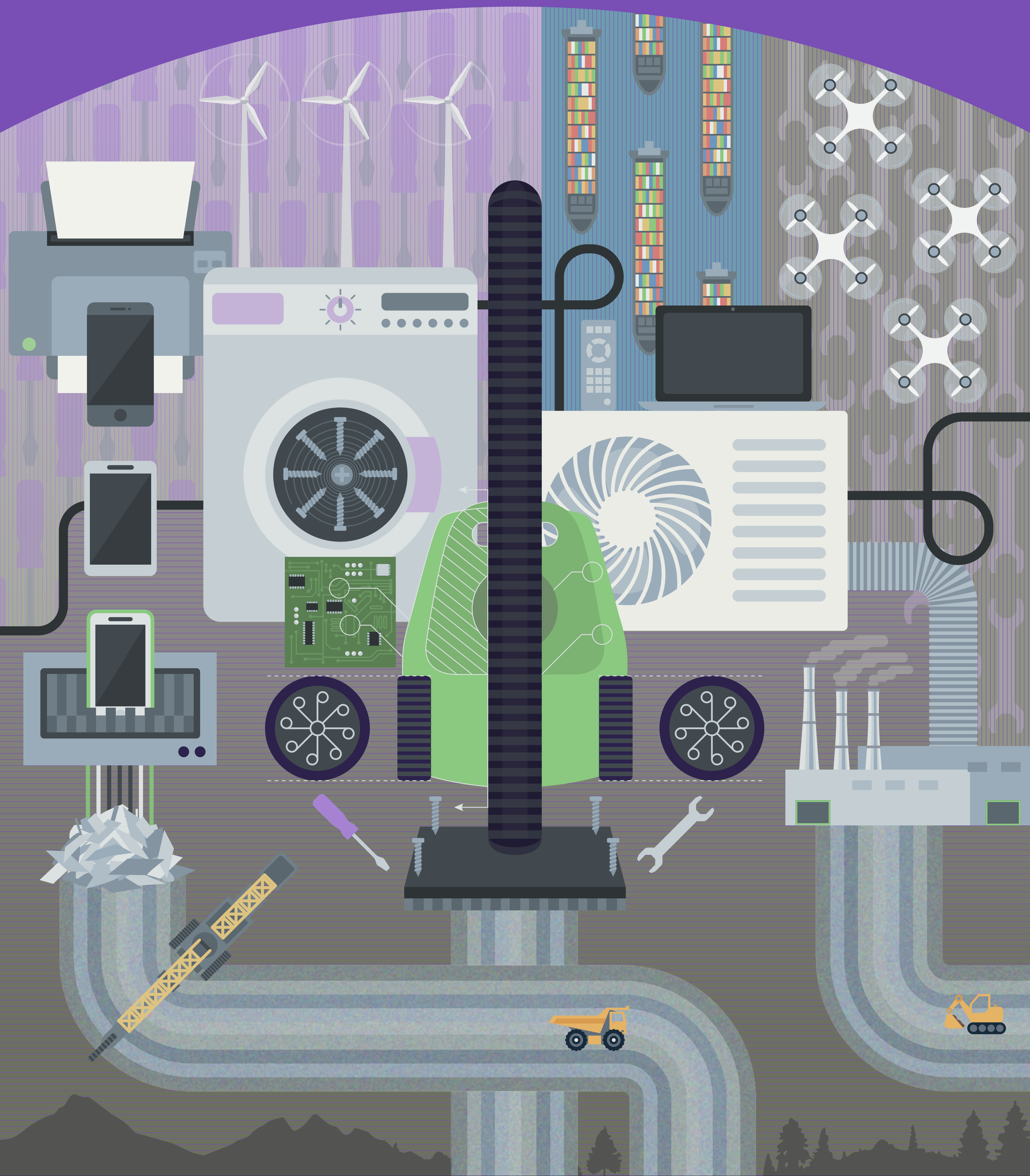
Rewiring Consumer Electronics

REDUCING DEMAND FOR CRITICAL RAW MATERIALS BY DESIGN



REPORT BY: TU Delft · CMR Centre for Materials & Resilience

COMISSIONED BY: INVEST-NL

Colophon

Date:

March 5th 2026

Authors:

Dr. Benjamin Sprecher
Anne Roorda
Raphael Jung
Prof.Dr. Ruud Balkenende

Reviewers:

Prof.Dr.Ir. Conny Bakker
Prof.Dr. René Kleijn
Dr. Franz Bormann
Ir. Guy de Sevaux
Drs. Eva Käller
Dr. Lewis Akenji

Comissioned by:

INVEST-NL

Graphic Design:

Cassie Björck

Acknowledgements:

We thank Cécile van Oppen, Marijn Polet, and Dennis Jansen (Copper8), as well as Niklas Engberg and Ids Grupstra (TU Delft) for their contributions.

How to cite this report: Sprecher, B., Roorda, A., Jung R., Balkenende, R., *Rewiring Consumer Electronics*. Centre for Materials and Resilience, 2026.

Contact:

www.c4mr.org/contact

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Executive summary

Consumer electronics are major drivers of global material consumption. Short product lifetimes, limited repairability, and linear value chains mean that many devices are replaced long before their potential is exhausted. In the Netherlands, electronics consumption requires approximately nineteen thousand tons of critical materials per year, most of which are lost at end-of-life. This report, commissioned by Invest-NL, examines how circular design principles can extend the lifespan of consumer electronics and facilitate material recovery, reducing demand for critical raw materials (CRMs) and improving European supply chain security.

The report covers four circular design strategies:

- Durability and reuse
- Repairability
- Refurbishment and remanufacturing
- Recyclability

For each, the report identifies specific design interventions, assesses corresponding business models, and examines barriers to implementation. A quantitative analysis estimates the reduction in CRM demand when these strategies are applied at market scale.

Circular potential depends above all on product architecture. A clear architecture that makes critical components accessible enables repair, refurbishment, reuse, and longer lifetimes. A comparison of two functionally identical vacuum cleaners showed motor disassembly times differing by a factor of six, depending entirely on component positioning and fastener choice. Repair and refurbishment should generally take priority over recycling. Current recycling processes still lose much of their value: plastics are often incinerated, alloys are downgraded, and critical materials are rarely recovered. Many Design-for-Recycling methods do not reflect how products are actually processed. These methods focus on manual disassembly, while large-scale WEEE recycling in Western Europe relies on mechanical shredding.

Professional repair is viable mainly for products worth more than roughly €100. Below that, labour costs exceed resale value regardless of how well the product is designed. For lower-value products, design for recycling and material substitution are the scalable alternatives. Circular business models exist, from product-as-a-service to OEM refurbishment, but they remain confined largely to niche markets or B2B contexts where total-cost-of-ownership reasoning is standard. Without regulatory interventions that create a level playing field, circular designs face a structural cost disadvantage against linear alternatives.

Material substitution reduces CRM demand faster than other strategies, because it takes effect as soon as a redesigned product reaches the market. Optimised motor design can reduce neodymium content by up to 20% per motor, and NdFeB-free motor types are viable for many applications. For batteries, shifting from NMC to LFP cathodes eliminates cobalt and nickel, and upcoming sodium-ion chemistries have the potential to eliminate lithium where lower energy density is acceptable.

For connected devices, software obsolescence drives replacement as much as physical failure. The discontinuation of Windows 10 left 500 million devices with functional hardware facing security risks. EU regulations now mandate minimum five-year security update periods for certain product categories, but five years is inadequate for products whose hardware routinely outlasts that period.

The combined effect of these strategies was quantified for washing machines, heat pumps, and vacuum cleaners. Doubling the average lifespan of washing machines from 12 to 24 years, combined with motor optimisation and increased use of recycled materials, reduces the annual inflow of critical raw materials by more than half by 2038. For heat pumps, a combination of refurbishment, lifetime extension, motor optimisation, and copper substitution achieves comparable reductions. For vacuum cleaners, doubling lifetime from 6 to 12 years halves magnet material demand by 2029, with further reductions from motor optimisation and recycling.

The barriers to circular design reinforce each other. Economic pressures drive cost reduction and miniaturisation, producing products that are difficult to repair. Low product prices make professional repair unattractive relative to replacement, removing incentives for manufacturers to design for repairability. Consumers adapt, and repair skills erode across generations. Separated budgets within organisations block total-cost-of-ownership decisions, and failure-mode data often never reaches design teams. Flat-rate Extended Producer Responsibility fees provide no financial incentive for better design. Dutch households hold an estimated 230 kton of working but unused electronics, 15.8% of total household stock, while broken products account for only 2.5%. The challenge is not primarily that products break, but that functional products are replaced or set aside.

The report makes recommendations across four areas.

Regulation

First and foremost, stronger regulation is essential to make circular design at scale a reality. Longer mandatory warranty periods should be introduced to incentivise durable design. A proposed warranty period of 12 to 15 years for washing machines would exceed the current average lifespan while remaining achievable for best-in-class manufacturers. Minimum software update periods for connected products should match expected hardware lifespans. Repairability scoring systems should be reformed to prevent effectively unrepairable products from achieving high scores. Repair labour should be exempt from taxation. Extended Producer Responsibility fees should be differentiated based on recyclability. Components containing CRMs (motors, PCBs, permanent magnets) should be subject to mandatory removal prior to shredding, analogous to current battery regulation. Enforcement of product regulations should apply consistently to both EU and non-EU manufacturers, including products sold through direct-to-consumer platforms.

Design and research

Design-for-Recycling guidance should be updated to reflect actual shredding-based processing conditions rather than idealised manual disassembly. Repair and refurbishment feedback should be built into product development processes, so that failure-mode data reaches design teams. Material substitution pathways for CRMs should be systematically assessed per product category and included as an explicit design strategy alongside durability, repair, refurbishment, and recycling.

CRM recovery infrastructure

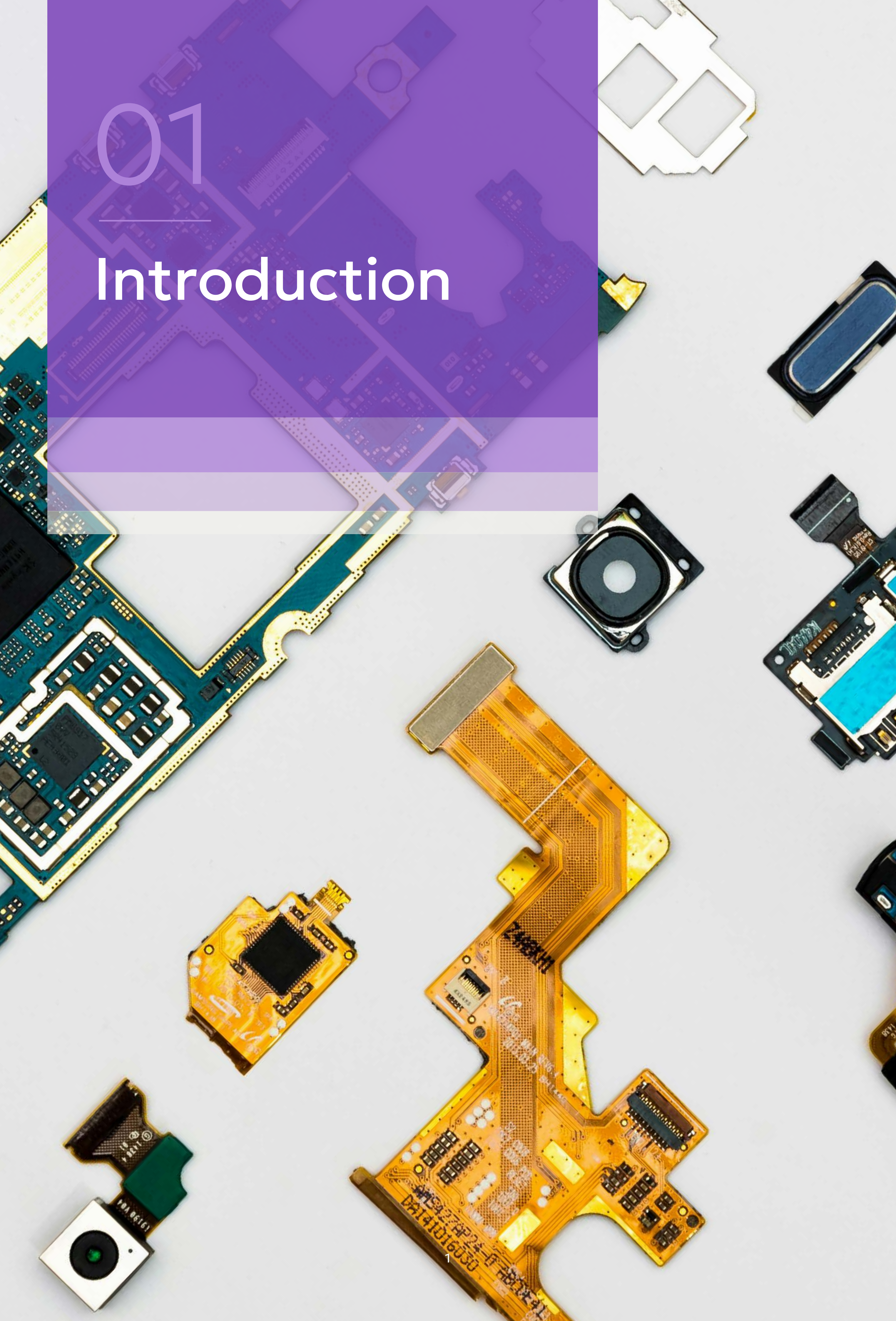
Scaling CRM recovery (as opposed to downcycling or non-functional recycling) requires investment in collection sorting, processing capacity, and data systems to track material composition. These infrastructure and technology investments are substantial, but nevertheless modest relative to the strategic value of reduced import dependence.

Consumer engagement and market development

Consumer awareness of existing warranty rights should be actively promoted. Collection campaigns should target the large stock of unused electronics in Dutch households. B2B markets offer the most immediate pathway for testing and scaling circular strategies, because total-cost-of-ownership reasoning is already standard and product recovery logistics are simpler.

01

Introduction



INTRODUCTION

Consumer electronics account for a significant share of global material consumption. Short product lifetimes, limited repairability, and linear value chains mean that many devices are replaced long before their potential is exhausted. In the Netherlands alone, electronics consumption requires approximately 18,592 tons of critical materials per year, most of which are lost at end-of-life (nlmtd, 2026). When devices are replaced quickly, hard to repair, or poorly collected at end-of-life, the result is recurring primary material demand, unnecessary exposure to supply disruptions, and avoidable environmental burden.

Fundamental changes in how products are designed, manufactured, and processed after disposal will be needed, if the EU is to achieve its goal of being fully circular by 2050. This report examines how circular design principles can extend the lifespan of consumer electronics and facilitate material recovery.

The report covers four circular design strategies (durability and reuse, repairability, refurbishment and remanufacturing, and recyclability), the business models needed to support them, and how their adoption is limited by economic, technical, behavioural, and regulatory barriers. We describe the European policy landscape as it relates to ecodesign and give a preliminary quantification of the potential reduction in critical raw material demand when circular design strategies are applied at scale.

This report was commissioned and funded by Invest-NL to support their investment decisions and identify focus areas.

RESEARCH QUESTION:

How can circular design principles for electronics be integrated to extend the lifespan of electronic devices and facilitate their repair, reuse, and recycling?

This question is addressed by examining: (a) design and product architecture decisions that lead to circular outcomes, (b) which business models can make these decisions economically viable, (c) which barriers currently block implementation, and (d) what material demand reductions can be expected when circular strategies are applied at scale for specific product categories.

Method

This report draws on multiple research methods. The findings are primarily informed by semi-structured interviews and literature research, complemented by quantitative modelling through Material Flow Analyses (MFAs). Unless otherwise indicated, statements are based on interview data; referenced sources are cited throughout the text where applicable.

Semi-structured interviews were held with actors of interest, including designers, academics, recyclers, retailers, materials specialists and manufacturers. In total 17 interviews were held (see Table 2, page 52). Interviews are listed anonymously to encourage open and candid responses from participants.

Literature research: academic and grey literature was reviewed to identify established circular design principles, known barriers to circular electronics, and existing conceptual frameworks such as strategic design management, design-for-X approaches and circular business models. We also extensively cite data and results from nlmtd (2026), which provides data on product inflows, outflows, collection, reuse, repair, recycling and leakage pathways in the Netherlands, and was also commissioned by Invest-NL.

Material Flow Analysis (MFA): for several products, dynamic MFAs are presented to estimate how circular design strategies reduce annual critical raw material consumption at equivalent usage rates. The selected products each illustrate distinct circular design opportunities (lifetime extension, refurbishment, material intensity reduction), contain relevant quantities of critical raw materials, and have been the subject of previous research. The MFAs are based on CMR (2026) and Copper8 & Delft University of Technology (2026a, 2026b).

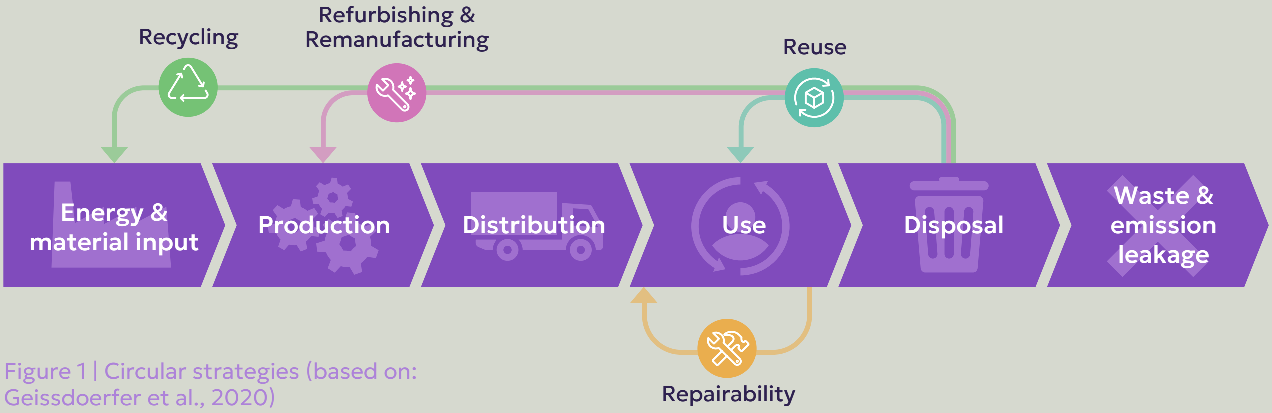


Figure 1 | Circular strategies (based on: Geissdoerfer et al., 2020)

Circular strategies explored in this report

Several circular strategies exist to extend the lifetime of products and their materials, based on the phase in which they are restored. Circular design implements these circular strategies in the manufacturing, use, and end-of-life of products. Business and revenue models ensure economic viability, while policy frameworks incentivise circular design by creating level playing field market conditions for circular and linear businesses.

