screws, or screws are even replaced by glue or welded joints. These are hard to open or impossible to close again. This barrier hinders easy opening of products and replacement of parts. Design-to-repair should use screws over glue and latches to snap open, not break. Design-to-repair has to be considered from the very beginning of the design process.

Another barrier is the availability and cost of spare parts, as well as the quality of the parts. Recent regulatory measures have been taken to improve the situation, but it must be controlled and enforced.

Drivers for repairability are new business models, including repair and life-cycle extension. Skilled workers can significantly influence the life cycle of products in Europe and generate value. For consumers and businesses, a warranty of the labour and spare parts will drive the acceptance of repairs.

6.4.3 Re-characterisation

With re-characterisation, electrical, optical and functional correctness is ensured. Barriers here are the re-certification and warranty of the repaired product. However, a proof of repair will drive repairs. A legal framework needs to provide clear guidance for repair shops and consumers, as well as producers. Synergies arise from the reuse of the characterisation method – in particular, safety aspects must be taken into account for safety-relevant parts.

6.5 Summary of actions to target groups and best practices

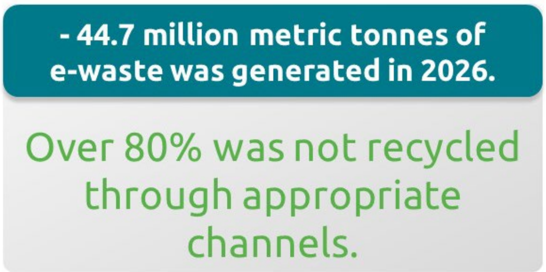

Figure 6.4 E-waste and recycling rates. TCO Development[123]

The shorter lifetime of electronics contributes to large amounts of e-waste in the EU. On the other hand, polls[124] show that 83.4% of consumers want to have longer-lasting products. Repair and reuse are important ways to extend the life of a product.

What can be done? There are many valuable initiatives on all levels (EU, consumers, grassroot initiatives, industry, research) aimed at reducing e-waste through repair or reuse. Nevertheless, only about 20% (2016 figures)[125] are recycled or repaired, with the rest ending up in landfills along with valuable and finite resources and partly as toxic waste. So, these waste reduction initiatives need to be supported and strengthened. We see two important levers to move forward: raising consumer awareness and strengthening legal support.

6.5.1 Introduce an EU-wide repair index

In January 2021, France introduced the French Repairability Index (see Figure 6.5), a major initiative (as described in section 6.2.2). This index provides guidance to the customer on the ability to extend the life of the electronic device based on a self-assessment by the manufacturer. It is expected that the repair rate within the warranty period in France will increase from 30% to 60%. We therefore strongly support efforts to introduce a Europe-wide index.

[123] TCO, "E-waste – a Toxic Waste Stream where Valuable Finite Resources are Lost“ (https://tcocertified.com/e-waste/?utm_term=%2Be%20%2Bwaste&utm_campaign=E-waste++-+spring2020&utm_source=adwords&utm_medium=ppc&hsa_acc=6451387163&hsa_cam=9522124036&hsa_grp=100698315281&hsa_ad=421524612214&hsa_src=g&hsa_tgt=kwd-299053005101&hsa_kw=%2Be%20%2Bwaste&hsa_mt=b&hsa_net=adwords&hsa_ver=3&gclid=EAIaIQobChMI45-11K-w_AIVxvhRCh3E2g3vEAMYASAAEgKvyvD_BwE).

[124] Zuloaga, F., et al., "Cool Products Don’t Cost the Earth“, September 2019 (https://eeb.org/wp-content/uploads/2019/09/Coolproducts-report.pdf).

[125] TCO, "E-waste – a Toxic Waste Stream where Valuable Finite Resources are Lost“ (https://tcocertified.com/e-waste/?utm_term=%2Be%20%2Bwaste&utm_campaign=E-waste++-+spring2020&utm_source=adwords&utm_medium=ppc&hsa_acc=6451387163&hsa_cam=9522124036&hsa_grp=100698315281&hsa_ad=421524612214&hsa_src=g&hsa_tgt=kwd-299053005101&hsa_kw=%2Be%20%2Bwaste&hsa_mt=b&hsa_net=adwords&hsa_ver=3&gclid=EAIaIQobChMI45-11K-w_AIVxvhRCh3E2g3vEAMYASAAEgKvyvD_BwE).

Figure 6.5 Example of the French Repairability Index

The French Repairability Score is a very important step towards a sustainable economy, and should not be limited to a single country. In fact, similar measures have been announced in Spain, Belgium, the UK, Ireland and 14 US states. These measures alone could result in a 10-year extension of average product life while reducing of e-waste by 1.5 million tons. According to a European Environmental Bureau (EEB) study[126], extending the lifetime of all washing machines, smartphones, laptops and vacuum cleaners in the EU by one year would lead to annual savings of around four million tons of CO_2 by 2030, equivalent to taking over two million cars off the roads for a year.

An important next step was supposed to be a legislative proposal from the European Commission to for adoption in November 2022 as part of the Circular Economy Package II, but unfortunately this is now delayed, was only briefly mentioned in the EU Commission work programme for 2023, and not listed as a project for 2023.

The Right to Repair proposal will include all the elements of the French index without explicitly mentioning a European Repairability Index. It remains to be seen if some shortcomings of the drafts and also of the French index will be addressed, such as considering cell phones, computers and tablets, which are not yet regulated by an EU Ecodesign Directive and constitute some of the most harmful consumer waste (and are sold in large numbers, with more than six smartphones being sold every second in the EU alone).

- It should not just be professional repairers that have full access to all spare parts. Access to spare parts for end-users must not be limited to batteries, casings, displays, chargers and SIM and memory card trays so that repairs can become commonplace.
- Prevent pairing – i.e. storing the serial number of a component so that a third-party repair shop cannot easily replace it and stockpile genuine parts for quick repairs.
- Avoid operation system updates for just three years (planned obsolescence).
- Ensure market surveillance to verify manufacturer self-declaration (including sanctions).
- The addition of more product groups.
- Greater transparency of calculation (summary on website, substantiation, a QR code for in-depth information).

On the positive side, the EU Commission agreed on new eco-design rules[127] for smartphones, tablets and wireless phones on November 18, 2022. These rules involve requirements for durability and improved repairability, and manufacturers must provide repairers and end-users with access to repair information and replacement parts for at least seven years after a product is withdrawn from

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[126] Zuloaga, F., et al., "Cool Products Don't Cost the Earth", September 2019 (https://eeb.org/wp-content/uploads/2019/09/Coolproducts-report.pdf).
[127] BMUV, "Smartphones and Tablets will be Easier to Repair in future" (https://www.bmuv.de/en/pressrelease/smartphones-and-tablets-will-be-easier-to-repair-in-future).

the market. Software updates must be available for at least five years after a product is removed from the market.

However, consumer groups[128] have pointed out an important flaw in the EU rules. Unlike the French repairability index, these rules do not consider the price of spares as a measure for repairability. It is well known that the cost of repair is a major hurdle that discourages consumers from repairing a broken device, so there is a high risk of false classification of repairability since costs are not being considered.

6.5.2 Raise consumer awareness

Although surveys indicate general agreement about repair and reuse, reality provides a different picture. The most important reason to replace a mobile phone is that is broken even if it could possibly have been fixed. While 77% of the EU customers[129] would rather repair their appliances than replace them, many are deterred by the cost and the level of service. Therefore, campaigns such as Right to Repair[130] are crucial to help customers make an educated decision in purchasing electronic products, and a repairability index could enhance customer awareness and influence purchasing decisions. The interaction to topics such as global warming needs to be highlighted: electronic devices account for 3.5% of global CO_2 emissions[131], mainly in the production phase. The ecological footprint of electronics production (gold for one cell phone = 100kg excavation material) must be emphasised. Governments need to launch campaigns to create a mindset and educate consumers about the problem and possible solutions. The most effective action for individuals is to use the products as long as possible, including extension of lifetime by repair.