Durability & Reuse

Durability: The capacity of a product to maintain its functional and physical integrity over an extended period, resisting wear, tear, and obsolescence. Durable products sustain their functional value (technical performance), physical value (material robustness), and aesthetic value (appearance) throughout their extended lifespan. Design for durability involves selecting robust materials, using high-quality components, and ensuring long-term software support.

Reuse: The practice of using a product again in its original form and function by another user, either directly (second-hand use) or after minimal intervention such as cleaning or repairs. Reuse maintains the product's identity and purpose. The strategy extends product lifetime by enabling additional use cycles beyond the original owner's period of use, whether through resale, donation, or other forms of redistribution. In this report, reuse explicitly excludes refurbishment activities involving systematic testing, grading, or proactive component replacement.

Refurbishment & Remanufacturing

Refurbishment: Brings products back to good working condition for resale through inspection and replacement of broken or deteriorated components. Any company with part-exchange capability can perform refurbishment using original or third-party parts. The process is less standardised than remanufacturing (see next section) and typically does not involve complete disassembly to component level. Quality refurbishment should provide warranty comparable to new products.

Remanufacturing: A standardised industrial process that completely disassembles products to the component level, restores them to original as-new (or upgraded) condition and performance, and produces fully warranted products for resale meeting specific technical specifications and testing standards. The process involves complete disassembly, inspection, cleaning, component replacement where needed, reassembly, and rigorous testing. OEMs are typically best positioned for remanufacturing due to their access to original specifications and technical knowledge.

Repairability

The process of restoring a malfunctioning product to working condition by fixing or replacing broken components. The repair process involves diagnosing the failure, disassembling the product, replacing or fixing defective components, reassembling, and testing functionality. Design for repair focuses on making products easy to disassemble and reassemble, with accessible components, available spare parts, repair information (manuals or guides), and consideration for safety and software updates. Repair can be performed by the user themselves (DIY repair), professional repair services, or manufacturers.

Recycling

The process of converting end-of-life products into secondary raw materials that can be used in new products. Design for recycling aims to make products suitable for the complete recycling value chain, ensuring all materials can be retained in the highest possible quality to maximise reuse. The recycling process typically involves collection, depollution (removal of hazardous materials), shredding, automated sorting using various technologies (image recognition, magnets, induction, density sorting), and material reprocessing. In Western European contexts, most electronics are shredded rather than manually disassembled due to labour costs.

Reader’s guide

This report is structured as follows.

Chapter 2

Establishes the policy context of ecodesign, outlining existing EU policies such as the ESPR and WEEE Directive.

Chapter 3

Describes circular design principles, methods and specific design interventions for each circularity principle (reuse, durability, repair, refurbishment, remanufacturing, and recycling).

Chapter 4

Addresses circular business models and their revenue streams for both manufacturing companies and supporting enterprises (e.g., repair shops), and gives guidance on selecting suitable circular business models.

Chapter 5

Examines economic, technical, cultural and behavioural, and institutional and regulatory barriers to address the question: why do so few circular businesses exist despite available circular design principles and business models?

Chapter 6

Quantifies the effect of circular design on critical raw material demand, comparing the cumulative inflow of materials in the Netherlands before and after implementing circular design strategies, for three product categories: washing machines, heat pumps, and vacuum cleaners.

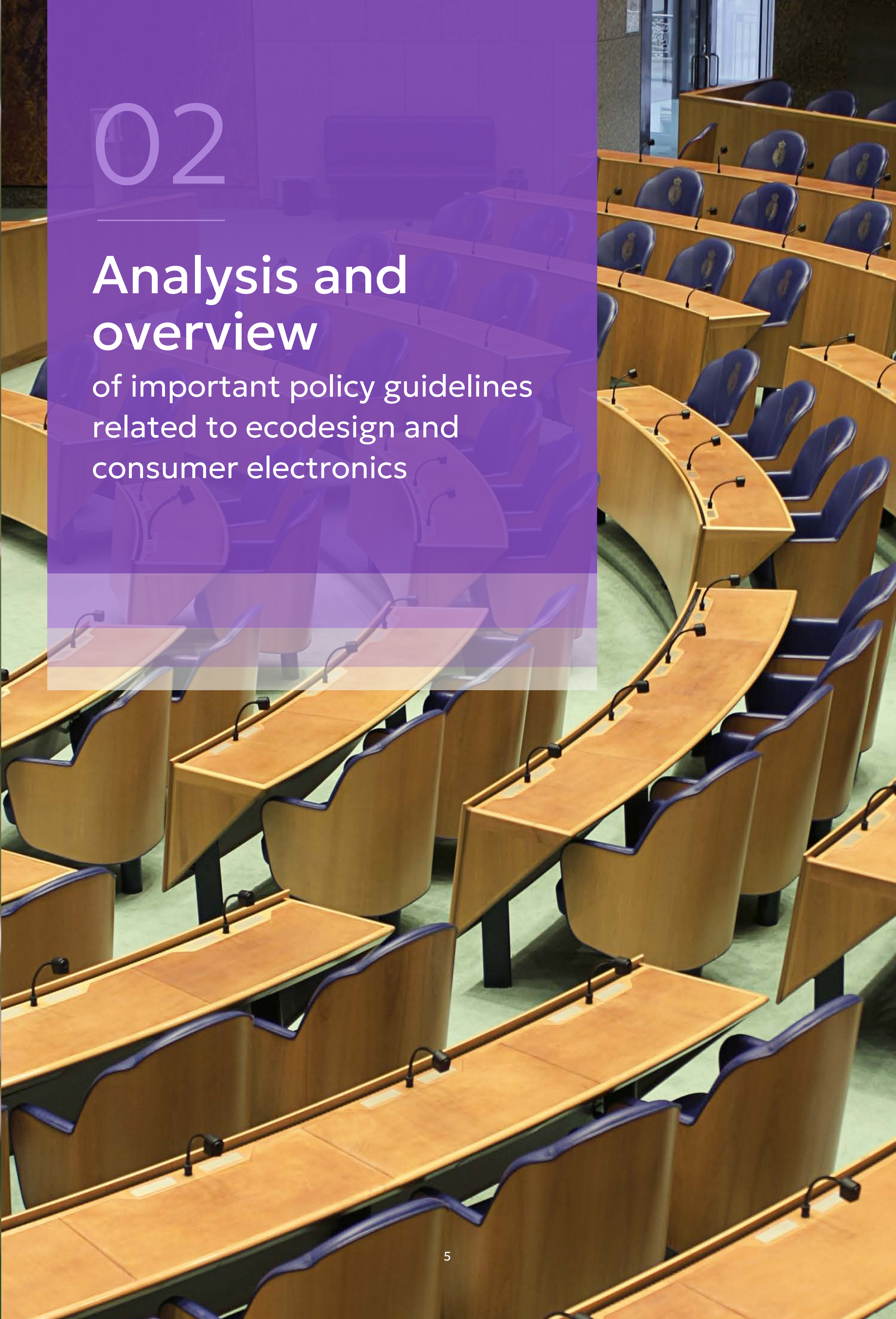
Chapter 7

Concludes the report by answering how to achieve circular design principles for electronics to extend their lifetime. The chapter presents the most salient conclusions followed by policy, industry, and research recommendations.

02

Analysis and overview

of important policy guidelines related to ecodesign and consumer electronics



ANALYSIS AND OVERVIEW OF IMPORTANT POLICY GUIDELINES

This chapter outlines the main European regulations and directives relevant to ecodesign and consumer electronics. These are essential interventions to move companies towards sustainable practices, because free market dynamics alone do not lead to sufficient circular design.

EU policies

European Union policy aims to establish ecodesign, both directly and indirectly. The most relevant policy interventions are the Ecodesign for Sustainable Products Regulation (ESPR), the Right-to-Repair Directive (R2RD), the Empowering Consumers for the Green Transition directive (ECGT), and the Waste from Electrical and Electronic Equipment directive (WEEE). Note that regulations apply uniformly to all EU member states, while directives set common goals but leave implementation to individual member states. See Table 1 for an overview.

Beyond these four key policies, two additional EU policies indirectly support circular practices for consumer electronics.

The Critical Raw Materials Act (CRMA) directly addresses critical raw materials through a variety of targets related to domestic (urban) mining, refining and processing of key materials. In relationship to ecodesign, the act mandates increased circularity of Critical Raw Materials (CRMs) on the EU market. Increasing collection and recycling rates of CRMs requires the widespread adoption of design for recycling practices (explored further on pages 19-23), and application of circular design strategies that reduce absolute demand for critical materials through (explored in Chapters 3 and 6).

The new Battery regulation, in force since August 2023, addresses the exponentially growing demand for batteries and associated environmental impact. The regulation aims for high-quality recycling and recovery of the materials within batteries. Regarding ecodesign, the regulation prescribes a recycled material content in batteries, restricts the use of hazardous substances, and prescribes removability and replaceability of portable and light-means-of-transport batteries by the end user. Further the regulation incentivises ecodesign practices through various indirect means, such as the establishment of targets for battery recycling efficiency and material recovery.

Policy	Aim	Design implications
ESPR	Establishes the core regulatory framework for future ecodesign measures across product groups	Improve durability, repairability, upgradability, disassembly, refurbishment, recyclability of products
R2RD	Increase repair and reuse of products	Ensure that goods are repairable
ECGT	Enable consumers to make more environmentally conscious purchase decisions	Only indirectly on product design
WEEE	Prevent EEE waste, promote recovery, and support efficient use of resources utilised in EEE.	Cooperation of recyclers with the manufacturers of the EEE, to establish ecodesign practices that allow electronics to be reused, disassembled and recovered

Table 1 | Overview of policy frameworks

Ecodesign for Sustainable Products Regulation (ESPR)

The ESPR establishes the core regulatory framework for future ecodesign measures across product groups, including all consumer electronics (European Commission, n.d.-b; European Parliament & Council of the European Union, 2024c).

The ESPR entered into force in July 2024. It aims to improve the durability, recyclability, energy performance, and overall circularity of products sold in the EU. The first working plan, which was published on April 16th, 2025, specifically lists information and communication technology products and other electronics as part of the targeted product selection.

Key provisions of the ESPR include:

- Delegated acts must improve durability, repairability, upgradability, disassembly, refurbishment, recyclability of products.
- Mandatory digital product passports will be introduced (estimated 2026-2027) for regulated product groups – likely to include consumer electronics. Product-specific information requirements are expected to include aspects such as materials, components, repair instructions, disassembly steps, recycled content, and hazardous substances.
- Electronics are major contributors to energy consumption, and energy efficiency is thus a major focus.
- The ESPR highlights premature obsolescence as a sustainability problem to be addressed through delegated acts (this could be for example achieved through software support, battery life, component quality).
- The ESPR contains rules against the destruction of unsold consumer products.
- Green Public Procurement: Mandatory GPP rules will require public sector buyers to use increasingly sustainable products. This shall incentivise the supply and demand for environmentally friendly products.

The ESPR is a framework legislation. Working plans will specify which products and measures receive priority.

Empowering Consumers for the Green Transition directive (ECGT)

The ECGT is demand-side-oriented and focuses on consumer protection (and therefore only indirectly on product design) (European Commission, Directorate-General for Energy, 2024; European Parliament & Council of the European Union, 2024a). The directive is relevant to circular design through its market transparency and anti-greenwashing rules. If consumers are enabled to make better informed purchase decisions, the expectation is that consumption will shift towards more sustainable products.

Key provisions of the ECGT include:

- Better consumer information on durability and repairability: The directive requires that consumers receive accurate durability and repairability information before purchase. This corresponds with the R2RD, but the ECGT applies before a purchase is made.
- Prohibition of misleading environmental claims: Electronics manufacturers cannot use vague sustainability claims. Ensuring that environmental claims are clear and reliable will create a level playing field and support consumers to make purchasing decisions taking into account environmental impacts.
- Prohibition of misleading sustainability labels: Labels that are not established by public authorities or based on certification schemes are prohibited. A certification scheme must meet the minimum requirements of transparency and credibility including an objective monitoring mechanism of compliance with the scheme (e.g., through third parties). Labels suggesting that a product has a positive, zero, or reduced environmental impact (compared to others) must also be treated as environmental claims (see previous paragraph).

Right-to-repair directive (R2RD)

The Directive on Common Rules Promoting the Repair of Goods (referred to in this report as the right-to-repair directive, R2RD) ties its obligations to various EU acts, including to ecodesign measures under the ESPR (European Commission, n.d.-a; European Parliament & Council of the European Union, 2024b). The R2RD aims to increase repair and reuse of products.

Manufacturers must make goods repairable rather than push consumers toward replacement, provided those goods fall under EU repairability requirements. Consumer electronics currently addressed are household washing machines, household dryers, household dishwashers, refrigerating appliances, electronic displays, vacuum cleaners, servers and data storage products, mobile phones, cordless phones, tablets and goods with light-means-of-transport batteries. The right to repair applies to both products within the legal guarantee, as well as those outside of it.

The regulation states that *"Repairability requirements do not oblige manufacturers to repair defective goods but ensure that goods are repairable"*. It addresses spare parts availability (though not spare parts pricing), repair and maintenance information, and repair-related software tools. These measures ensure that not only manufacturers, but also other repairers can carry out repairs, ideally close to the consumer, to limit further impacts stemming for example from transportation. The R2RD directive does not cover defects occurring due to "non-conformity" of the product, therefore manufacturers can charge a price for repairs paid for by the consumers. This aims at incentivising sustainable business opportunities for the manufacturer, e.g. by offering repair services. The R2RD also extends the legal guarantee by one year when a consumer chooses repair over replacement.

From the repairer side, the directive demands to provide consumers with information on their service to enable a free choice for consumers to choose a suitable repair provider. For this, the EU recommends utilising the standardised European Repair Information Form, containing the key factors influencing the consumer repair decisions, such as price, defect, and duration of repair.

Beyond obligations for repair, the R2RD further introduces various means to increase awareness, promote and inform repair. Directives must be translated into national law by July 2026, with implementation depending heavily on national laws.

Waste from Electrical and Electronic Equipment directive (WEEE)

The WEEE directive has three aims: preventing electronic and electric equipment (EEE) waste, promoting recovery of secondary raw materials through reuse and recycling, and supporting the efficient use of resources (European Parliament & Council of the European Union, 2012; Publications Office of the European Union, n.d.).

While the directive addresses most consumer electronics, some EEE categories are not addressed, such as defence applications, medical implants or transportation means. While the WEEE mostly focuses on the actual disposal of WEEE in member states, it also carries some implications for the design of consumer electronics. A key element is that EU member states must incentivise cooperation between recyclers and EEE manufacturers, so that ecodesign practices (as set out in the ESPR) lead to more reuse, disassembly, and recovery of electronics.

An environmental and socioeconomic impact assessment will determine whether the WEEE directive will be revised by the end of 2026.

Impact on Design of Consumer Electronics

In aggregate, European ecodesign policies support circular design in consumer electronics but are in their current form not strong enough to ensure that consumer electronics will be as circular as they could be. Interviewees characterised the current set of European ecodesign policies as 'a step in the right direction.'

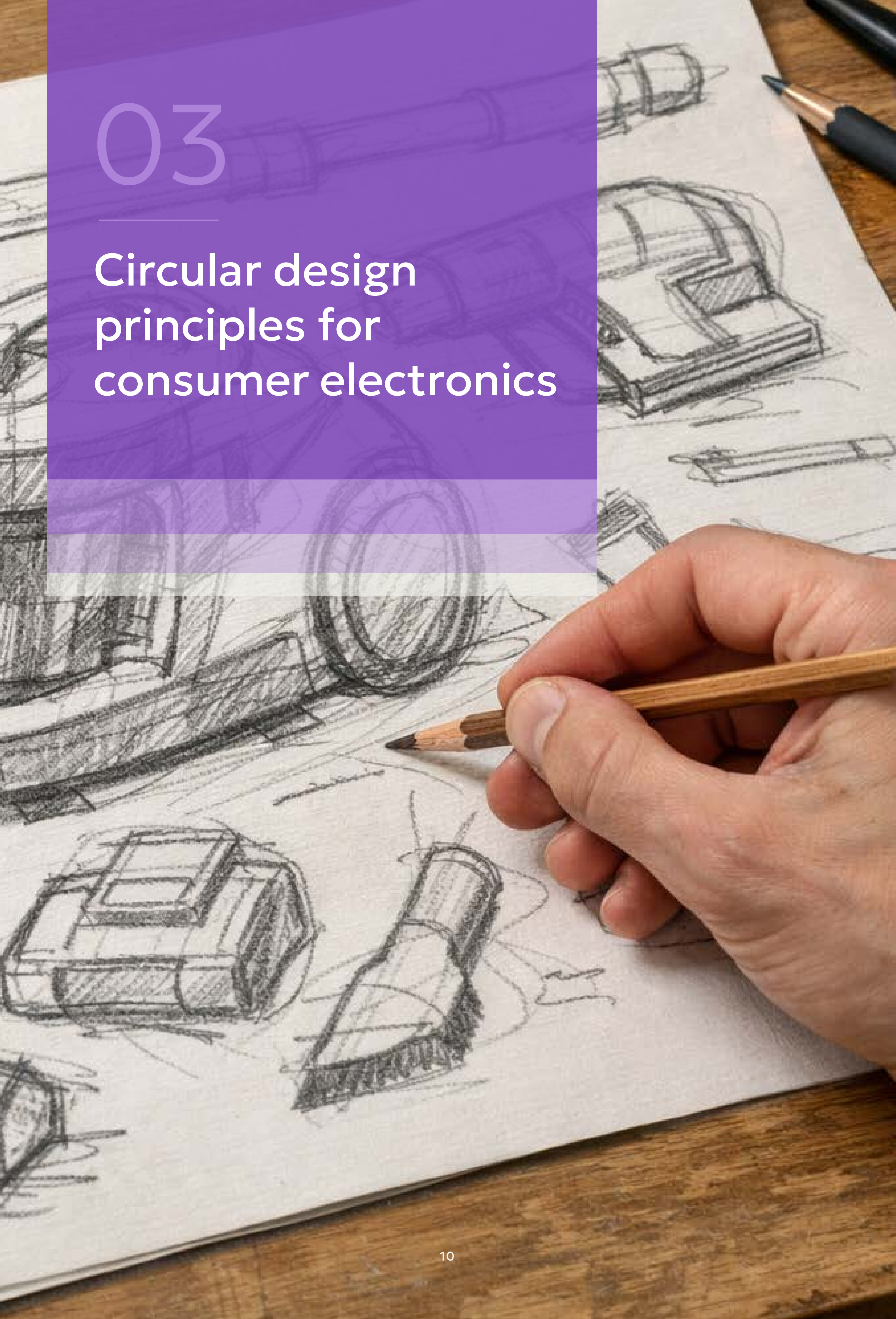
Policy instruments nevertheless have significant impact, even when the underlying mechanisms are imperfect. For example, energy labelling was successful in improving appliance efficiency despite loopholes such as using warm water as input when assessing the energy efficiency of washing machines (E2, interview). Regulations can be significantly more effective if they enforce a minimum standard, and if they are routinely reviewed and updated with stricter standards when possible (E2, interview).