6.5.3 Provide financial incentives, reduce repair cost to avoid replacement

A major barrier for consumers to repair is cost. A repair could be more costly than simply throwing away the defective product and replacing it with a new one. Incentives for repairs can be created in several ways to alleviate the problem. Here some examples:

- Promote repair through vouchers (for example, the City of Vienna subsidises repairs by 50% of cost).
- In Sweden and Norway they are considering lowering the VAT for repairers[132].
- The warranty period is crucial for whether an appliance is repaired or not. Extending the warranty of products from two to five years, or even longer for selected product groups, would significantly increase the repair rate. In Norway, the warranty for electrical appliances, including cell phones, is already five years.

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[128] Vallauri, U., "New Rules for Smartphones and Tablets: Still far from a True Right to Repair“, Right to Repair, November 25, 2022 (https://repair.eu/news/new-eu-rules-for-smartphones-and-tablets/).

[129] HOP, "Durable and Repairable Products: 20 Steps to a Sustainable Europe“, White Paper, 2020.

[130] https://repair.eu/.

[131] HOP, "The French Repairability Index: A First Assessment – One Year after its Implementation“ (https://www.halteobsolescence.org/wp-content/uploads/2022/02/Rapport-indice-de-reparabilite.pdf).

[132] Laitala, K., *et al.*,”Increasing Repair of Household Appliances, Mobile Phones and Clothing: Experiences from Consumers and the Repair Industry”, *Journal of Cleaner Production,* 282, 2021 (https://doi.org/10.1016/j.jclepro.2020.125349).

Lowering the cost would increase demand for repair, allow the development of profitable business models, and create an ecosystem for repairs within a circular economy.

6.5.4 Create a legal framework to promote repair/reuse for a circular economy

In addition to the above actions such as tax incentives and vouchers, misuse by manufactures needs to be eliminated through legislation. We propose the following measures:

- Planned obsolescence must be banned, including software-related aspects such as discontinued support.
- Industry must be obliged to take back defective devices.
- To emphasise repair on the part of the electronics industry, a mandatory scoring system on repair in sustainability reports should be introduced.
- Rules for take-back systems to prioritise repair over dumping.

6.5.5 Create an infrastructure for repair, incoming tests, repair, outgoing tests

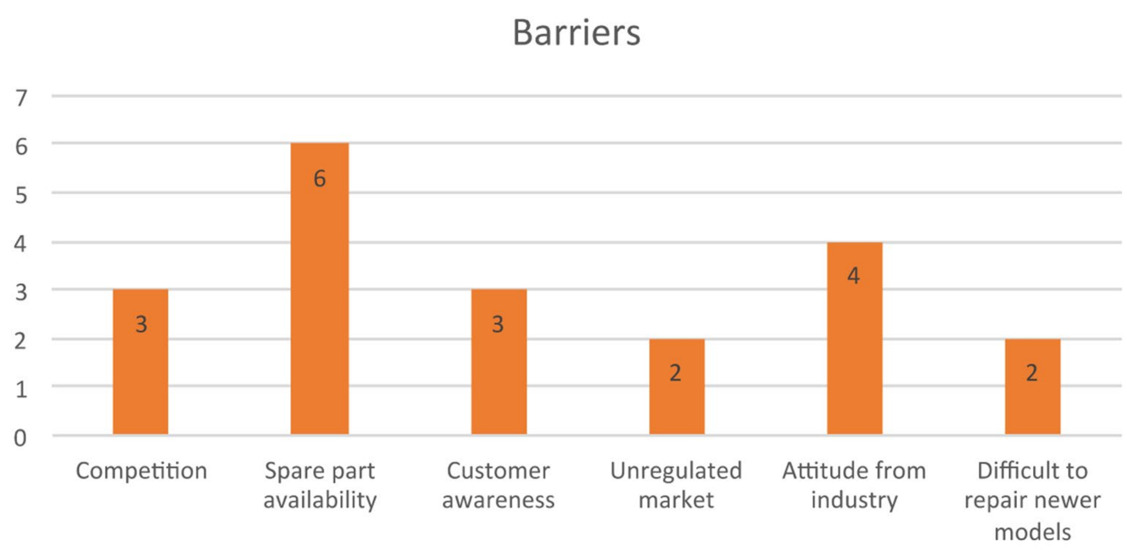

Figure 6.6 Barriers noted by interviewed repair shop representatives[133]

Repair shops have noted many barriers to repair. The second largest of these is the attitude of industry. Several approaches can be taken to lower this barrier: repairability must become a selection criterion for purchasing; new products need to be supplied with manuals and repair instructions; and governments must promote the training of skilled repairers. Enforcement of the obligation to accept defective devices by industry, as defined in the WEEE directive 20212/19/EU, would create pressure to set up the infrastructure to repair defective devices, or at least recycle them.

There are certain requirements for successful and cost-effective repairs. A database of manuals, schematics and disassembly instruction would greatly facilitate the process. If every new electronic consumer product was subjected to independent repair analysis and added to the database, "on-site

[133] Andersson, A., *et al.*, "Circular Economy: Research into the Availability and Willingness to Repair Consumer Electronic Products“, Lund University, 2018 (https://portal.research.lu.se/portal/files/66110470/Electronics_repair_Sk_ne_REFER_background_report_20_March_2018.pdf).

repair" could be strengthened. The availability of spare parts must be ensured and contractional status of repaired goods must be clarified.

The idea of a database of a European digital platform is also being pursued by DigiPrime[134], an EU-funded project. One of its pilot projects[135] explicitly addresses use cases of remanufacturing/repair in the automotive and electronic industries. The goal is to set up an information platform to ensure constant supply and plannability to create a successful business model.

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[134] https://www.digiprime.eu/.

[135] https://www.digiprime.eu/pilots/.

7 Recommendations for the next steps toward green European electronics

As the next steps towards achieving green and sustainable European electronics, EPoSS proposes both general and specific recommendations. In section 7.1, the general recommendations resulting from Chapters 4 to 6 are summarised. Section 7.2 describes the specific contribution of this White Paper to the ECS-SRIA[136], and outlines the specific and technical actions that should be included in the roadmap for achieving a more sustainable ECS, and which are needed in addition to the ongoing European activities in the area (see section 3.4).

7.1 Overall recommendations for sustainable ECS

EPoSS recommends actions in various areas, such as design, manufacturing processes and business models, as well as tools and infrastructure for circularity. The recommendations are summarised in Figure 7.1 and elaborated in more detail in sections 7.1.1–7.1.4.

First of all, EPoSS experts recommend expanding investment in **research and development**. Continued investment in R&D is needed to develop new technologies, processes and materials that are environmentally friendly and sustainable. The spectrum of research requirement is of course extremely broad, but the focus should be on accelerating the uptake of greener solutions that are already in use (evolutionary greening, from niche markets to large markets), and in parallel funding novel ideas with strong environmental potential and which deviate from current business practices (radical green innovation).

Promoting awareness and education is also key. This should include enhanced awareness among both consumers and stakeholders regarding the importance of sustainability in electronics manufacturing and consumption. Education can help drive demand for sustainable products and encourage the industry to prioritise sustainability.

[136] Sixth edition of 'Electronic Components and Systems (ECS) Strategic Research and Innovation Agenda (SRIA) 2023-ECS-SRIA 2023' (see https://www.smart-systems-integration.org/publication/ecs-sria-2023).