Anticipation of stricter future requirements further encourages companies to integrate circularity into their product designs. Over time, the repairability score of the R2RD may be extended to a broader durability or sustainability score incorporating product lifetime and reliability. This is critical because products can be made more repairable, but this should not be at the cost of decreasing lifetime (E1, interview).

Unfortunately, implementation into product design faces constraints because few electrical products are designed or produced in the EU, let alone the Netherlands. Furthermore, enforcement of ecodesign policies is uneven, and direct-to-consumer platforms like AliExpress face almost no scrutiny with respect to the quality of products on sale (E9, interview).

03

Circular design principles for consumer electronics

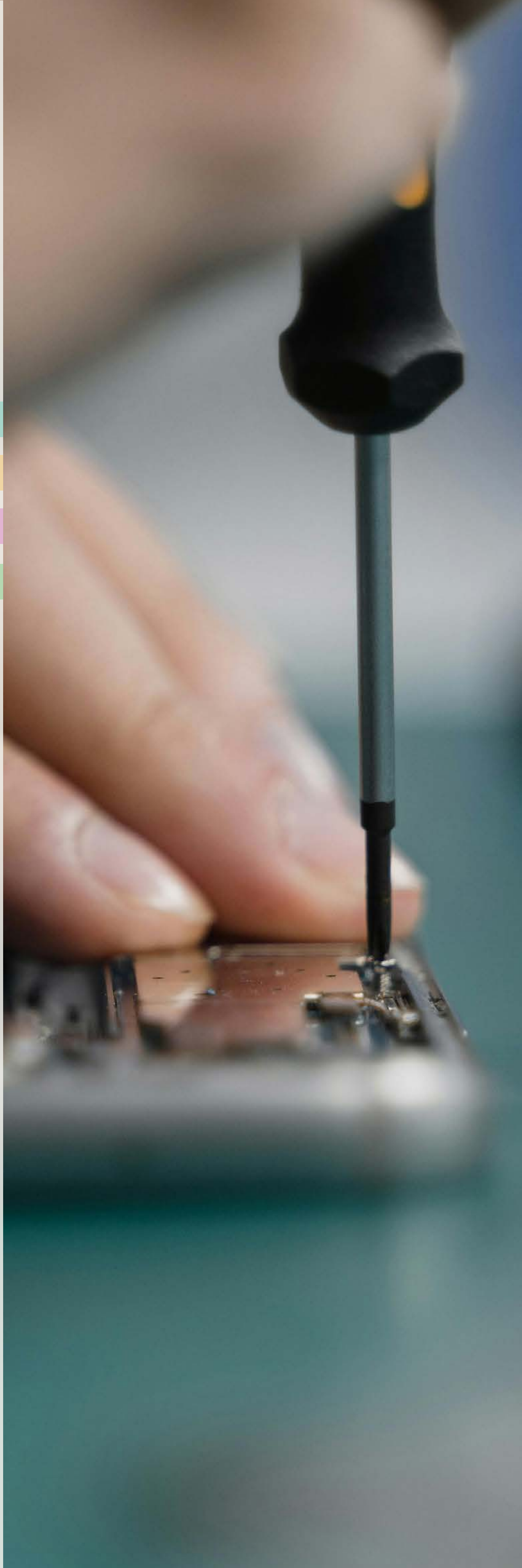


CIRCULAR DESIGN PRINCIPLES FOR CONSUMER ELECTRONICS

Reaching the EU stated goal of being fully circular by 2050 requires fundamental changes in how products are designed, manufactured, and maintained. This chapter addresses the design principles, methods and specific design interventions for four core circular strategies:

- Durability and reuse
- Repairability
- Refurbishment and remanufacturing
- Recyclability

Throughout this chapter, repair refers to failure-driven interventions at component level that restore functionality. Refurbishment and remanufacturing are interventions at product level that proactively replace degraded components. Refurbishment brings the product back to a good working condition; remanufacturing restores the product back to the original specification (see definitions on page 3).



Durability and Reuse

Durability is essential in circular design. Longer functional life reduces material use and associated externalities while also allowing for reuse. Lifetime extension also directly reduces demand for the critical raw materials embedded in replacement products. While electronics can be designed to operate reliably for decades, consumer electronics generally do not remain in use for such a timespan. Individual components such as servo motors however can remain operational for 20-30 years (E10, interview). The quantitative scenarios in Chapter 6 illustrate that durability strategies can drastically reduce the cumulative inflow of CRMs required for consumer products over the 2025-2050 period.

Whether durability and reuse are appropriate circular strategies depends on the technological maturity of the product category. Products in rapidly developing markets are better suited to design-for-recycling approaches, because each generation differs substantially from its predecessor. In mature markets, where successive generations offer diminishing functional improvements, durability and reuse strategies become more effective.

Consumer behaviour can serve as a market signal as to when a platform has matured. When replacement cycles lengthen and consumers start to express frustration with backward-incompatible software updates, one can assume demand for longer-lasting products (E3, interview).

Durability Through Material Selection and Component Quality

Product architecture and component quality are critical determinants of product lifespan. Best-in-class manufacturers achieve much longer lifespans than product category averages. Miele appliances typically function for 20 years compared to an industry average of 7-12 years, and iPhones maintain functionality for approximately 6 years, against the industry average of 4.7 years (European Environment Agency, 2024; E1, interview). Early Philips Senseo coffee machines experienced frequent failures of a specific magnet-based sensor. Fixing this component improved product reliability significantly (E2, interview).

Material selection also influences product longevity. Metals generally exhibit superior durability compared to plastics. Metal components may dent from impact without affecting functionality, and such damage can often be repaired. Plastic components tend to degrade irreversibly through cracking, ageing, or structural fatigue (E2, E5, interviews). This consideration is particularly relevant for external housings and moving parts.

Trade-offs exist between durability, cost, and End-of-Life recyclability. For example, epoxy encapsulation in electronic products operating in unfavourable environments (e.g. electric toothbrushes in wet bathrooms) provides essential protection against humidity, impact, and temperature variations. This extends operational lifespan, but it renders the product effectively non-repairable and non-recyclable at end-of-life (E2, E5, interviews).

Reuse

Reuse extends product life by transferring functional products to new users. Design considerations for reuse overlap with general durability considerations, discussed in more detail above. Design factors specifically affecting reuse include cosmetic durability (resistance to scratches and wear marks), battery longevity, data security (e.g., factory reset capability), and continued software support.

The effectiveness of reuse as a demand-reduction strategy depends on actual consumer behaviour. One study found that in the U.S. smartphone market, each second-hand transaction displaces only 0.40 new devices, well below the 1:1 substitution rate commonly assumed in environmental assessments (Amatuni et al., 2026). Consumers with access to resale shorten their ownership periods, eroding roughly 41% of the potential carbon savings.

Reuse after disposal remains negligible in practice. Of the roughly 170 kton of small consumer electronics discarded in the Netherlands in 2024, less than 1% (~450 ton) was reused after entering waste streams (nlmtd, 2026). At the same time, Dutch households hold an estimated 230 kton of working but unused electronics, representing 15.8% of total household stock (nlmtd, 2026). This indicates the scale of both the opportunity and challenge to achieving higher reuse numbers.

Even under optimistic assumptions about adoption, reuse faces a ceiling set by product durability. Amatuni et al. (2026) estimate that universal smartphone reuse could reduce production volumes by approximately one third, if no additional design measures are taken to improve the maximum functional lifespan of devices in circulation.

Second life networks

The Netherlands has an extensive informal reuse network. Marktplaats handles consumer-to-consumer sales. Kringloop stores process donations. Professional platforms (BuyBay, Swappy, BackMarket) test and resell electronics. These channels handle around a quarter of Dutch electronics volume (E9, interview). This network functions particularly for relatively recent products. E9 (interview) reports that at the end-of-life stage, reuse potential drops to 2-3%.

Because neither reuse platforms nor repair businesses report their volumes, the dynamics and mass flows in second life networks are difficult to quantify.

Consumer Lifetime Expectations

Product lifespan is partly a matter of expectations. Consumers' beliefs about how long a product "should" last directly influence actual replacement timing. If someone assumes a washing machine will last 10 years, they may stop considering repair at that point, even when the actual fault is minor and the product was designed for a 15-year lifespan (van den Berge, 2024). This is illustrated by data on Dutch households, which reportedly have a total stock of around 1,500 kton of small consumer electronics, roughly nine times the annual put-on-market volume (nlmtd, 2026). Broken products account for 36 kton (2.5%), while the hibernating stock of working but unused products is around 230 kton (15.8%).

Design can influence these expectations. Products that appear sturdy and robust through material choice and form factor lead to longer lifetime expectations. Fragile-looking designs, even when technically durable, lead consumers to expect shorter lifespans and to replace earlier (E4, interview). Material selection also plays a role: plastic components tend to discolour, while metal components do not (although they can corrode when not cared for adequately). Although less common in consumer electronics, materials such as leather and brass are often considered to become more beautiful over time. Timeless design ensures that products are not discarded because of an outdated design.

Emotional bonds to a product can also extend its lifespan (e.g. an inherited watch), though this typically applies to specific product categories and user segments. An example is painting a bicycle to make it more distinctive. Research has shown that such product personalisation can foster emotional attachment by requiring users to invest effort. People tend to value products more after spending time with them, so this investment directly strengthens their emotional connection. Additionally, effort enhances a product's self-expressive value – the more someone invests in customising a product, the more it reflects their identity, which further deepens the emotional bond (Mugge, Schoormans, & Schifferstein, 2009).

Software Considerations and Planned Obsolescence

For connected devices and smart electronics, software obsolescence often makes hardware functionally obsolete long before physical failure occurs. In a study on high-tech appliances, published by the European Environment Agency (2024), "a common reason for replacement was out-of-date software rather than malfunctioning hardware."

European Union regulations now mandate minimum security update support periods of five years for certain product categories. However, five years is inadequate for product categories where hardware durability exceeds this period (e.g., laptops, smart home appliances; high-end smartphones, E1, E5, interviews). Recent well-publicised cases where a premature end of software support led to products losing functionality include Sonos speakers, Neato vacuum cleaners, and the discontinuation of Windows 10. The latter left 500 million devices with fully functional hardware become security risks and lose compatibility with current software ecosystems. Dell framed this as a great sales opportunity, when it reported this figure in its Q3-2025 quarterly earnings calls (Warren, 2025).

As an alternative to extending security update support, low-tech design that does not lean on 'smart' features can prevent software issues from arising.

Repairability

Whether a broken product is repaired depends on design, information access, and cost. While the R2R directive aims at boosting product repair, reality is still far from ideal. Today, repair is mainly viable for high-value ICT products. Low-value appliances are almost never repaired, with an economic threshold for repair reported at approximately €100 in new product value. Below this threshold, labour costs for professional repair often exceed the product's resale value, making repair unviable regardless of product design (nlmtd, 2026). The Dutch repair market for all consumer electronics is estimated (with high uncertainty) at 8.7% of products put on market (Stichting OPEN & YAG, 2023, cited in nlmtd, 2026). Improving this situation requires changes in both product design and the surrounding repair infrastructure.

Repair cafés

Repair cafés are a community-based DIY repair effort that aim to restore products to working condition. These initiatives are distinct from professional repair services. The Delft repair café for example provides accessible, educational repair services. Foenix is an Apeldoorn-based repair café that guarantees visitors that they will take home a working product (E2, interview).

Repair cafés commonly are staffed by retired volunteers who possess extensive repair knowledge that is disappearing with younger generations (E2, interview). Repair cafés serve an educational function by demystifying repair and making it more accessible to the general public (E5, interview).

Challenges faced by repair cafés include accessibility to spare parts and repair-resistant design features such as snap-fit closures (E1, interview) and position of priority parts. Repair cafés should not be seen as a large-scale solution (E5, interview), and some interviews noted that government policy should not aim at promoting consumer self-repair, but rather support professional repair services.

Design Principles for Repairability

Repairability requires clear design principles. Products must be easy to open, fix, and put back together without damage (E1, interview). Figure 3 gives an overview of all related design considerations. The most salient principles are:

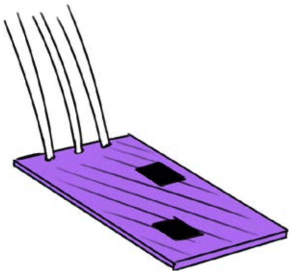
- **Physical accessibility:** Components prone to failure should be accessible within reasonable time and effort. This requires understanding failure patterns and positioning vulnerable components accordingly. Design features such as access hatches can drastically reduce repair and maintenance barriers (E2, E6, E7, interviews).
- **Standard fasteners:** Use of standard, easy to remove and reassemble fastening methods such as screws rather than proprietary or destructive fasteners. Avoid combining priority parts with other components with non-removable fasteners.
- **Spare parts availability:** Components must be available for purchase at reasonable prices. Using standardised components and interfaces makes this more feasible. Limiting spare parts availability or pricing replacement parts near total product cost effectively prevents repair regardless of product design (E1, interview).
- **Information provision:** Repair manuals, video guides, disassembly and reassembly guides, and diagnostic procedures help with both professional and consumer repair.
- **Diagnostic capabilities:** Products that communicate their status and failure modes assist with better repair. Self-diagnostic features in coffee machines that indicate cleaning needs are a typical example of this principle (E2, interview).
- **Safety considerations:** Haphazard repair can involve safety issues, which can be prevented through design considerations for safe repair, e.g., with clear identification of hazards.

Designers should consider not just physical accessibility but also behavioural aspects. Besides being technically repairable, users need to perceive that repair of their product is both possible and worthwhile. One example of an improvement related to behaviour is that performing regular maintenance tasks makes repair feel more achievable when needed, because it familiarises users with product internals (E4, interview).

Research indicates that consumers often need a specific trigger before considering repair. Products that display fault indicators with specific error codes for repair or maintenance provide such a trigger and increase consumer willingness to attempt repair by raising perceived self-efficacy (van den Berge, 2024).

The use of cable plugs makes liberating components easier

Wires: *are soldered to the PCBAs, making it difficult to liberate the PCBA components containing CRMs*



Cable plugs: *the components can be disconnected from the wires and recovered more easily.*

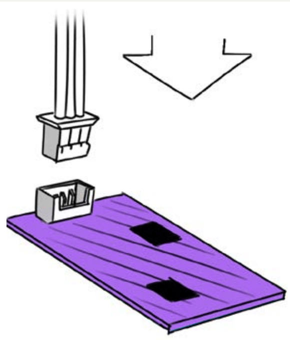


Figure 2 | Use of reversible fasteners such as cable plugs. Illustration by Ids Grupstra.

iFixit Europe

iFixit is an example of an online platform that provides consumers with instructions on repairing products. The platform also provides quality parts, tools, and community expertise. While iFixit started in the US, it has had a European division since 2013 (Haeussermann, 2023), and has collaborated with TU Delft since 2017 to develop and test repairability scoring systems. Beyond scoring systems, iFixit plays an important role in addressing the disappearing repair skills that interviewees identified as a barrier to circular electronics.

As consumer electronics grow more complex and consumers' technical knowledge erodes, some experts argue that policy and design should prioritise professional repairability over end-user repairability. Many consumers lack basic technical knowledge, such as the difference between battery types or even awareness that devices contain batteries (E3, interview). Given this lack of baseline knowledge, repairability requirements should not focus on consumer-facing features (like user-replaceable battery), but rather ensuring third-party repairers can access components, documentation, and parts.

National Repairer Register

The Nationaal Reparateursregister is an initiative by Techniek Nederland and the Ministry of Infrastructure and Water Management (Nationaal Reparateursregister, n.d.), launched officially in March 2025. It helps Dutch consumers find certified repair businesses for consumer electronics. Almost 400 repairers who meet strict quality standards are registered (Ministerie van Infrastructuur en Waterstaat, 2025). The Netherlands is the first European country with an official register supported by both government and the repair industry, giving form to the EU's "Right to Repair" legislation.

Designers may wish to create more serviceable products, but economic pressures within organisations often prevail, unless repairability is formally specified as a design criterion. Without explicit KPIs or hard requirements, the focus on profit through high sales volumes typically overrides repairability considerations during product development. Therefore, companies should formally integrate repairability into their design requirements (E3, interview).

Access a product's components → **...to keep the product alive longer...** → **...and give its parts multiple lives**

DESIGN FOR DISASSEMBLY
Ensure products are easy to take apart quickly

Parts
- Minimise the number of parts.
- Simplify structure and form.
- Use ferromagnetic materials to enable sorting and disassembly.

Tools & Fasteners
- Require only a few standard tools.
- Avoid requiring tools for the most common actions.
- Minimise the number and variety of fasteners.
- Use intuitive snap-fits, clips, or sliding connections.
- Design connections that are visually and physically accessible.
- Access fasteners from the same axis.
- Hold multiple parts with one fastener.
- Use coarse threaded screws for speed; use nuts and bolts for strength.
- Use human-scale fasteners.
- Use hand-strength press-fits instead of tight press-fits.
- Avoid glues, and use only glues that are easily soluble or heat reversible.
- Ensure fasteners are adequate for structural integrity.
- Use fasteners that will hold up over repeated use.

Documents
- Embed clear, graphical disassembly instructions into the product.
- Document materials and methods for deconstruction for the user.

DESIGN FOR REPAIR
Easily fix failures through disassembly and:

Product Architecture
- Use modular assemblies that enable the replacement of discrete components.
- Ensure easy access to parts likely to need maintenance.
- Use self-locating parts.
- Use robust connectors.
- Label and colour-code parts to enable troubleshooting.
- Standardise parts between product lines and across generations.

Documents
- Make technical documentation freely available or open-sourced.
- Include parts list and part numbers.
- Create user interfaces and troubleshooting tools to diagnose problems.

Business
- Make repair and service options clear to customers.
- Consider repair-friendly warranty terms.
- Make replacement parts available and affordable.

DESIGN FOR UPGRADE
Keep products relevant and useful longer

Product Architecture
- Use standard-size modular parts to enable interchangeability and customisation.
- Design easy access to parts likely to become obsolete.
- Use standard, cross-platform connections (for example, USB).

Tools
- Build diagnostic tools to help users understand the components that are limiting performance.

DESIGN FOR REMANUFACTURING
Enable reuse of old components in new products

Business
- Design collection infrastructure with smooth touchpoints between the company and users.
- Design a quality-control system for testing returned components.
- Use a take-back programme, product-service-system, or other enabling business model.

Figure 3 | Complete overview of design considerations for design for repair (Faludi et al. 2025).

The Miniaturisation and Integration Challenge

Product miniaturisation often impedes repair. This challenge comes from supply chain structures rather than fundamental technical constraints. The fragmentation of electronics supply chains means that product designers often lack detailed knowledge of component-level construction and specifications (E5, interview). Miniaturisation does not inherently preclude repair. Skilled technicians can perform PCB-level repairs on miniaturised electronics, but these require practice to obtain (E2, interview).