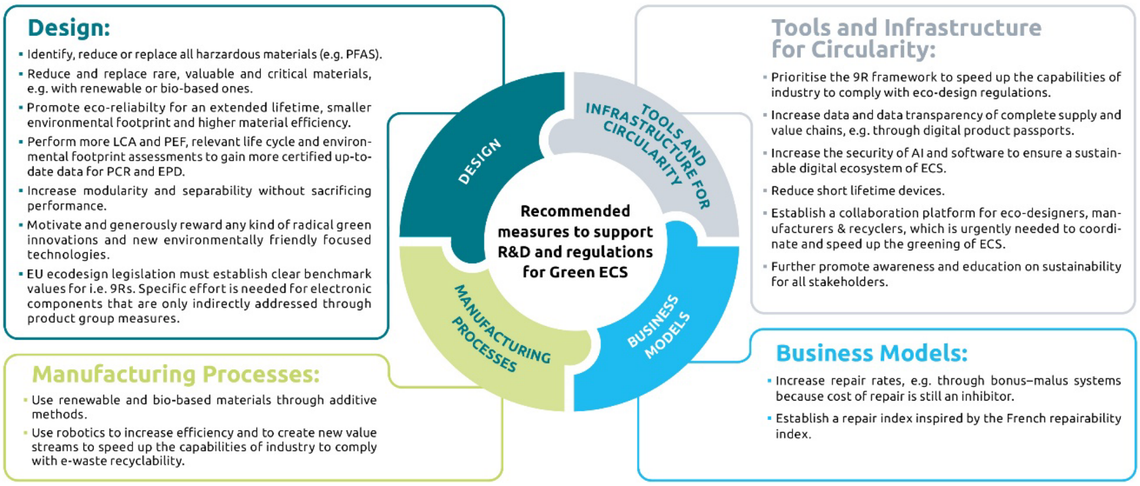

Figure 7.1 Summary of recommended actions in the area of R&D and regulation for green ECS and a succesful reduction of e-waste

7.1.1 Design

A key approach to achieving sustainable green ECS will be to invest in **design capabilities** fort he following.

- *Eliminating hazardous materials*: The use of hazardous materials (such as lead, mercury and other metals, flame retardants and certain phthalates) in electronics manufacturing must be eliminated to prevent environmental pollution and harm to human health. The urgent case of PFAS elimination in electronics shows that research needs to be set up earlier. Furthermore, use of valuable, rare and critical materials should be decreased and/or replaced with renewable materials to guarantee material sufficiency and autonomy.
- *Eco-reliability*: To promote longer lifetime and circular economy for electronics, reliability will becom a lever to guarantee the lifetime of the systems, and possibly extend them. In the eco-design of systems, reliability aspects must be taken into account jointly with the environmental impacts, with the final objective of responding to material efficiency requirements and providing an optimum balance on a life-cycle scale.
- To perform reliable and relevant life-cycle impact assessments of electronic components and systems, certain *standards* need to be established. Product category rules for components and systems are needed to encourage the use of LCA based environmental product declarations. To use these methods and tools, a certification of (up-to-date) data supplied is required. It must be established in a collegial manner with all the players in the value chain (manufacturers/foundries, suppliers, system and integrated circuits providers, etc) who have constraints and needs that may be antagonistic.
- *Adopting circular economy principles*: The electronics industry must adopt circular economy principles that prioritise the reuse, repair and recycling of products and materials. This means eco-designing modular products with longevity in mind, and ensuring they are easily repairable and recyclable to meet the existing and emerging regulatory requirements (e.g. EU’s proposal on ‘Regulation on Ecodesign for Sustainable Products’ (ESPR), which covers all products placed in the EU market).
- *Advancing recyclability*: To overcome technical challenges, research needs to address two points: increasing the modularity of systems (separability of components) for easier recycling

without sacrficing performance; and efficient and environmentally benign recycling techniques have to be advanced in accordance with the legislative agenda.

- For the successful eco-design of ECS, the adoption of the proposed "Ecodesign for Sustainable Products Regulation" 2022/0095 (COD)[137] and the proper implementation of product group-specific measures/delegated acts pursuant to the regulation is crucial. To this end, good and precise benchmark values for the different eco-design relevant aspects are needed (such as energy and resource efficiency, durability, reusability, upgradability and repairability, presence of substances that inhibit circularity, recycled content, remanufacturing and recycling, carbon and environmental footprints, expected waste generation and information requirements such as the digital product passport). Since the current and planned eco-design legislation focuses on measures for product groups (e.g. consumer goods), the eco-design of electronic components only enters indirectly. Therefore, specific efforts are required to incorporate benchmarks for modularity, upgradeability and repairability of electronic components, for example.