Modularity and standardisation

Modularity is a design approach where products are composed of independent, self-contained units (modules) that can be easily separated, replaced, or upgraded without affecting other parts of the product. Modular design enables component-level intervention by structuring products as discrete building blocks with clear interfaces between modules (van den Berge, 2024). This can help overcome repairability obstacles caused by miniaturisation and integration.

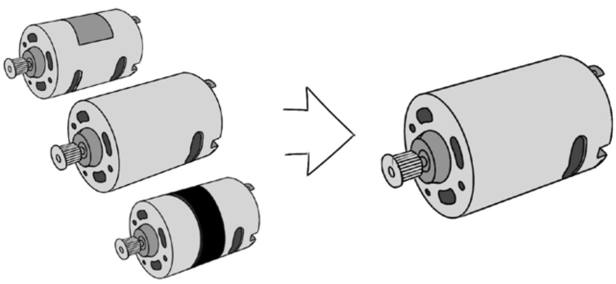


Figure 4 | Example of motor standardisation. Illustration by Ids Grupstra.

Modular design is often seen as a promising direction for extending product lifespan. However, most attempts at modular consumer electronics have failed to achieve market success (E3, interview). Modularity requires connectors, interfaces, and separable enclosures, all of which work against properties valued by consumers, such as miniaturisation, waterproofing, cost, and durability.

Modularity can introduce inefficiencies in repair when a module integrates multiple functions (e.g., camera and audio functions). When one component fails, the entire module requires replacement (E1, E2, interviews). Further, highly integrated modules (e.g. a single module with both the screen and motherboard of a smartphone) might prohibitively raise the cost of a module. So, although an interesting approach to increase repairability, the level of modularity needs to be carefully considered.

Standardisation, which is distinct from modularity, is the practice of using uniform, interchangeable components across product portfolios, generations, or models to enable easier sourcing, repair, and reuse. Standardised parts are identical in function and specification across different products. Design for standardisation prevents component obsolescence by ensuring parts fit multiple product generations, extending the potential for repair and refurbishment over time (E1, interview; Boorsma, 2022).

Currently, functionally identical components such as water pumps in washing machines vary across manufacturers, complicating spare parts procurement. Standardised components would likely lead to easier parts availability, shorter delivery times, and multiple supplier options (including a second-hand market) (E1, E5, interviews). For high-volume consumer products like washing machines and vacuum cleaners, standardisation could help, though this should be balanced against hindering innovation (E11, E12, interviews). Standardisation is even more critical for low-volume products, where maintaining manufacturer-specific spare parts inventories becomes economically unfeasible.

Limitations of Current Repairability Scoring Systems

The main repairability principles mentioned on page 14 have been captured in at least four repairability scoring systems. However, current repairability assessments still have significant issues. Furthermore, how these scores are communicated to consumers is also crucial, for example to prevent creating a false sense of accuracy (E1, E5, interviews). Below we discuss several weaknesses of current scoring systems.

The French Repairability Index (FRI) measures the number of disassembly steps rather than actual repair time or difficulty. This does not always lead to a representative score. An HP laptop requiring 6-7 steps and approximately 20 minutes to repair scores similarly to a MacBook requiring the same number of steps and approximately 90 minutes (E2, interview).

Spare part pricing is often not incorporated into repairability indices (nor is it regulated under the R2RD), despite being a decisive factor. The FRI does penalise if spare parts cost more than 10% of the product price. An inevitable issue is that this relies on prices at the time of calculating the score.

The R2RD's 'within reasonable time' requirement is also problematic. It can be expected that companies will lobby for a different definition of 'reasonable' than what is acceptable to consumers, who are used to online shopping with next-day or even same day delivery. Consumers facing a significant delay often choose immediate replacement instead of repair.

A final critical flaw in the current scoring systems is the way that different elements are counted. Information provision, ease of disassembly, and spare parts availability are weighted equally. This means that a product that cannot be disassembled can still obtain a high score. An obvious solution is to apply limiting or threshold scores (i.e. the overall score cannot exceed a particular sub-score, or weights are dependent on sub-scores). Unfortunately, the JRC scoring system that will be the foundation for the European scoring system did not apply such adaptations.

Refurbishment & Remanufacturing

Refurbishment and remanufacturing extend product life at industrial scale with formal quality control. Refurbishment differs from repair by proactively replacing components that have not yet failed but show signs of degradation. Remanufacturing goes further, completely disassembling and rebuilding products before resale as functionally new. The refurbishment market for small consumer electronics is estimated at 0.3% of put-on-market volume, based on ICT market data only (Stichting OPEN & YAG, 2023, cited in nlmtd, 2026). Products that enter refurbishment come from return streams, business disposals, and consumer waste collection. The main products being refurbished are smartphones, laptops, tablets, game consoles, smartwatches, PCs, monitors, and (portable) speakers (nlmtd, 2026).

Design Requirements for Refurbishment

Refurbishment shares many technical requirements with repair, particularly regarding disassembly and reassembly. However, additional considerations apply as refurbishment aims at industrial-scale operations and targets components that show signs of degradation before actual failure. A battery that still functions but has lost capacity would typically be replaced during refurbishment, whereas repair would only address it upon failure. This requires different design considerations, including diagnostic capabilities to assess component condition (E3, interview). Furthermore, appearance and cleanability are particularly important because refurbished products are sold as fully functional alternatives to new products. Design features supporting refurbishment include at least easy-to-clean, scratch-resistant finishes, avoidance of fabric finishes that absorb odours, in addition to the requirements for repairability (E1, E5, interviews).

Slow innovation cycles or product maturity also support refurbishment. For example, improvements in servo motors are not happening very fast (E10, interview), leading to servo motors in e.g. automotive manufacturing robotics applications routinely being refurbished.

Quality Assurance and Market Acceptance

Consumers are averse to traces of previous ownership, including scratches, wear marks, and contact surfaces used by others. Research shows that replacing contact components (such as ear cushions on headphones) significantly increases purchase willingness, often more than price reductions or extended warranties (E4, interview). Effective refurbishment should also provide warranty coverage comparable to new products, requiring thorough inspection and proactive replacement of deteriorated components rather than only addressing current failures (E1, interview).

Return stream data illustrates the scale of the missed opportunity. Approximately 9% of all products put on market are returned to retailers. About two-thirds of returns arrive within the cooling-off period, and one-third follow later as warranty claims. An estimated 50 to 70% of returns receive a second life, meaning 30 to 50% end up as waste even when still functional or only lightly damaged (nlmtd, 2026).

Recyclability

Recovery of critical materials increases supply chain resilience by reducing reliance on concentrated primary production, provided the recycled material is of sufficient quality. Dutch electronics consumption contains approximately nineteen thousand tons of critical materials annually. Recycling rates differ strongly between materials. Copper, aluminium, silicon, tungsten, and precious metals are recycled, but many others are not, including rare earth elements, indium, gallium, tantalum, and cobalt (nlmtd, 2026). For these materials, the collection and recycling infrastructure does not yet exist at scale (E9, interview).

Recycling networks

The Netherlands has an extensive recycling infrastructure. In each country, there is an EU-mandated Producer Responsibility Organisation, which is a collaboration of all electronics manufacturers and importers. For the Netherlands, this is Stichting Open. They employ a contract-based approach, paying gathering stations, sorting companies, and processors in the Netherlands in return for the agreed output in the chain (E9, interview). This way, it is aimed to create a stabilising network of players through supporting regulations of stream volumes. Municipal collection points and retailers play a key role in collecting products for reuse, before they are sent to recycling.

According to E9 (interview), the Netherlands has a best-in-class recycling infrastructure in Europe. Leveraging this existing infrastructure could be a key opportunity in the Dutch context of circular consumer electronics.

This existing system is not without flaws. In the current system, companies need to pay a fee to Stichting Open for end-of-life treatments (E5, interview). However, the fee does not differentiate on the recyclability of products, so there is no incentive to design for maximum recyclability.

Figure 5 shows the common recycling process for electronic products. The process begins with mechanical destruction of the product, after which sorting technologies separate different materials for further processing.

A variety of Design for Recycling (DfR) methods for electronics have been developed over the past decades. A systematic review spanning roughly 30 years identified 16 distinct methods and design guides, most of which lack validation through recycling experiments and have not been tested in design practice. Recyclability guidance is often generic, and product-category-specific translation to design practice remains underdeveloped (van Dolderen, 2026).

Although many materials are technically recyclable, only a limited number of materials are recycled in practice. Bulk metals (steel, copper, aluminium) and precious metals (gold, silver, palladium) recycle well. Among plastics, ABS, PP, PE, and occasionally PC are commonly recycled. Other plastics are typically incinerated (E5, interview). Critical materials such as rare earth elements, indium, and cobalt are present in small quantities dispersed across many components, making recovery economically unviable at current volumes and prices (E9, E14, interviews).

The discrepancy between technical recyclability and actual recycling rates is related to the scale at which these materials are used and the business case for the recycler, which requires large volumes of homogeneous material. Connection methods between parts (and thus between different materials) determine to a large extent if fragments resulting from shredding are homogeneous or heterogeneous. This will be further discussed in the next section.

Furthermore, actual recycling is only realised when products enter recycling streams. Many electronic products, particularly smartphones, hibernate in household drawers and other storage for years after functional replacement. Motivating consumers

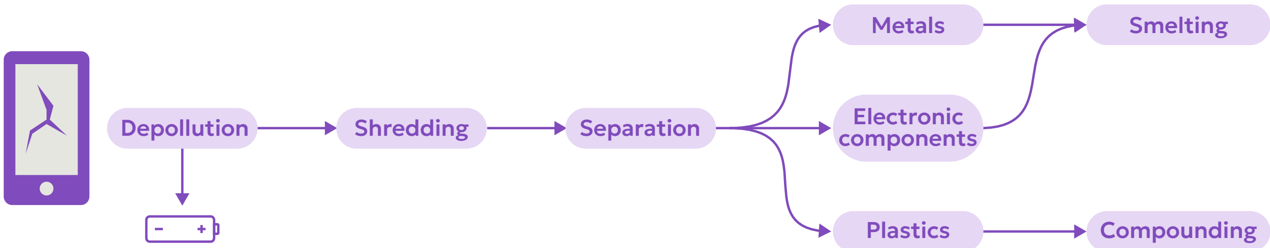


Figure 5 | A simplified visualisation of the E-waste recycling process.

to return products is a distinct challenge. As with repairability, it requires designing for specific user behaviour, for example by making disposal information clearly visible on the product itself.

Permanent magnets present a specific Design for Recycling challenge. Neodymium magnets in electric motors can be recycled through hydrogen decrepitation, a process in which hydrogen gas causes NdFeB magnets to disintegrate into reprocessable powder. Short-loop recycling using this method can produce magnets at grades up to N48 from clean feedstock (E14, interview). Rotor design determines whether this process is feasible. Exposed magnet ends allow powder to escape during processing; full end caps covering the magnets prevent this and require manual removal, which is often prohibitively expensive. Coating choice also matters. Phosphate or metallic coatings are preferable, while epoxy coatings and transfer-molded polymer encapsulation obstruct hydrogen access. These design considerations are analogous to the fastener and adhesive choices elsewhere in this chapter, where small design decisions made during product development determine whether material recovery is feasible at end-of-life.

Recycling Indicator Definitions *(based on Bradley et al. 2024)*

There are many recycling metrics, which causes some confusion. Here the most important indicators are defined.

End-of-life recycling rate (EoL RR):
The share of post-consumer waste that is recycled. This indicator measures waste management efficiency and is often used for circularity assessment.

End-of-life recycling input rate (EoL RIR):
The share of total production volume (primary and secondary) that comes from recycled post-consumer waste. This indicates reduction of primary consumption.

Recycling input rate (RIR):
The share of total material weight in a product from all secondary sources, including both post-consumer (old) and post-industrial (new) scrap. Often used interchangeably with “recycled content,” though definitions can vary by regional scope.

Old scrap ratio (OSR):
The share of total recycled material that comes from post-consumer sources rather than manufacturing waste. Old scrap (post-consumer scrap) comes from products at end-of-life. New scrap (post-industrial scrap) is manufacturing waste recycled before products reach consumers. Old scrap recycling contributes to supply security; new scrap recycling should be seen as reflecting manufacturing inefficiency.

Two additional concepts are of importance:

Functional vs. non-functional recycling:
Functional recycling recovers materials for reuse in their original application. Non-functional recycling occurs when a material becomes an impurity in another material’s cycle and is no longer available for its original use. For example, tin in recycled steel cans enters the steel cycle as a contaminant rather than being recovered as tin.

Pure metal vs. alloy recycling:
Recycling can recover materials as pure metals or in alloyed form. Most end-of-life electronics recycling recovers metals in alloy form, with negligible pure metal recovery for many elements.

Design for Shredding

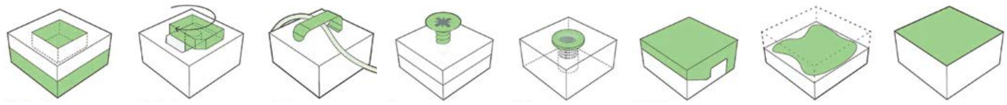
Large-scale WEEE recycling in Western-Europe is typically driven by mechanical disintegration (shredding). Published Design-for-Recycling guidance typically focuses on manual disassembly, and most product designers have never observed their products undergoing shredding. This limits the real-world usefulness of disassembly-centred Design-for-Recycling guides. Figure 6 gives an overview of common connections and the extent to which they enable recycling through shredding. For comparison also the behaviour of these connections in manual disassembly (as needed for repair) is shown.

Once bottlenecks in recyclability have been identified, Design for Recycling can focus on improving shredding outcomes, for example facilitate fracturing of screws by fracture lines or weakened zones in brittle components. "When it goes through the shredder, it breaks at the cut line instead of randomly, freeing up materials better. This leads to us being able to organise material separation instead of leaving it to serendipity" (E1, E5, interviews).

Glue is often seen as bad for recycling. However, there are differences in adhesive types. Some adhesives pose minimal barriers, while e.g. epoxy creates permanent bonds. Heat or even electro-reversible adhesives (the latter being used by Apple) support both repair and recycling (E2, interview).

Design for shredding is particularly important for components containing critical raw materials. Figure 7 illustrates the location of CRM-containing components in a cordless vacuum cleaner. Avoiding deep embedding of motors and magnets within product assemblies improves the likelihood of material liberation during mechanical processing. Furthermore, if components are easily accessible, they can be removed before shredding while also facilitating disassembly for component reuse and repair.

Suitable
Design dependent
Not suitable



	Friction fit	Turn-lock	Hook	Screw	Insert	Snap-fit	Glue	Coating
REPAIR (manual disassembly)	Suitable	Suitable	Suitable	Suitable	Not suitable	Design dependent	Not suitable	Not suitable
RECYCLING (mechanical disintegration)	Design dependent	Suitable	Suitable	Design dependent	Design dependent	Suitable	Design dependent	Not suitable

Figure 6 | Suitability of connections for repair and recycling, based on disassembly and shredding experiments.

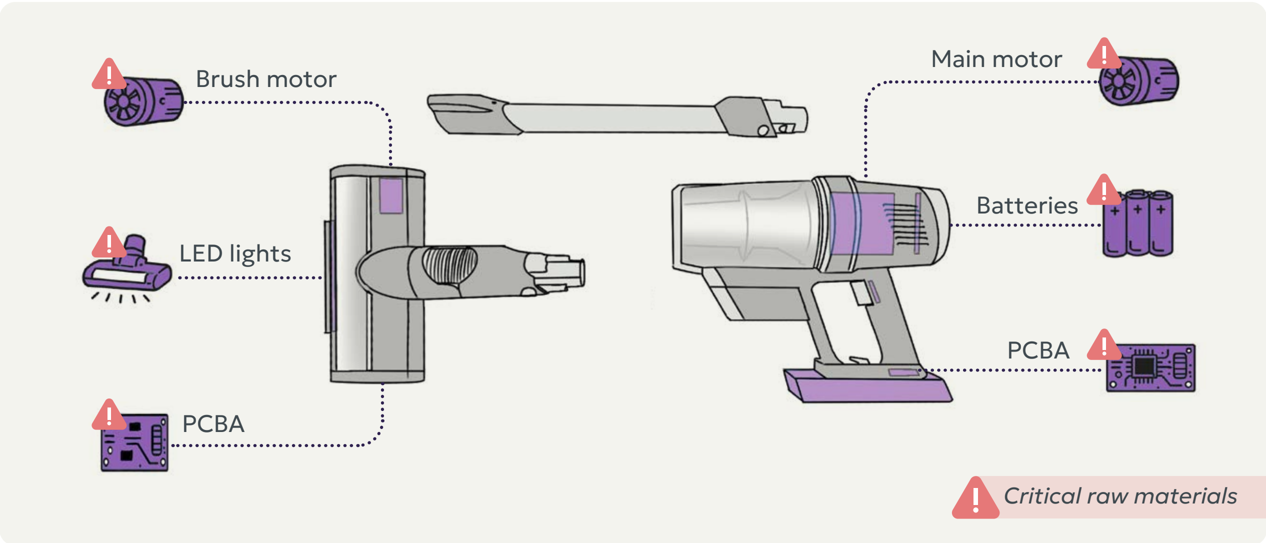


Figure 7 | CRM components in cordless vacuum cleaners. Illustration by Ids Grupstra.

Substances of Concern

Another consideration when designing for recycling is 'Substances of Concern' (SoC), which is an umbrella term for chemicals that pose, or are suspected to pose, safety risks to human health and ecosystems. From a design perspective, these materials often fulfil essential functions (e.g. cooling agents in refrigerators) and cannot be avoided without severe performance loss. Recycling leads to an accumulation of such substances in each cycle, particularly in recycling. To address this issue, the safe-and-sustainable-by-design (SSbD) approach has been developed. At EU level, the Commission Recommendation (EU) 2022/2510 established a voluntary assessment framework for SSbD, currently scoped to chemicals and materials rather than product design broadly, as part of the Chemicals Strategy for Sustainability (European Commission, 2022). From a design perspective, the aim is to avoid and/or substitute the SoC. Recently, Bolaños Arriola et al. (2024) developed a method that takes a product life cycle perspective to generate SSbD strategies for product developers. This method considers a more extensive range of mitigation strategies (Figure 8: Design Strategies to deal with SoC in products).

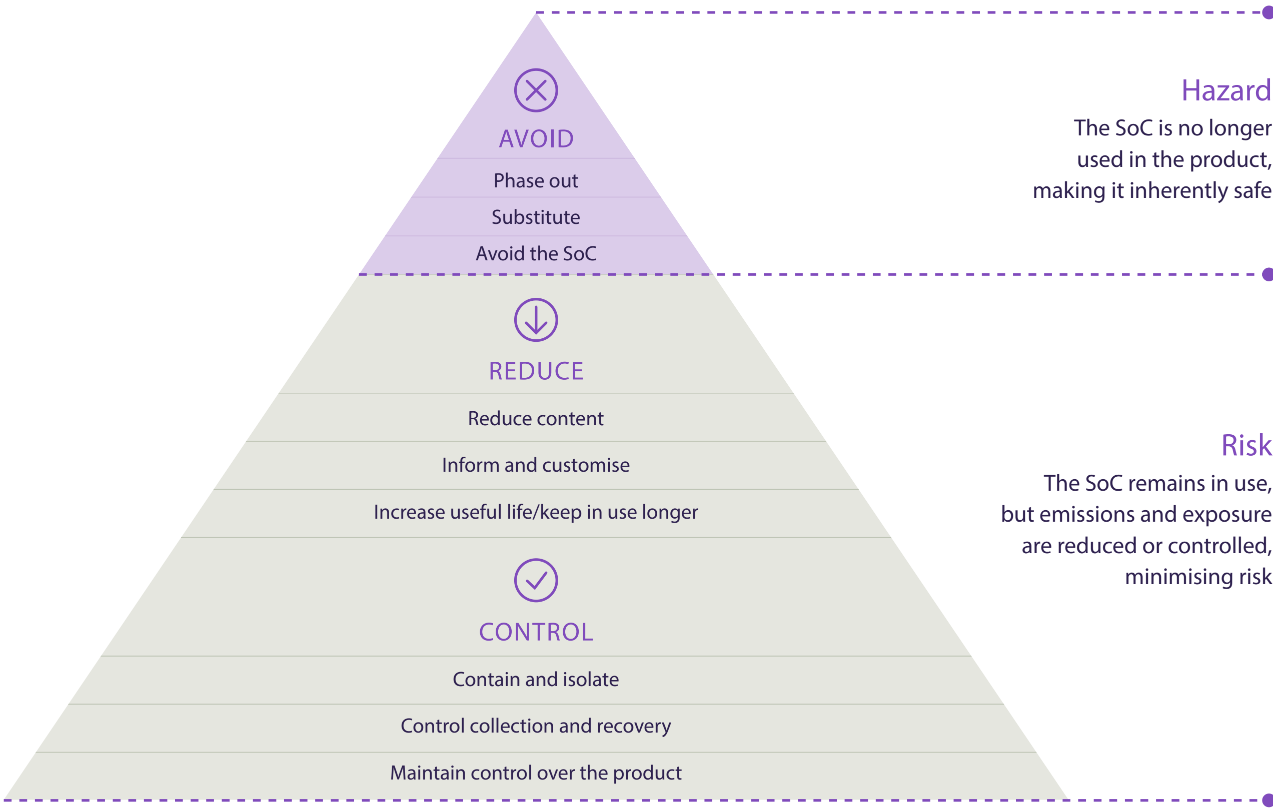


Figure 8 | Design Strategies to deal with SoC in products, (Bolaños Arriola et al., 2024). The three strategy types are arranged in a triangle to indicate priority: strategies that eliminate the SoC entirely (Avoid) are preferred over strategies that mitigate its effects while retaining it (Reduce, Control). Each strategy group depicts several sub-strategies and illustrative examples.

Design with recycled materials

Beyond designing for recycling, designing with recycled materials aims to incorporate recyclates into new products, thereby enabling circular material loops in consumer electronics. Recycling of CRMs is a complex topic, and many CRMs are either not recycled or disappear into non-functional recycling. Designing with recycled CRMs is a novel topic of research that is out of scope of this report. Recycling of plastics is a more common occurrence in consumer electronics. Logitech, for example, implements substantial quantities of recycled plastics in their product portfolio (E5, interview). In this section, we discuss recycling of plastics in a bit more detail, because it is indicative of the challenges of recycling with recycled materials in general.

Recycled materials typically exhibit degraded mechanical properties compared to virgin materials. Blending virgin materials with recyclates can compensate for these deteriorated properties, allowing manufacturers to meet performance specifications while maintaining recycled content.

Since recycling combines batches of different polymer grades, the output can show a broad distribution of properties and additives, depending on input homogeneity. Separation is not perfectly selective either, meaning cross-contamination with other plastic types typically occurs. These combined factors make mechanically recycled plastics less consistent and predictable than virgin materials, limiting their use to applications where performance requirements are less demanding. This progression toward lower-grade uses is known as "downcycling". This can be mitigated (partially) by blending virgin plastics with recyclates to compensate for these deteriorated properties, allowing manufacturers to meet performance specifications while maintaining recycled content. The alternative is that designers redesign products to meet requirements, implying that product design should consider the limiting values within the distribution of properties as starting point for design.

The potential presence of a wide variety of additives is another bottleneck. Application regarding e.g. food safety should therefore be avoided unless the origin of the recycled plastics can be guaranteed. Closed loop recycling in which known products are selectively returned is most interesting here.

The Design from Recycling method described by Du Bois et al. (2025) considers both the technical properties of recyclates and the user-centred material experience. The rationale is that while technical properties of recyclates are inherently limited compared to virgin materials, the material experience can provide compelling motivation for selecting recycled materials.

Material Substitution for Critical Raw Material Reduction

The circular strategies (discussed on pages 12-22) reduce critical raw material demand by extending product and material lifetimes. Substitution strategies instead replace critical raw materials with more abundant alternatives at the point of product design, reducing CRM demand before any circular loop begins. Substitution operates at three levels.

Component technology substitution

Component technology substitution replaces an entire component type with one that requires fewer or no critical materials. Synchronous reluctance (SynRM) motors, for example, eliminate permanent magnets entirely and can achieve the highest (IE5) efficiency class. They are suitable for stable-load applications such as pumps and fans, though not for high-precision applications such as servo motors (E10, interview). In the automotive industry, partial substitution of NdFeB motor power with NdFeB-free alternatives is already applied by Audi and Volkswagen (CMR 2026). For batteries, shifting from nickel-manganese-cobalt (NMC) to lithium iron phosphate (LFP) cathodes eliminates cobalt and nickel entirely, at approximately 20% lower energy density but with better cycle life and safety (E15, interview). The upcoming Sodium-ion batteries also substitute lithium, using iron-manganese or iron-phosphate cathodes instead (E15, interview).

Technology substitution

Technology substitution is highly application-dependent. LFP is already the dominant chemistry for stationary storage, where energy density is less critical (from the strategic autonomy perspective, it is relevant to note that currently, LFP batteries are mostly made in China). For consumer electronics, where size and weight matter significantly, NMC batteries are still preferred. SynRM motors work well for fans and pumps but cannot replace NdFeB in robotics or CNC machining. Designing product architectures that accommodate multiple component technologies (e.g., motor mounting standards that accept both NdFeB and SynRM units, or firmware that supports different motor types) increases flexibility to substitute as supply conditions and technology readiness evolve (E12, interview).

Material substitution

Material substitution within a component changes the composition of a component while retaining its basic technology. For example, Cerium, a low-value byproduct of rare earth processing, can replace approximately 5 percentage points of the much more expensive neodymium in permanent magnets with only 2-5% reduction in magnetic properties. Asian producers are already shipping magnets with 22% neodymium + 5% cerium instead of 27% neodymium (E10, interview). Material substitution introduces trade-offs. Cerium-doped magnets complicate recycling feedstock uniformity. Substitution can also be triggered by indirect policy signals. The replacement of copper boiler tanks with steel in heat pumps, partly driven by the Dutch Environmental Performance of Buildings (MPG) requirement, reduces copper demand from 16 kg to 1 kg per unit without product-specific CRM regulation (Copper8 & Delft University of Technology, 2026a).

Material intensity reduction

Material intensity reduction achieves equivalent performance with less critical material through optimised design. For example, with permanent magnets the progression from block to arc-shaped to lens-shaped geometries saves approximately 10% of magnet material. Optimising the interplay between electrical steel grade, copper windings, and magnet specification can reduce neodymium content by up to 20% per motor (E10, interview). For batteries, higher energy density per unit weight (through anode improvements such as silicon) means less cathode material is needed for a given storage capacity.

High levels of optimisation require significant investment in engineering and product design. This can be problematic due to lack of highly skilled personnel, prohibitive costs of spending engineering time, or product development timelines being too compressed due to the competitive pressure of keeping up with the regular release of new products.

Trade-offs

Design for repair versus recycling

Potential tensions exist between design for repair and design for recycling as is evident from Figure 6. For example, screws facilitate disassembly for repair but can complicate shredding processes during recycling. When trade-offs are unavoidable, prioritising repairability over recyclability is generally recommended, as higher R-strategies (repair, refurbishment) retain more value than recycling. Current recycling processes lose substantial material value: most plastics are incinerated, metal recycling leads to degraded alloy qualities, and critical raw materials are generally not recovered (E3, interview). While blending virgin materials with recyclates can compensate for degraded properties, high-purity alloys with tightly controlled compositions still require primary metals.

Design for repair versus durability

Enhancing repairability can sometimes reduce product durability. For instance, smartphones with adhesive-sealed enclosures achieve dust and water resistance, but this sealing method complicates repair. Making the back cover removable typically improves repairability but compromises ingress protection against environmental factors.

Durability versus material efficiency

Enhancing product durability can reduce material efficiency. For example, increasing wall thickness improves structural integrity and longevity but requires more material per unit.

Integrated approach

To navigate the trade-offs inherent in these sustainability approaches, designers currently lack an overarching tool that enables conscious, balanced, and transparent decision-making. While higher-level circular strategies (product longevity and repair) should generally be prioritised over lower-level strategies (recycling), end-of-life recycling occurs more reliably than repair in practice. Product-specific considerations determine which approach(es) are most appropriate.

Design-for-X Methods

Many design methods have been proposed. A full review is outside the scope of this report. Here we discuss several that are used by the interviewees.

Methods for Mapping the Product Architecture

To apply circular design strategies, one needs to understand the product architecture. The Disassembly Map is a method for making the product architecture explicit. It quantifies and visually illustrates the number and difficulty of steps needed to liberate components that are targeted for repair or recovery. The disassembly map visually indicates the difficulty of each disassembly step, making it apparent where improvements can be made. Figure 10 shows a disassembly map of a vacuum cleaner, clearly indicating how many steps it takes to reach various components, and what level of effort is needed.

Figure 9 | A disassembled vacuum cleaner (Grupstra, 2026).

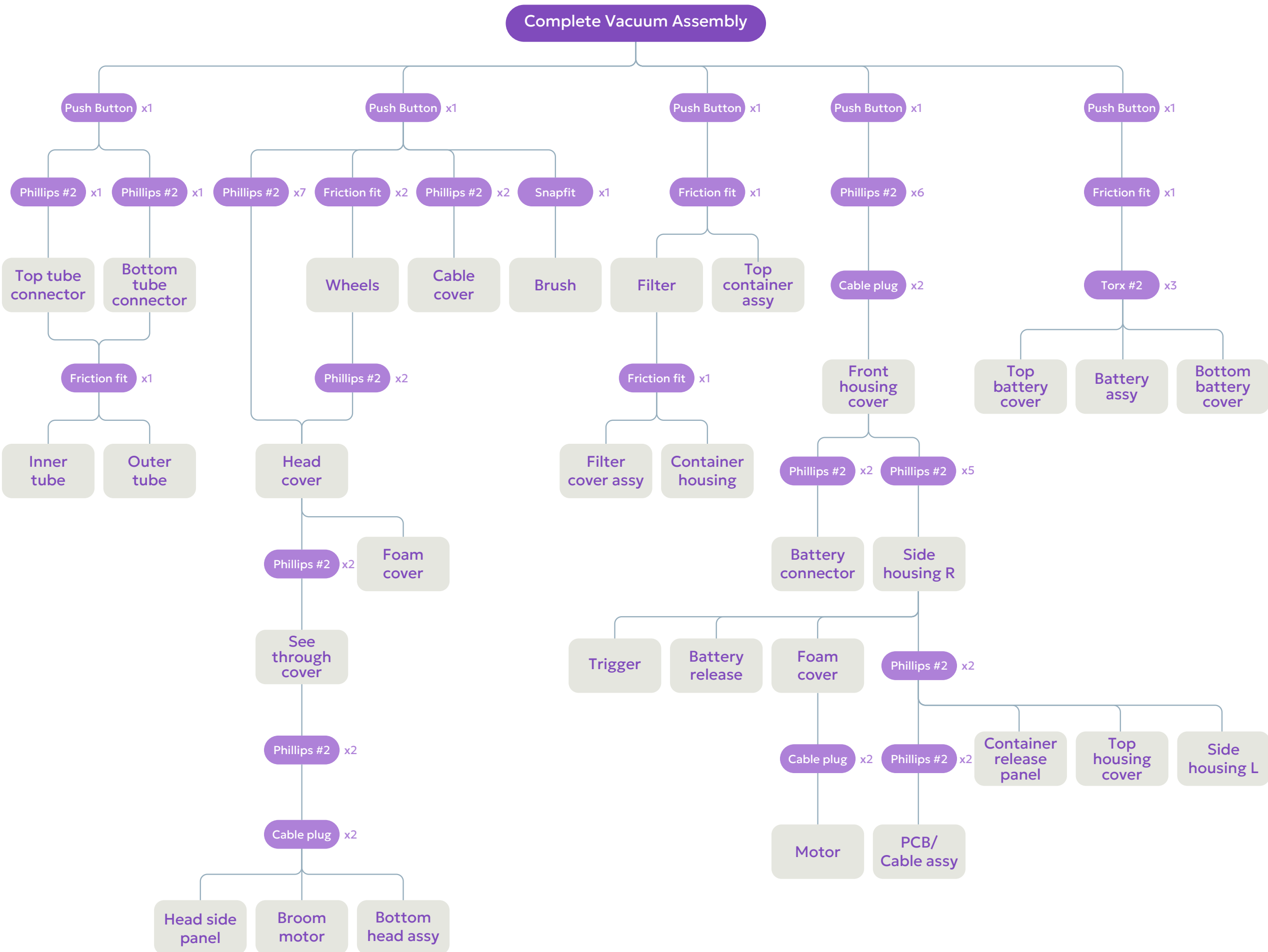


Figure 10 | Vacuum cleaner disassembly map, slightly simplified (based on: thesis Ids Grupstra, 2026)

Figure 11 shows two commercially available and functionally similar vacuum cleaners motor assemblies. Differences in product architecture lead to disassembly time being different by a factor of 6. The associated disassembly map clearly illustrates the difference. Based on the Disassembly Map method, various tools have been developed. The repair safety map adds zones of safe and unsafe repair, for example because of unsafe electrical components (Ingemarsdotter et al, 2021). A map was developed identifying the presence of components with critical materials (Grupstra, 2026). Finally, the recyclability map incorporates information on recyclability of materials as well as behaviour of connections in shredding (van Dolderen, 2025).

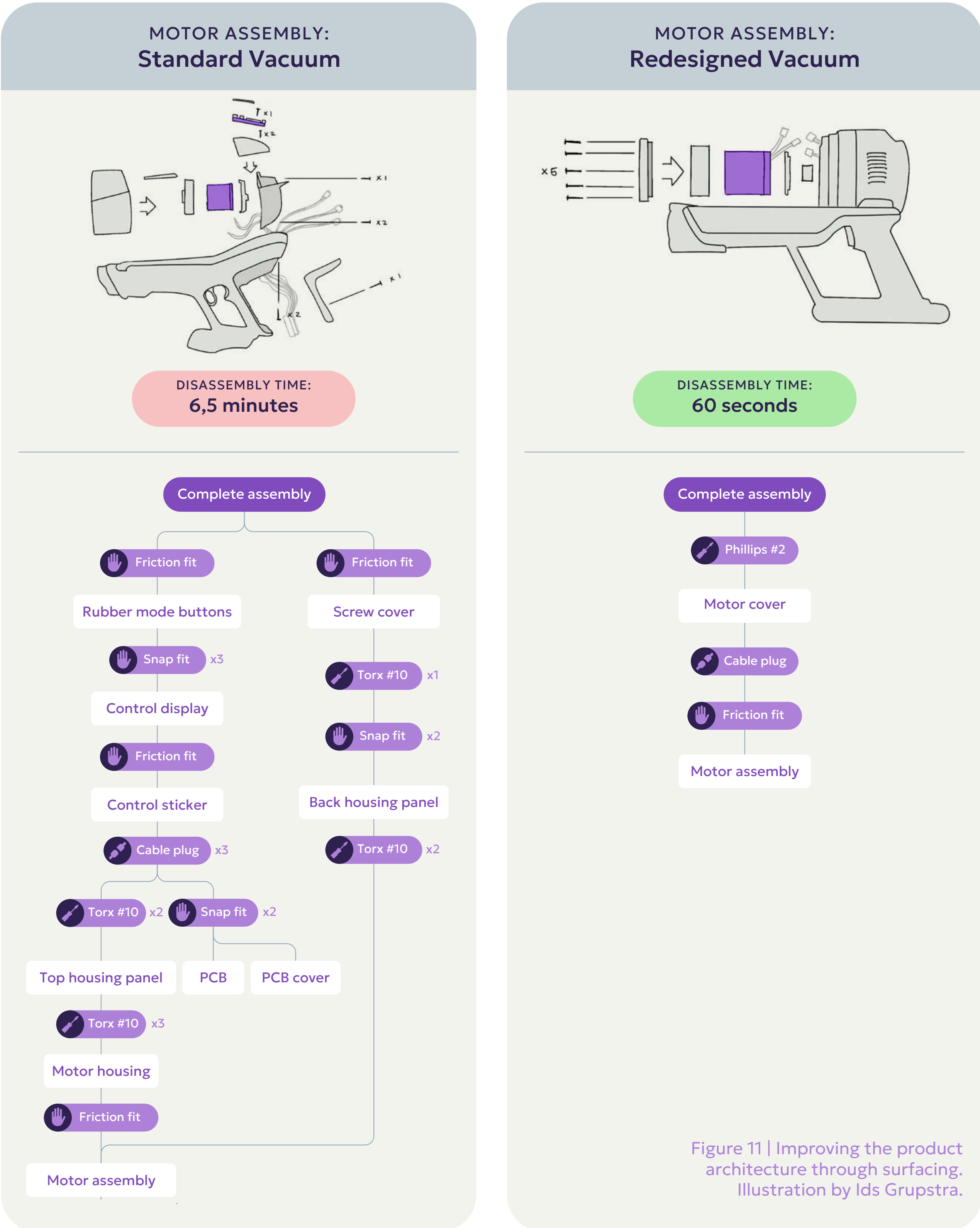


Figure 11 | Improving the product architecture through surfacing. Illustration by Ids Grupstra.

CHAPTER 03

Circular Product Readiness Tool for Remanufacturing

The Circular Product Readiness tool addresses non-technical barriers to remanufacturing (Boorsma, 2024). The method helps firms assess how far circular design is embedded in their product-service systems, and to identify gaps in capabilities, data, and metrics. These gaps align closely with the soft barriers from our interviews: lack of internal buy-in, unclear responsibilities, and absence of design indicators.