7.1.2 Manufacturing

The manufacturing of ECS needs to:

- *Shift towards sustainable manufacturing methods*: Use of additive manufacturing methods, such as printing, that consume less resources (energy, materials, water) and are compatible with renewable materials, such as bio-based substrates. At the same time, additive manufacturing offers new design capabilities for circular, thin and flexible devices, even for single use (e.g. wearable electrodes) with specified end-of-life management.
- Improve efficiency of e-waste *recyclability* by robotics, thereby increasing new value streams and business through reuse.
- *Reducing energy and water consumption*: Electronics manufacturing consumes a significant amount of energy, so reducing energy consumption through the use of renewable energy sources and energy-efficient technologies or cleanroom tools is critical. Also, water reusage in electronics manufacturing facilities needs to be increased. Furthermore, reduction of the energy consumption of electronic devices by either using ultra-low-power components or energy harvesting needs to be increased.

7.1.3 Business models

- Encourage *new business models* to see value in eco-design and recyclability: To meet warranty obligations, it often makes more sense for economically operating companies to deliver new products instead of repairing defective parts. This could be remedied by a legally enshrined bonus–malus system. Likewise, a business model can emerge for third-party repair centres if repair documentation and repair parts have to be made available at reasonable prices.
- *Value the repairabilit*y: An EU-wide repair index inspired by the French repairability index needs to be introduced. In particular, the availability of inexpensive spare parts must be ensured. Generally, repair cost is a decisive obstacle to repair. Unfortunately, this aspect is not considered in the current EU proposals. Other measures can increase the repair rate,

[137] COM/2022/142 final, "Proposal for a Regulation of the European Parliament and the Council establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC" (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0142).

such as raising customer awareness, tax incentives for repair shops, repair vouchers and the creation of an appropriate legal framework.
- In future there will also be other relevant and important areas in combination with electronics, such as microplastics, persistent chemicals and biodiversity, where studies are needed to quantify the impact – i.e. to what extent is ECS responsible for environmental harm, and to which degree can the ECS community implement changes.

7.1.4 Tools and infrastructure for circularity

The following tools have been identified to enable future circular ECS economies.

- Development of design, fabrication, integration, recovery, reconfiguration/reuse and disassembly strategies for short lifetime devices (e.g. single-use medical devices, radio-frequency identification, RFID, tags and printed sensors). These **co-optimisation strategies** will seek to *maximise performance and security while minimising cost and cradle-to-grave environmental footprint*.
- Encouraging sustainable supply chains: ECS manufacturers must work with their suppliers to ensure they adopt sustainable practices, such as reducing GHG emissions, conserving water and protecting biodiversity. The main gaps in this respect are still *data and data transparency* through the supply chain. **Digital product passports** should be promoted, tested and then widely established, which still needs greater political support.
- For a sustainable interconnected digitalised ecosystem of ECS, the **software and AI** must be secure, reliable and constantly automatically and autonomously adapted.
- **Circular infrastructure**: Circular economy needs suitable products and components, but also *networks of stakeholders for implementation*. Knowledge and capabilities selecting the most suitable treatment are required. Upstream supply chains need to incorporate recirculated products and components. In short, identifying partners, and building and maintaining a circular infrastructure, is essentia (see also the last recommendation regarding a platform).
- Use software extensively to increase the sustainability of ECS by **extending their lifetime through continuous optimisation and adaptation**, by making existing ECS more intelligent through the *use of AI*, in particular at the Edge, and by *optimising the resource usage* through hardware and software co-defined strategies. Ensure the *trustworthiness and reliability* of the ECS, including its software components, with a special attention to approaches involving AI.
- Promote **methodologies allowing for the co-design of ECS hardware and software** involving simulations and realistic models, including AI-aided development tools, to continuously estimate key metrics. This must be complemented by intrumentation of the ECS hardware and software to continuously assess the achievements of the key figures of merit over the entire ECS lifetime (including shelf and post-decommissioning).
- EPoSS proposes the **setting up of a collaboration platform between eco-designers, manufacturers and recyclers**, as this is urgently needed to coordinate and speed up the greening of ECS. This activity goes beyond the purview of EPoSS, and hence additional funding will be sought.

7.2 Specific and technical actions recommended to be added to the current ECS-SRIA Roadmap

The insights and recomendations from this White Paper can contribute to several areas of the ECS-SRIA. The necessary actions towards sustainable ECS in the context of the ECS-SRIA 2023 are shown in Fiure 7.2.