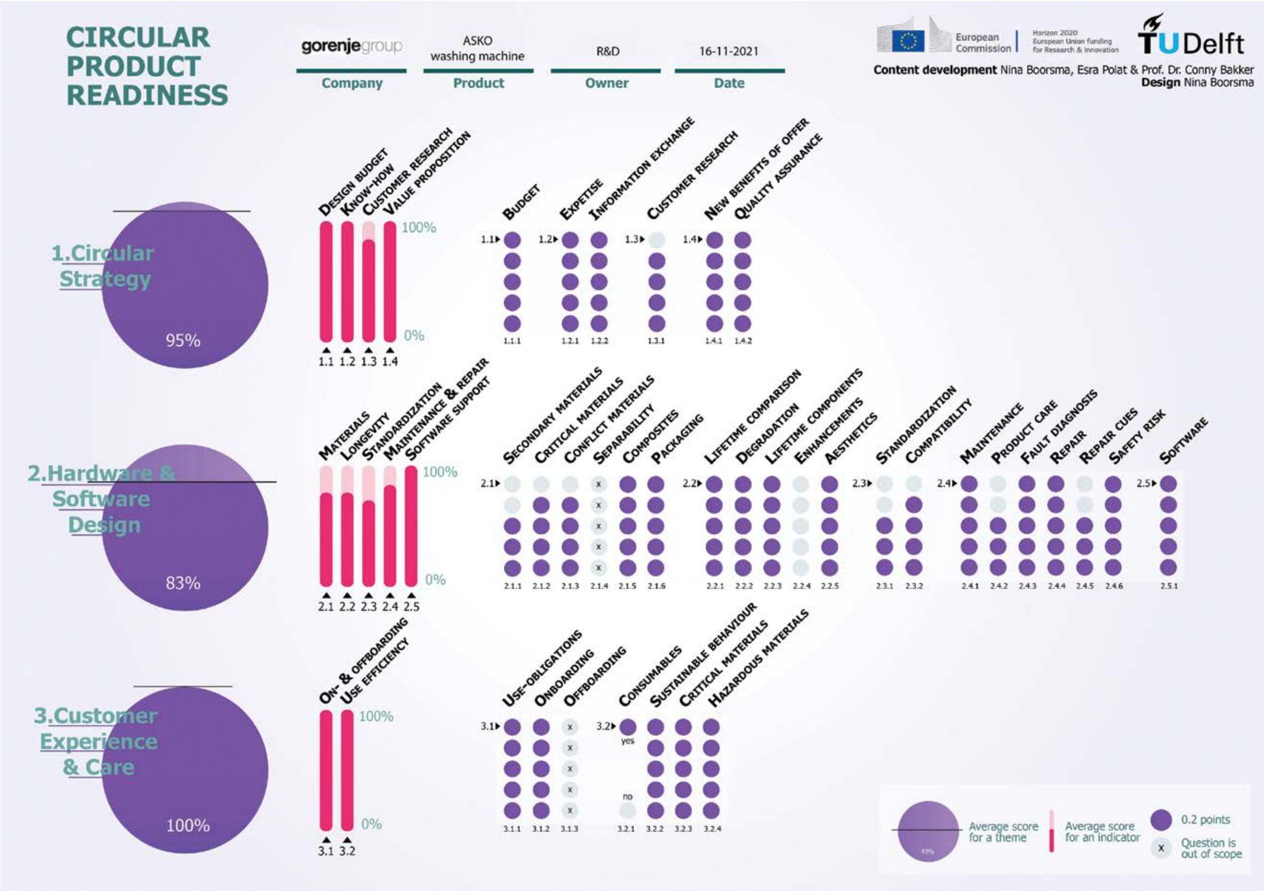


Figure 12 | Circular Product Readiness Tool excerpt

Life Cycle Assessment to Quantify Trade-Offs

The trade-offs described on page 24 illustrate that optimising for one circular strategy can worsen outcomes for another. Life Cycle Assessment (LCA) provides a systematic method for evaluating these trade-offs by quantifying environmental impacts across the full product life cycle, from raw material extraction through manufacturing, use, and end-of-life processing.

For circular electronics, LCA can show effects that are not visible from a design perspective alone. Extending product lifetime reduces the per-year impact of production but could increase cumulative use-phase energy consumption. Designing for repair may add material (e.g. thicker housings, additional fasteners) while avoiding the far larger impact of manufacturing a replacement product. LCA allows designers to compare these effects and identify which strategy yields the lowest overall environmental burden for a given design.

LCA has known limitations in the context of this report. Standard impact categories do not capture supply chain disruption risk or material criticality, both of which are emerging concerns in circular electronics design. A product with lower global warming potential may still depend heavily on materials with concentrated and vulnerable supply chains. The April 2025 neodymium magnet export restrictions illustrate how the risk of supply concentration manifests into real disruptions. Methods that integrate criticality assessment with LCA are under development (e.g., the ESSENZE and Geopol methods) (Bach et al., 2024; Yavor et al., 2021; Cimprich et al., 2017), but it is not clear whether LCA is a suitable method for integrating criticality into product design. Social impacts, such as labour conditions in mining, are similarly underrepresented in conventional LCA.

04

Business models for circular design

BUSINESS MODELS FOR CIRCULAR DESIGN

Circular design is only economically viable if it is paired with the correct business model.

This section links the four design strategies discussed in Chapter 3 to appropriate circular business and revenue models. We then give a framework for selecting the most viable business model.

We define a business model as the activity logic of how a company creates and delivers value. A revenue model is a component of the business model that specifies how and when money is earned. The same circular design strategy can be supported by different revenue models depending on context (Jonker et al., 2022). Business models shape design incentives, and vice versa, while design choices can enable specific business models. Besides the interviews, this chapter makes extensive use of Jonker et al. (2022), and Atasu et al. (2021).

Business Models Supporting Durability and Reuse

Durable products models

The most straightforward business model for durability involves designing high-quality products built to last longer. Selling longer-lasting products seems to inevitably lead to fewer sales and thus lower profit. However, durability can be used as a key competitive differentiator, which, if marketed correctly, provides manufacturers with a strong rationale for premium pricing. In literature, this approach is known as Product Life Extension (Atasu et al., 2021), or Design-for-Longevity (Jonker et al., 2022). The revenue stream originates from higher prices at point of purchase, making it dependent on consumers' ability and willingness to pay a premium for extended lifespan. A focus on quality should ideally improve brand image, leading to improved pricing power and market share. Furthermore, a long-lasting relationship with a consumer through a durable product also allows a company to develop other revenue streams attached to product ownership.

Demographic shifts can create new market opportunities for durability-focused products. As populations age (the proportion of consumers over 65 is projected to exceed 25% in many European countries), consumer preferences may shift toward ease of use, product stability, and longer lifespans. The older demographic values reliability over novelty and is less motivated to learn new interfaces or adapt to frequent product changes. Products designed for this segment would naturally align with circular principles like durability and repairability (E3, interview).

Product-as-a-service and leasing models

An alternative approach is the Retain Product Ownership (RPO) model (Atasu et al., 2021), where manufacturers maintain ownership of products and provide them through leasing or product-as-a-service (PaaS) arrangements. This eliminates the barrier of high upfront costs for consumers while businesses retain financial exposure to product performance over time, creating direct incentives to extend product lifespan as this reduces costs and increases margins.

The revenue model for RPO consists of recurring payments over the product's lifetime. There are two associated business models. 1) Leasing, where users pay to access a product for a defined period without owning it. The provider retains legal ownership; responsibility for maintenance can sit with either party. 2) Product-as-a-service, where users pay for the function or performance of a product rather than the product itself, with the provider retaining ownership and responsibility for maintenance, repair, and product performance throughout the use period.

There are real-world examples where RPO models demonstrate clear durability benefits. NS (the Dutch national railways) operates Europe's largest shared bicycle system (OV-fiets) with associated refurbishment and repair operations. The bicycles have been redesigned for increased durability (Fietsen123, 2009). Similarly, leasing or pay-per-use washing machines create financial incentives for manufacturers to prioritise durability (E5, interview).

However, RPO models face challenges around user behaviour. Users who do not own products may handle them with less care. For example, battery longevity in leased electric vehicles can be lower because users charge to 100% rather than the 80% threshold that extends battery life (E2, interview), echoing the saying "don't be gentle, it's a rental". This is not an unavoidable dynamic but rather depends on the relationship between the user and the product. For example, residents exhibit care for shared apartment washing machines, knowing damage affects their own access, whereas easily replaceable ride-by-ride e-scooter rentals are often not as carefully treated.

RPO models also face economic barriers, particularly if cumulative costs exceed the product's purchase price. In one – perhaps extreme – case, the total cost of a Product-as-a-Service washing machine was calculated to be roughly 5 to 7 times higher than outright purchase including occasional repairs (Consumentenbond, 2017). These cost structures make RPO models most viable for shared use or temporary ownership situations, where the convenience of the service justifies the premium.

Platform and resale models

In addition to business models centred on producing durable products, platform and resale models support durability by extending product lifespan through reuse, connecting used products with new users. Platforms such as Marktplaats, Kringloop stores, BuyBay, and BackMarket collectively handle a significant portion of Dutch electronics volume (up to 25%, E9, interview). These platforms create value by offering a marketplace infrastructure and reach, generating revenue through listing fees, commissions, or resale margins.

Notably, these models operate largely without involvement of the OEM. However, the design choices made by the OEM remain influential: products with cosmetic durability, data security features (factory reset capability), and continued software support maintain higher resale value, making them more viable for secondary markets. Since OEMs do not benefit from such a business model, this does not offer a design incentive for durable products.

Business-to-business

Business-to-business (B2B) contexts tend to favour durability-focused models. Buyers in B2B settings are more used to total-cost-of-ownership reasoning and product costs calculated on a per-use basis, which supports paying more upfront for higher quality goods. As the Dutch saying goes, ‘goedkoop is duurkoop’ (buying cheap is buying expensive). An example is Strijbosch in Heesh, that provides institutions (e.g. health care institutions, childcare, and government institutions) with long-lasting white goods (Strijbosch BV, n.d.).

Conversely, organisational structures and accounting practices can impede the integration of B2B circular practices. For example, separate budgets for purchasing and maintenance in municipalities has hindered the implementation of service models (E17, interview). Similarly, buy-back arrangements can negatively affect revenue figures, particularly when a high buy-back amount is agreed upon in advance, thereby discouraging companies from adopting them (E17, interview).

Business Models Supporting Repairability

Repair-focused business models earn revenue from maintenance and component replacement rather than exclusively from selling new products. In practice, repair is currently viable mainly for high-value ICT products; low-value appliances are almost never repaired (nlmtd, 2026).

Products with repairability as an explicit value adding feature

Design-for-Repair products are designed with accessible, modular components that can be easily replaced or repaired (Jonker et al., 2022). Two examples are Fairphone, which sells repairable mobile phones and has experimented with upgradable modules, and Framework, which sells repairable, upgradable and customisable laptops. In both cases, the revenue model combines initial product sales with ongoing parts revenue.

Such modular designs rely heavily on users’ self-repair capabilities, requiring both motivation and technical knowledge. Successful self-repair depends on consumers being motivated and guided through the repair process (E4, interview). Whether self-repair is feasible for consumers beyond a small niche group is uncertain, and interviewees have divergent opinions on this (E2, E3, interviews).

Professional repair services

Repair services are amongst the most prevalent lifetime extension business models (Jonker et al., 2022). Revenue models in this category include per-repair fees, buy-and-resale operations, subscription maintenance contracts, spare parts sales, and repair integrated into product-as-a-service arrangements (adapted from Jonker et al. 2021).

Professional repair addresses the knowledge gaps inherent in self-repair models but introduces different challenges. Consumers face uncertainty due to repair wait times (E4, interview). Additionally, products are often not designed with repair in mind, and information exchange between manufacturers and independent repair shops may be limited. The economic viability depends significantly on labour costs and repair time requirements. Product-as-a-service arrangements partially address these issues, as manufacturers retain ownership and have stronger incentives to design for repairability and collaborate with repair providers.

Lifetime repair and extended warranty models bundle repair services with product purchase. For example, Repeat Headphones sells high-end headphones (€300-400) with lifetime repair for an additional €100. When cables or ear cushioning fail, the company sends replacement parts and recycles returned components. This model works for products where the repair cost remains below the cost of replacement and/or where customers value the product enough to pay for repair assurance.

Repair knowledge platform

Platform (sharing) models are an alternative business model to support repair (Jonker et al., 2022). These platforms can facilitate repair by providing knowledge resources and connecting users with repair information and supplies. They can be independent but might also collaborate with manufacturers.

iFixit exemplifies this (Jonkers et al., 2021), providing over 75,000 free repair guides while generating revenue through sales of repair parts, tools, and accessories. The revenue model combines free educational content with e-commerce sales of repair-related products. By providing repair knowledge, these platforms lower barriers to both self-repair and professional repair services. Although iFixit is independent in its repairability evaluation, it recently started collaboration with companies on spare part delivery (e.g. Fairphone, Microsoft, Samsung).

Business Models Supporting Refurbishment and Remanufacturing

Refurbished and remanufactured products are sold as functionally equivalent to new. Because these business models operate at industrial scale, they require reliable access to used products and cost-effective reconditioning processes.

OEM refurbishment and remanufacturing

OEM refurbishment and remanufacturing leverages manufacturer knowledge of product specifications and access to original components. For example, Bosch Power Tools remanufactures its tools, enabling it to compete with products from low-cost, low-quality producers (Atasu et al., 2021). The previous example of OV-fiets also includes a remanufacturing operation that processes over 1,000 OV-fiets bicycles annually (Roetz Bikes, n.d.).

The revenue model involves selling refurbished products at lower prices than new equivalents while maintaining acceptable margins through reduced material and production costs. Refurbishment becomes economically viable when products retain sufficient residual value and refurbishing costs remain contained. OEMs offering refurbishment are therefore incentivised to optimise product design for efficient reconditioning, reducing processing costs. Refurbishment and remanufacturing can even benefit from automated processes, which may require different design considerations than manual repair (E1, interview). Most companies with refurbishment activities do not address this at a strategic level during design, causing missed margin opportunities on refurbished products.

Third-party refurbishment

Third-party refurbishment serves markets where OEMs are absent. Companies including Forza Refurbished, Leapp, and Remarkt focus on laptop and desktop refurbishment. Coolblue operates an extensive refurbishment programme covering smartphones and other consumer electronics. Quality concerns affect this segment: reports of short lifetimes of refurbished laptops reduces consumer trust of these types of products (E1, interview). Effective refurbishment should provide warranty coverage comparable to new products, requiring proactive replacement of deteriorated components rather than addressing only current failures (E1, interview).

Slowing innovation cycles in mature product categories also support refurbishment because refurbished products remain competitive with new alternatives (E10, interview).

Business Models Supporting Recyclability

Recycling recovers value from materials rather than products. The business case depends on material value, separation costs, and the existence of markets for recovered materials.

Recyclable product models

The business models associated with Design-for-Recycling (DfR) entails selling products designed to maximise recoverability of materials (Atasu et al., 2021). This often involves partnerships with recycling companies to address the challenge that manufacturers often lack recycling expertise while recyclers lack influence over product design.

Economic viability of DfR is challenging without supporting legislation, and depends on recycling costs and material value of recovered materials, which depends on both the value of the virgin material and the purity achieved during recycling. Labour costs add tremendously to recycling costs. In consumer electronics, batteries are removed prior to shredding because of safety and legal requirements, but removing other valuable parts is too expensive with European labour costs (E5, interview). Instead, designs can be optimised for shredding to ensure maximised material separation (page 21).

Automation offers a possible solution to labour costs. Apple explored automation with disassembly lines Liam (2016) and Daisy (2018), that disassemble up to 200 iPhones per hour to recover cobalt, tin, aluminium, and other valuable materials (Atasu et al., 2021). This is possible because Apple's ecosystem (retail presence, trade-in programmes, rapid product cycles) provides reliable access to used devices, and because Apple has enough information on its own products to program the disassembly line. Despite these advantages, the Apple disassembly programme has not moved beyond pilot scale.

Several examples outside consumer electronics: Adidas partnered with Parley for the Oceans to use ocean plastic waste in shoe and apparel production (Atasu et al., 2021). Carpet manufacturer Interface manufactures modular carpet tiles from recyclable materials, which reduces carbon emissions by 75% compared to industry average (Atasu et al., 2021). Notably, Interface started selling modular carpets after their initial circular carpet leasing failed to achieve scale. DSM and Niaga developed fully recyclable carpets using a mono-material (polyester) that simplifies separation and recovery. Auping then partnered with Niaga to develop mono-material mattresses (Auping, n.d.).

Recycling services

Recycling services operate as independent businesses that process end-of-life products to recover materials. Revenue models for recycling services include sales of recovered materials, processing fees charged to product manufacturers, and avoided disposal costs.

Extended Producer Responsibility (EPR) organisations coordinate end-of-life processing. Manufacturers fund these organisations through fees. In the Netherlands, Stichting Open employs a contract-based approach, paying collection points, sorting companies, and processors in return for agreed outputs (E9, interview). This structure supports a functional recycling network. However, the EPR system currently lacks differentiated fees based on product recyclability, providing no design incentive for improved recyclability (E5, interview).

Critical materials recovery represents an emerging business opportunity driven by supply security concerns. The April 2025 disruption in neodymium magnet exports led to several months of supply chain chaos (E11, interview). Such disruptions increase the strategic value of recycling, though the timeline for developing processing capacity often far exceeds the horizon of typical investment cases. The Critical Raw Materials Act creates some regulatory pressure toward design strategies that reduce dependence on critical materials and improve their recoverability.

Selecting the most Viable Business Models

The preceding sections present various options for business models. We now turn to the question of how to select the optimal circular strategy from a business perspective.

Product category

The right circular business model depends on product category and is not easily generalisable. Factors such as product characteristics, user behaviour, and innovation rates affect viability of circular business models. While higher R-strategies such as repair and reuse lead to greater circularity, their suitability must be evaluated within the specific context of the product.

In some cases, lower R-strategies are preferable. For example, users are unlikely to bring products such as disposable vapes (E5, interview) or bike lights (E6, interview) in for repair. In such cases, design for recycling is a more suitable business model. Similarly, when users replace products not due to functional failure but in response to new features in newer models, life extension strategies focused on lengthening functional performance (such as repair) will not effectively delay disposal (E4, interview). For product categories with high innovation rates, design for recyclability is therefore the more appropriate circular strategy (E3, interview).

Regarding selecting a suitable revenue model to the circular business model, the 'revenue model ladder' from Figure 13 can be used.

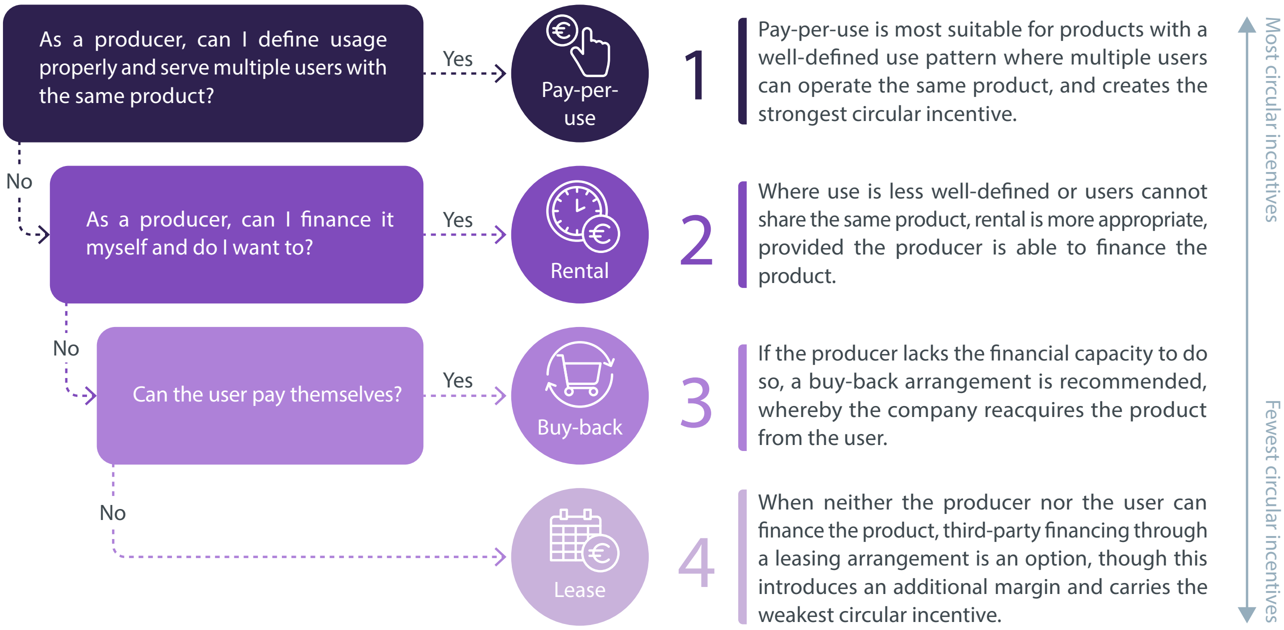


Figure 13 | Circular revenue models (KPMG et al., 2019).

For example, the use of cars is well-defined and multiple users can share the same vehicle, making pay-per-use a suitable model (E17, interview). In the case of a printer, the product cannot be as easily moved between clients, and each office typically requires its own unit. Here, a buy-back arrangement can be considered if the producer is unable to finance the product themselves (E17, interview).

Organisational capabilities

Finding the right business and revenue model depends not just on product category, but also on a realistic assessment of organisational capabilities. Circular business models often require capabilities that a sales-led product organisation does not have. As circular ambitions rise, coordination across design, procurement, service, and logistics becomes more demanding, sometimes prohibitively so. Successful circular business models typically combine multiple revenue models (Jonker et al., 2022). Xerox utilises pay-per-use pricing, maintenance contracts, and buy-back arrangements. Repeat Headphones combines product sales with lifetime repair subscriptions.

Business-to-business implementations are easier than consumer-focused models (E2, interview). This is because economic incentives can be more clearly calculated in a B2B context, while consumers often focus on upfront price rather than cost per use over the whole lifespan of a product. Furthermore, businesses often have more predictable usage patterns, and simpler logistics for product recovery. Agricultural machinery, medical devices, and industrial equipment (such as conveyor belt systems for logistics) continue to advance serviceability, modularity, and standardisation. Companies like Vanderlande maintain sustainability and circularity initiatives in their B2B operations. The hospital equipment sector shows active interest in refurbishment (E3, interview). Generally, products with high investment costs and known, centralised locations are more conducive to circular business models than dispersed, low-value products such as lamps, even in a B2B context.

Nonetheless, organisational structures present a significant hurdle in the adoption of circular business models, also in B2B contexts. As discussed on page 30, budgeting conventions and accounting practices can impede progress. So-called special-purpose vehicles (SPVs) are often required to realise circular transitions, particularly in tender processes where lease or rental constructions complicate suppliers' liquidity and solvency requirements (E17, interview).

05

Barriers to Circular Design Implementation

BARRIERS TO CIRCULAR DESIGN IMPLEMENTATION

Why do so few circular businesses exist, despite available circular design principles and business models? This section examines economic, technical, cultural and behavioural, and institutional and regulatory barriers. We then address the interlocking nature of these barriers, and how they together keep the sector locked into a largely linear model.

Economic & Market Barriers

Economic factors constitute the primary barrier to widespread adoption of circular design in consumer electronics.

No business case for most R-strategies: generally, and for the largest volume of the consumer electronics market, there is limited economic incentive for companies to incorporate circular design principles such as repairability and design for recycling. Although viable revenue models for these strategies exist, the current economic playing field and consumer behaviour collectively favour linear business models.

Labour cost disadvantage: Repair and refurbishment are labour-intensive, particularly if the product is not designed to be easily repaired. There are various solution spaces, including reducing or eliminating taxation on labour, design considerations to keep the time requirements for repair as low as possible, and far-reaching automatisation.

Economic pressure on development: Economic conditions directly affect sustainability efforts. Interviewees noted that the overall economic situation is limiting eco-design projects, even if they are economically viable resource efficiency projects. Interviewees noted that "there is pressure to bring out new products fast, sustainability topics will be skipped." Development teams are "really time pressured" leading to resistance to even following eco-design workshops (E10, interview).

Separation between repair operations and product development teams is a structural barrier to design improvement. When repairs are outsourced to third parties, information about common failure modes and repair difficulties rarely reaches designers. This organisational learning gap prevents iterative improvement in repairability (E3, interview).

Unclear liabilities of repaired products: The distribution of liability for products following repair remains unclear. To mitigate potential legal risks, companies actively discourage independent repair practices. Furthermore, companies generally do not give product reuse strategic priority, as they perceive it as cannibalisation of new product sales.

Compartmentalised business culture leads to misalignment of internal goals. For example, in a case study of professional imaging equipment, Boorsma (2022) identified a disconnect between the remanufacturing and production divisions of the company. As a result, the company only captured a fraction of the potential value that design for remanufacturing could offer. Additionally, the separation of purchasing and maintenance budgets within companies complicates the transition to a service model (E17, interview; see page 30).

Accounting regulations can discourage the implementation of circular revenue models. For example, buy-back arrangements must be directly reflected in accounting records, which can negatively affect revenue figures for that year and thereby discourage companies from adopting them.

Technical Barriers

While most technical issues surrounding circular design are solvable with the current state of knowledge, there are three main technical barriers that require research attention.

Inherent trade-offs: Design principles for different circular strategies can conflict with each other. A clear trade-off exists between material reduction (thinner components) and durability/wear resistance. Other trade-offs are e.g. between performance and sustainability (PFAS for example); safety and sustainability (e.g. flame retardants), and between different impact categories (global warming potential, toxicity) or between societal goals (environmental vs social).

Temporal uncertainty: Products designed today may be recycled in 10+ years, when material compositions of products will likely have changed. For example, recycling Europium from the phosphorous layer in old fluorescent tubes, into a market where fluorescent tubes have been replaced by LED-lights. This temporal uncertainty also affects design methods. Static Design-for-Recycling guidance can become outdated as products, legislation, and recycling technologies change over time.

Low CRM-volumes: CRM recovery faces additional technical barriers specific to the small quantities and dispersed distribution of critical materials in electronics. Most critical materials are present as trace elements, thin coatings, or small components embedded within larger assemblies. Recovering them requires either selective pre-processing (manual or automated removal of specific components before shredding) or specialised post-shredding separation technologies. Neither pathway is economically viable at current material prices and collection volumes (E9, E13, interviews). Rotor design choices, such as the presence of end caps covering Rare-earth permanent magnets, can determine whether hydrogen processing can successfully liberate magnet powder for recycling (E13, interview). Such design details are rarely considered during product development.

Cultural & Behavioural Barriers

Despite being often overlooked in favour of technical and economic barriers, cultural and behavioural barriers nevertheless prove to be tenacious.

Attitude-action gap: Consumers often express strong interest in various forms of product longevity and sustainable consumption but then do not translate these values into behaviour. Fogg's behaviour model (Fogg et al., 2009) describes in generic terms what is needed to achieve a certain behaviour:

- Motivation (wanting to do it)
- Ability (knowing how to do it)
- Trigger (something pushing you to do it now)

Ackermann et al., (2018) describes various factors related to motivation, ability and triggers when it comes to product care and maintenance. One salient example is the lack of immediate urgency. A product that worked well yesterday continues working acceptably today. Often there is no clear moment when maintenance becomes obviously necessary, so there is a lack of clear trigger. The washing machine does not suddenly announce "descale me now or I'll break in 3 months." This can be solved through product design, for example by built-in self-diagnosis tools (page 30).

Skill erosion: many technical skills across the product manufacturing supply chain are being lost in Western-Europe, including the skills needed to repair products, and design repairable products. Consumers lack not just repair skills but fundamental conceptual understanding of how devices work. This affects the feasibility of any self-repair strategy.

Convenience priority: "It's not about engineering alone - it's also easier to buy a new one than repair. You can buy before 11pm, new one arrives in the morning" (E2, interview). Replacement frequently offers greater certainty than alternatives such as repair, which can be time-consuming and may yield unsuccessful results (E4, interview).

Holding on to end-of-life electronics: effective recycling relies on consumers correctly and timely disposing of their end-of-life electronics. Smartphones, for example, are often retained by consumers when no longer actively used rather than being returned for recycling.

Premature product replacement: Consumers disposing of products before reaching their functional end-of-life negates design for durability efforts. Magnier and Mugge (2022), for example, found that consumers often replace televisions because they are attracted by the new features rather than a loss of function in the existing product. Furthermore, consumer expectations regarding product lifespan tend to influence its actual lifespan, suggesting that shorter life expectations make consumers feel more comfortable with premature replacements (E4, interview).

Rebound effects can negate the benefits of any circular strategy. Consumers may, for example, justify unsustainable behaviour based on a previous circular purchase decision. This makes the actual cumulative effect of circular design efforts difficult to predict.

Institutional & Regulatory Barriers

Political prioritisation significantly affects industry engagement with circular design. Following changes in Dutch government priorities, companies rapidly deprioritised sustainability and circularity initiatives. Right-to-repair legislation had prompted serious industry engagement with repairability criteria, but this momentum dissipated when political signals shifted (E3 interview). Industry action depends heavily on perceived regulatory direction, and that regulatory uncertainty or reversal can quickly undo progress. Furthermore, companies also often use broad references to 'regulatory barriers' as an excuse to not make meaningful improvements. As one researcher put it: "companies put a lot of lobbying effort to make these things [regulatory barriers] far more prominent than they might be in practice. They basically use it as an excuse to block progress" (E1, interview).

With the above caveats, this section reviews institutional and regulatory barriers. EU member states have significant discretion to interpret EU directives. In practice, competitive pressures between member states and industry lobbying tend to produce convergence toward minimum standards rather than leadership toward strict implementation. Consequently, exercising the theoretical flexibility for ambitious national action often proves challenging. The French Repairability Index is a notable counterexample, where national regulation strongly influenced EU regulation.

Below are the most salient institutional and regulatory barriers.

EPR fee structure: Throughout the EU, companies pay uniform fees to organisations such as Stichting Open regardless of product recyclability, providing no incentive for improved design (E5, interview).

Enforcement asymmetry: European manufacturers face regulations while some forms of import, particularly consumer imports through webshops that directly import from e.g., Asia, are not held to the same standards. Similarly, CE marking can be obtained from notified bodies outside the EU without meaningful verification. This puts companies that adhere to strict regulations at an upfront-cost disadvantage.

The Limits of Self-Assessment: The French Repairability Index, which serves as a model for broader EU implementation, requires manufacturers to evaluate their own products against defined criteria. Research indicates significant problems with this approach. The assessment methodology permits substantial interpretive flexibility: the same product can receive different scores depending on whether criteria are interpreted strictly or loosely (Dangal et al., 2025). Irrespective of interpretation, products that are effectively unrepairable in practice can achieve high repairability scores (E3, interview), partly due to a lack of limiting scores (E1, interview; Dangal et al., 2025). When high scores can be achieved without substantive design changes, the regulatory mechanism fails to create incentives for improvement. Manufacturers optimise for scores rather than for actual repairability. Third-party verification or standardised testing protocols could address this weakness but add costs and complexity that face industry resistance.

Lack of communication to consumers: consumers are not always aware of warranty periods (E4, interview). As a result, warranty rights are often not exercised, thereby losing their intended effect. For example, in the Netherlands the legal minimum warranty period is not two years (as mandated by the EU), but rather as long as the product can be reasonably expected to last. However, this is mostly unknown, and it is almost impossible for consumers to actually obtain warranty beyond the better-known two-year period.

The Systemic Nature of Barriers

The barriers previously described do not operate in isolation. They interact and reinforce each other, creating systemic lock-in that is more resistant to change than any individual barrier would be on its own. Economic pressures drive manufacturers toward cost reduction and miniaturisation, which produces products that are technically difficult to repair. Low product prices, in turn, make professional repair economically unattractive relative to replacement, removing the market signal that would otherwise incentivise design for repairability. Consumers adapt their expectations and behaviour to this reality: replacement becomes the default response to product failure, and repair skills erode across generations (E2, interview). Institutional structures then consolidate this pattern. Flat-rate EPR fees provide no financial incentive for better design (E5, interview), and enforcement asymmetries between European manufacturers and non-compliant imports further tilt the playing field toward disposable products. As one researcher summarised: “All barriers interact and stem from fundamental economic system structure” (E5, interview).

An example of a systemic intervention would be extending warranty periods, which creates a financial incentive for manufacturers to improve durability and repairability, because repair costs fall on them rather than on consumers. This single intervention affects economic incentives, prompts technical improvements in product design, and may gradually shift consumer expectations about product lifetimes. Conversely, a policy that addresses only one barrier category, such as requiring spare parts availability without addressing the labour cost of repair or the lack of consumer repair skills, is more likely to fail. Effective interventions should either be implemented as policy packages or aimed at leverage points where a single change affects multiple domains.

06

Quantitative analysis

CHAPTER 06

QUANTITATIVE ANALYSIS

This chapter quantifies how circular design strategies reduce demand for critical raw materials. For three consumer product categories (washing machines, heat pumps, and vacuum cleaners), we calculate the required annual inflow of critical materials under baseline conditions and compare it with scenarios where the design interventions from Chapter 3 are implemented at market scale. The analysis covers lifetime extension through durability and repair, magnet optimisation through motor design, material substitution, and recycling. These products are selected based on three key criteria:

1. **Representative design intervention opportunities:** These products exemplify different circular design principles across the product life cycle, such as lifetime extension (washing machines), refurbishment potential (heat pumps), and material intensity reduction through motor optimisation (vacuum cleaners).

2. **Critical raw material content:** Each product contains relevant quantities of strategic and/or critical raw materials.

3. **Data availability and quality:** All three products have been the subject of previous research reports. The MFAs are based on CMR (2026) and Copper8 & Delft University of Technology (2026a, 2026b).

The results illustrate how design changes of products can – if they were to be applied to the whole market – significantly influence the aggregate material intensity of that sector of the economy. Reducing material intensity while retaining functionality and, ultimately, quality of life, is one of the core objectives of circular design.

The material flow analyses (MFAs) presented in this chapter would be complemented by LCA. Where MFA quantifies how much material is needed, LCA can additionally assess whether the associated environmental impacts (energy, emissions, toxicity) are also reduced. Combining both methods provides a more complete basis for evaluating circular design strategies. This type of mixed-method analysis is outside the scope of the present report.

Washing machines
increased lifespan

Current washing machines have an average lifespan of 12 years (Boyano Larriba et al., 2017), while high-end models can last over 20 years. Manufacturers have developed prototypes capable of lasting 50 years (E2, interview). We model the design of more robust washing machines (pages 12-13) that are more often repaired (pages 14-17) (Tecchio et al., 2019). This increases the average lifetime of washing machines to 24 years. By 2037, when all 12-year-lasting washing machines will have reached their end of life, average lifespans will have effectively doubled.

Additionally, we model the reduction of permanent magnet demand. Motor design improvements (such as arc-shaped and lens magnets, optimised interplay of electrical steel, copper, and magnet material) can reduce NdFeB magnet demand by approximately 20% per motor (E10, interview). Combined with adoption of synchronous reluctance motors for suitable applications, the average demand for NdFeB magnets is modelled to decrease by 50% by 2035. Through increased recycling an average of 25% of virgin materials can be saved (E16, interview). See Figure 14 for an overview of scenario parameters.

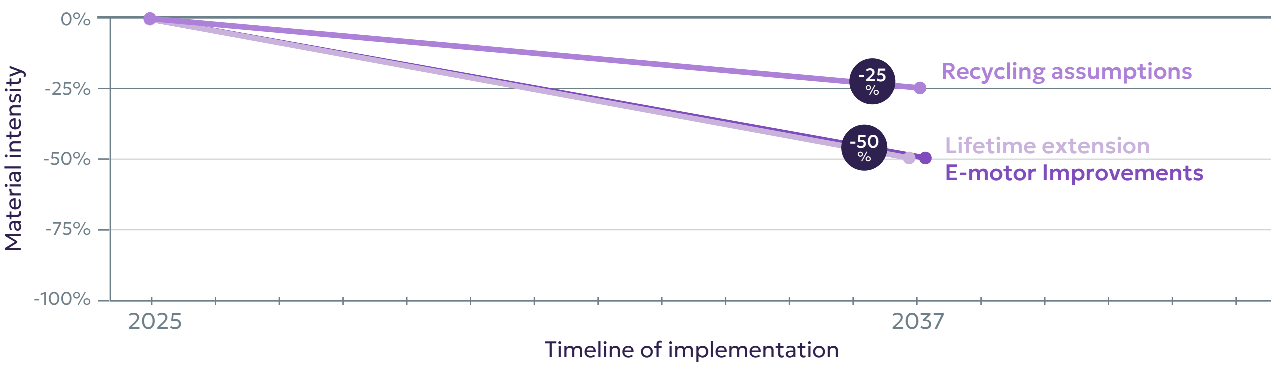


Figure 14 | Washing machine scenario parameters

Figure 15 shows the required inflow of (critical raw) materials to maintain the marginally increasing Dutch washing machine stock under these scenarios in comparison to the baseline. Components containing critical raw materials generally last very long (e.g., motors), so no additional demand from spare parts is modelled. As a result, the inflow of materials decreases by more than half by 2038, the cumulative inflow required in the period from 2025 to 2050 is consequently also significantly reduced. The bar chart ranks the measures from left to right by their overall impact on material demand, with each measure's contribution stacked on top of the previous ones.