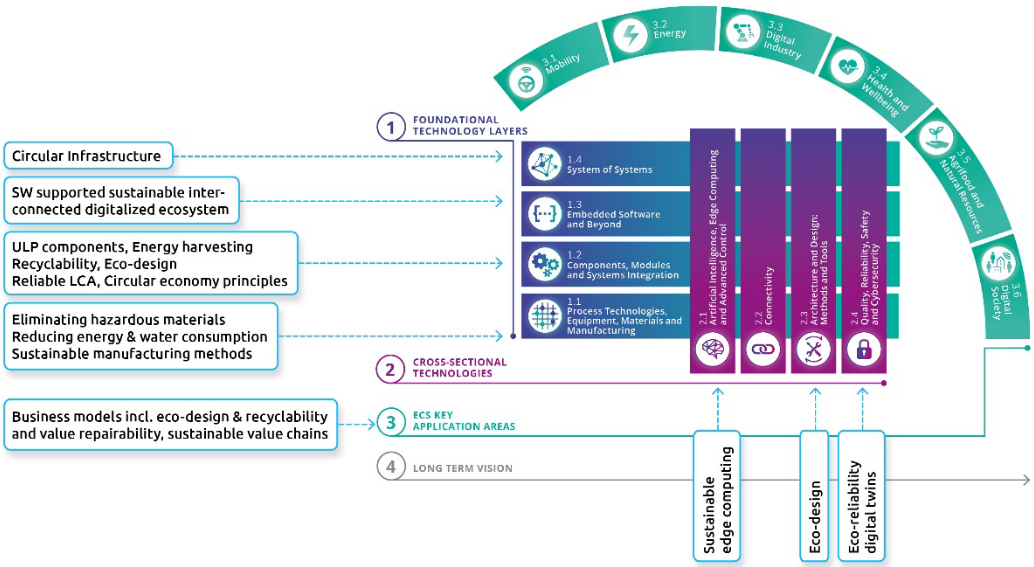

Figure 7.2 Contribution of sustainability aspects for the reduction of e-waste in the structure of the ECS-SRIA

Figure 7.3 summarises the specific and technical actions identified by the EPoSS experts in the scope of this White Paper that need to be added to the current ECS-SRIA for sustainable ECS design and manufacturing, and for the reduction of e-waste.

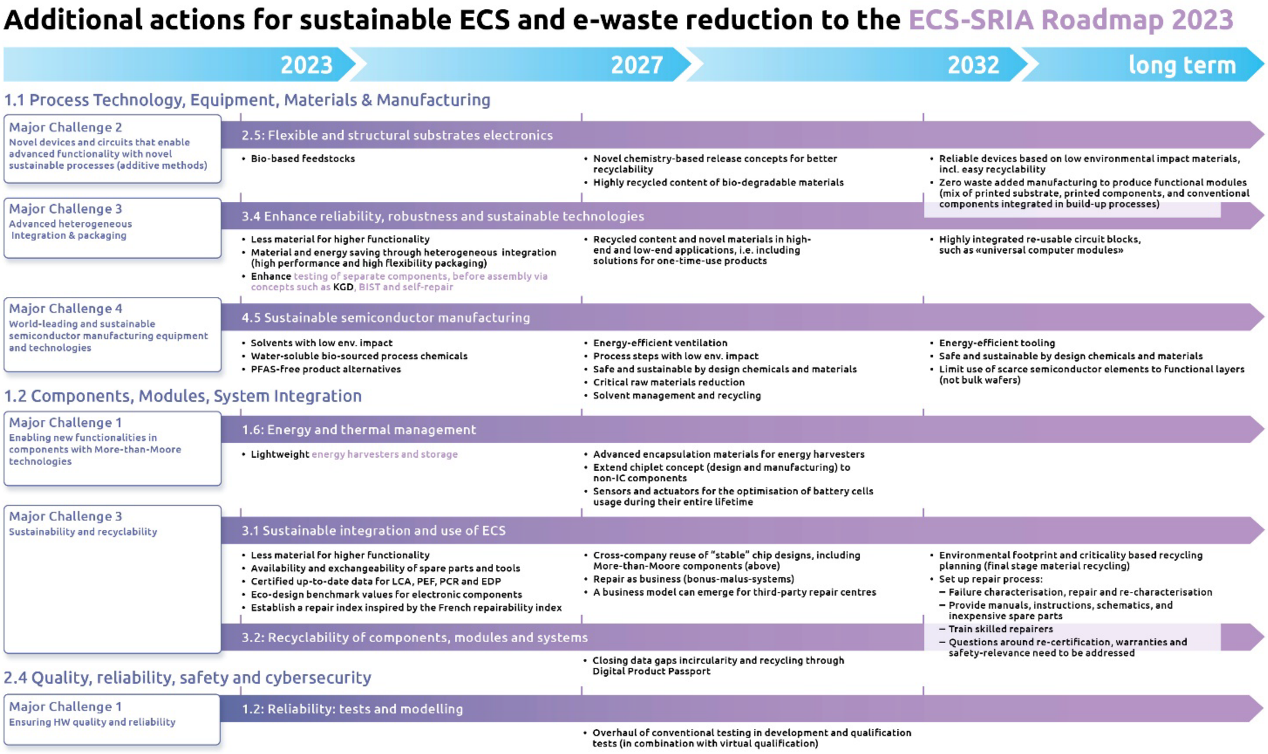

Figure 7.3 Specific and technical actions that need to be added to the current ECS-SRIA Roadmap for more sustainable ECS

Abbreviations

9R – Refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover
AE – Accumulated exceedance
AI – Artificial intelligence
B2B – Business-to-business
B2C – Business-to-consumer
BFR – Brominated Flame Retardants
CE – Circular economy
CEAP – Circular Economy Action Plan
CPE – Customer premise equipment
CRM – Critical raw material
CTU – Comparative toxic unit
DALY – Disability-adjusted life years
DD – Data-driven
Design for X – Design for Excellence
GDM – GreenDataManager
DfR – Design for reliability
DoE – Define of experiments
ECS – Electronic Components and Systems
EEA – European Environment Agency
EEB – European Environmental Bureau
EEE – Electrical and electronic equipment
EF – Environmental footprint
EI – Economic importance
EoL – End-of-life
EPD – Environmental Product Declaration
EPLCA – European Platform on Life Cycle Assessment
ESPR – Regulation on Ecodesign for Sustainable Products
EU – European Union
FDSOI – Fully depleted silicon on insulator
FPGA – Field-programmable gate array
GHG – Greenhouse gas
(H)CFC – (Hydro)chlorofuoro-carbon
HMI – Human/machine interface
ICT – Information and communication technology
IMSE – In-mold structural electronics
IoT – Internet of things
IP – Intellectual property
JRC – Joint Research Centre
KDT – Key Digital Technologies
LCA – Lifecycle Assessment
LIG – Graphene-like carbon
MEMS – Micro-electromechanical systems
ODP – Ozone depletion potential
OEF – Organisation Environmental Footprint

OEM – Original equipment manufacturer
PCB – Printed circuit board
PCR – Product category rule
PEF – Product Environmental Footprint
PEN – Polyethylene naphthalate
PET – Polyethylene terephthalate
PFA – Per- and polyfluorinated alkyl
PGM – Platinum group metal
PHM – Prognostic health management
PLA – Polylactic acid
PMIC – Power management integrated circuit
POC – Point of care
PoF – Physics of failure
REACH – Registration, Evaluation, Authorisation and Restriction of Chemicals
REE – Rare earth element
RF – Radio-frequency
RFID – Radio-frequency identification
RIA – Research and innovation action
RoHS – Restriction of Hazardous Substances
RTO – Real-time operating system
RUL – Remaining useful life
SDG – Sustainability development goal
SE – Structural electronics
SiP – System-in-package
SME – Small and middle-sized enterprise
SoC – System-on-chip
SR – Supply risk
SRIA – Strategic Research and Innovation Agenda
SSbD – Safe and Sustainable by Design
TEG – Thermoelectric generator
UN – United Nations
UNITAR – United Nations Institute for Training and Research
VOC – Volatile organic compound vapour
WEEE – Waste from electrical and electronic equipment

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