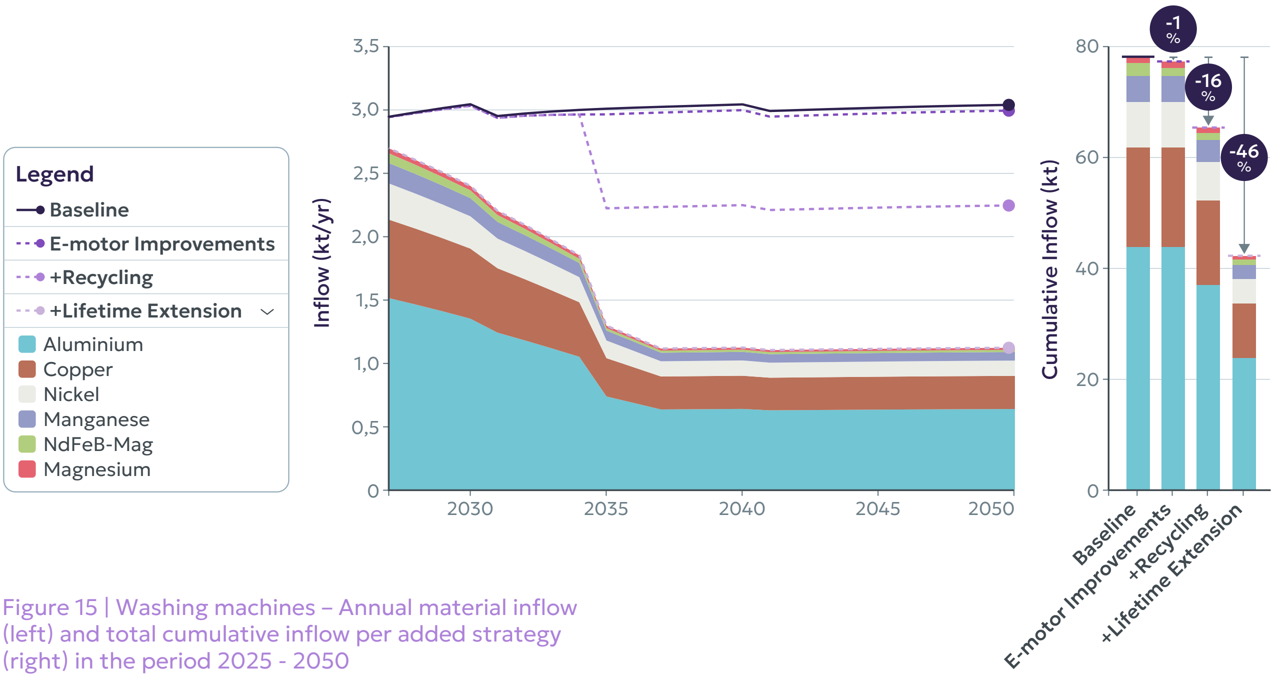


Figure 15 | Washing machines – Annual material inflow (left) and total cumulative inflow per added strategy (right) in the period 2025 - 2050

Heat pumps
refurbished, and more durable

Heat pumps have high potential to be refurbished (E13, interview). This scenario assumes implementation of the design requirements for refurbishment (page 18), resulting in an increase from 20% refurbished heat pumps in 2026, to 40% in 2030. Distinct from refurbishment, modular design and Design-for-Repairability (pages 14-16) can extend the average lifespan of heat pumps from 17 years to 27 years. This leads to a 37% material reduction by 2035. Current heat pumps are mainly equipped with copper boiler vats. Assuming a 3-year design cycle, we model a substantial potential reduction in copper demand from 2029 onward by replacing copper boiler vats with steel alternatives. See Figure 16 for an overview of scenario parameters.

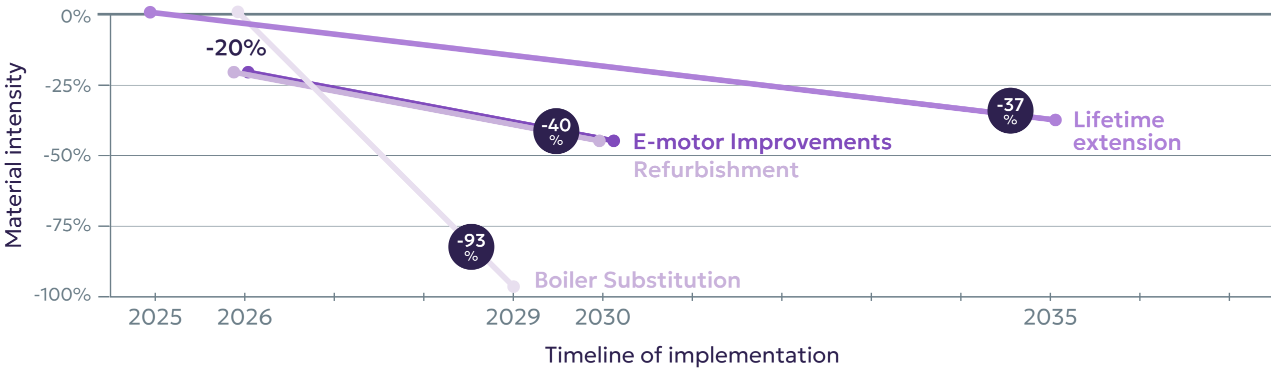


Figure 16 | Heat pump scenario parameters

Figure 17 shows the resulting annual and cumulative inflow of (critical raw) materials for the projected heat pump stock when all described strategies are combined. The individual measures are stacked in the order of their respective effect on the material demand, as shown in the bar chart. In comparison to the baseline (hatched) the area chart shows the substantial reduction in annual material demand through the introduced measures.

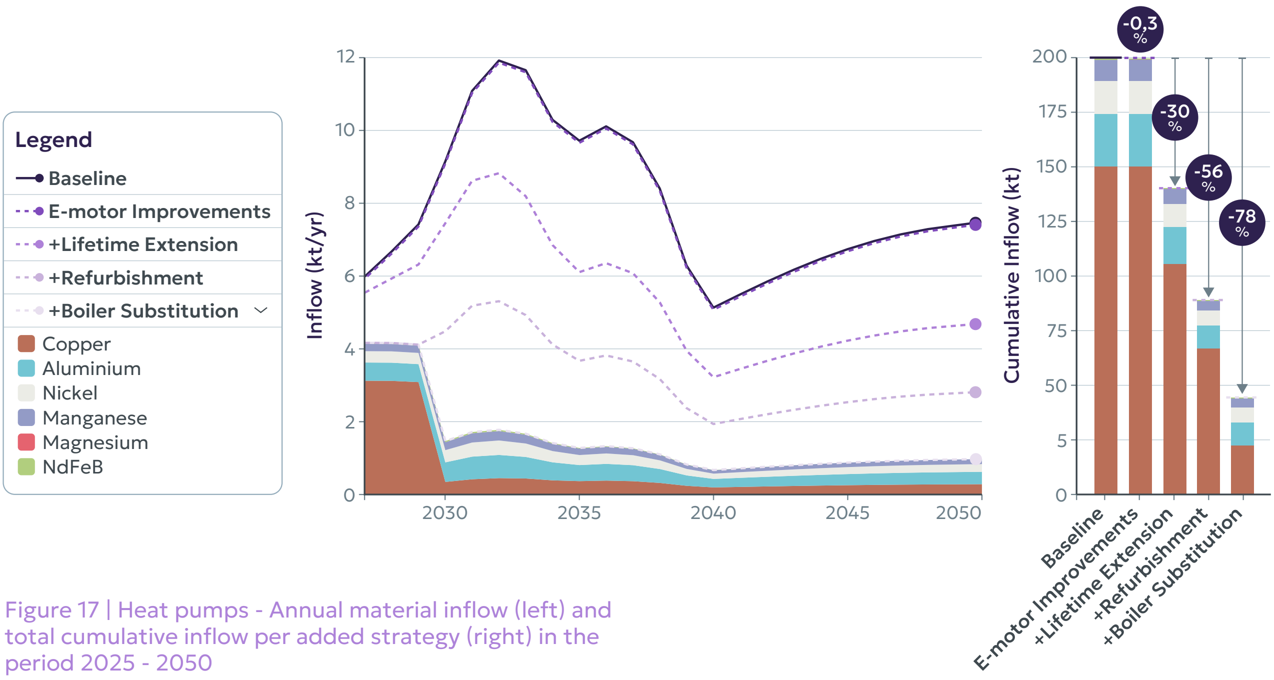


Figure 17 | Heat pumps - Annual material inflow (left) and total cumulative inflow per added strategy (right) in the period 2025 - 2050

Vacuum cleaners

reduced material intensity, recycling and lifetime optimisation

Regarding vacuum cleaners, tripling the lifetime is achievable (E2, interview) through applying modular design and Design-for-Repairability from pages 14-17. The model takes a conservative approach and assumes an average doubling in lifetime from the current 6 years to 12 years over the next three years. This results in a 50% reduction in magnet material used in vacuum cleaners by 2029. See Figure 18 for an overview of scenario parameters.

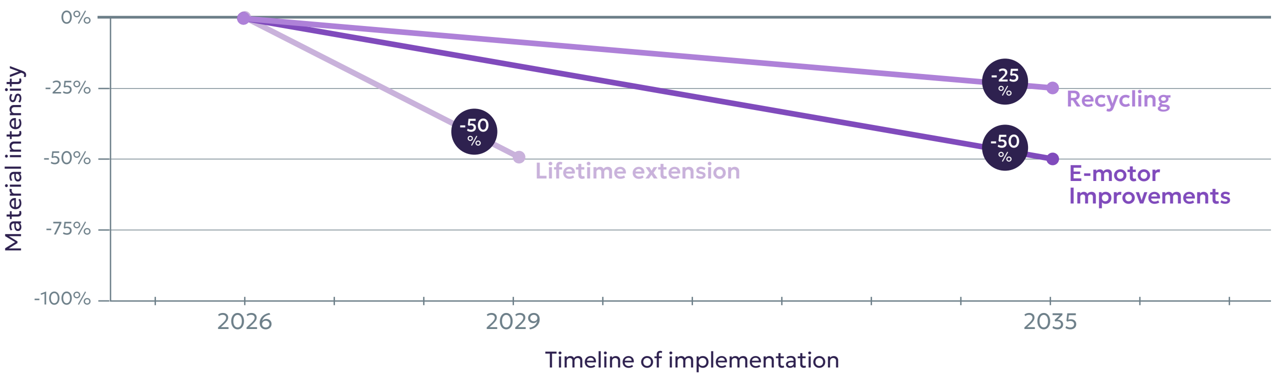


Figure 18 | Vacuum cleaner scenario parameters

Figure 19 shows the required inflow of magnet material for the projected vacuum cleaner stock in the Netherlands. Beyond lifetime extension, design interventions such as magnet optimisation can further reduce material demand. When combined with lifetime extension and recycling, these strategies produce a significantly greater cumulative reduction.

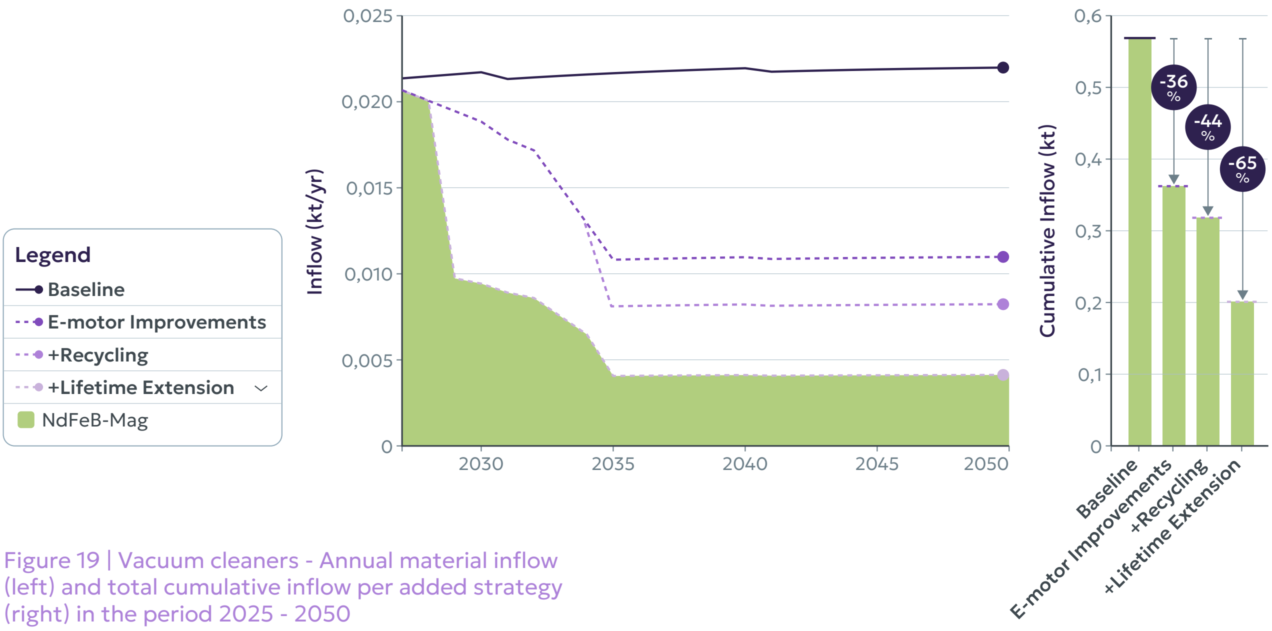


Figure 19 | Vacuum cleaners - Annual material inflow (left) and total cumulative inflow per added strategy (right) in the period 2025 - 2050

07

Conclusions and recommendations

The material flow analyses in Chapter 6 show that lifetime extension alone can halve the annual inflow of critical raw materials for product categories like washing machines and vacuum cleaners.

Design-for-Recycling guidance does not yet reflect how products are actually recycled. Most published methods focus on manual disassembly, while large-scale WEEE recycling in Western Europe relies on mechanical shredding (page 21). Few product designers have ever observed their products undergoing shredding. Design decisions that seem small during development, such as whether screw connections include fracture lines or whether adhesives are used, can determine whether materials separate cleanly or end up mixed. The same holds for NdFeB permanent magnets. Rotor end-cap design and magnet coating choices similarly determine whether innovative recycling techniques such as hydrogen decrepitation can recover NdFeB powder (page 19). Effective Design-for-Recycling requires starting from actual end-of-life processing conditions rather than idealised disassembly sequences.

The knowledge required for enabling circular consumer electronics exists, including established design methods, and business model frameworks. Products can be made durable, repairable, and recoverable at end-of-life. What prevents this from happening at scale is a set of interlocking economic, behavioural, and institutional conditions rather than a lack of technical understanding. Regulation is needed to change that. Today, the design strategies that deliver the largest reductions in critical raw material demand are precisely those that are only weakly supported by current policy.

Conclusions

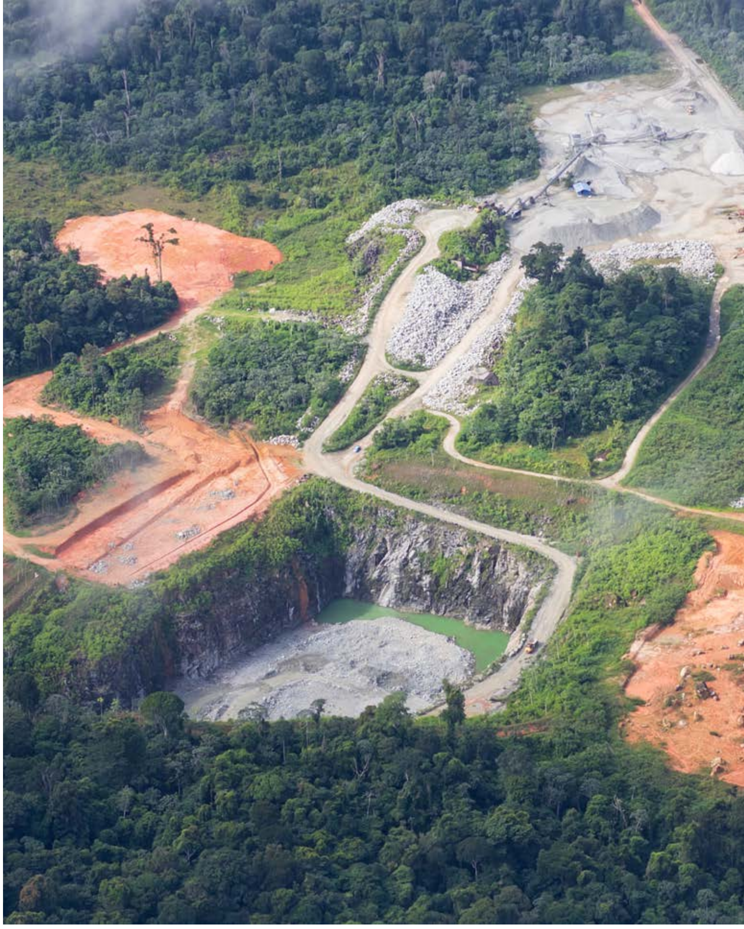
Product architecture is the central determinant of circular potential. A clear product architecture makes critical components accessible in a reasonable amount of time and effort, and supports repair, refurbishment, reuse, and longer lifetimes. Tools such as disassembly mapping make product architecture explicit and identify where design interventions are most effective. A comparison of two functionally identical vacuum cleaners, for example, showed motor disassembly times differing by a factor of six, depending entirely on component positioning and fastener choice (page 24). The prioritisation among circular strategies depends on product-specific considerations. In most cases, repair and refurbishment should come before recycling. Reuse without improved durability is constrained by the maximum functional lifespan of devices in circulation (page 12). Current recycling still loses a lot of value. Plastics are often incinerated, alloys are downgraded, and critical materials are rarely recovered (page 19).

The economics of circular strategies vary fundamentally by product value. Professional repair is currently viable mainly for high-value products. Below approximately €100 in product value, labour costs for professional repair typically exceed the

product's resale value, making repair economically unviable regardless of product design (page 14). Hence, repair-oriented interventions mainly apply to higher-value products. For lower-value products, strategies like design for recycling or material substitution are often the only options that can scale. More broadly, the current economic system favours linear models. While circular business models exist, from product-as-a-service to OEM refurbishment, they typically remain confined to niche markets or B2B contexts where total-cost-of-ownership reasoning is more common (pages 32-33). Without regulatory interventions that create a level playing field, circular designs will be at a structural disadvantage.

Material substitution is the fastest way to reduce CRM demand. Substitution can reduce CRM demand as soon as a redesigned product enters the market. The other strategies take longer, because they depend on replacement cycles, end-of-life infrastructure, or return logistics. Optimised motor design can reduce neodymium content by up to 20% per motor, and magnet-free motor types are viable in many applications. For batteries, shifting from NMC to LFP cathodes eliminates cobalt and nickel, and sodium-ion chemistries eliminate lithium entirely for applications where lower energy density is acceptable (pages 23-24). Substitution is highly application-dependent and can affect performance. Product architectures that accept multiple component technologies keep options open as supply conditions change.

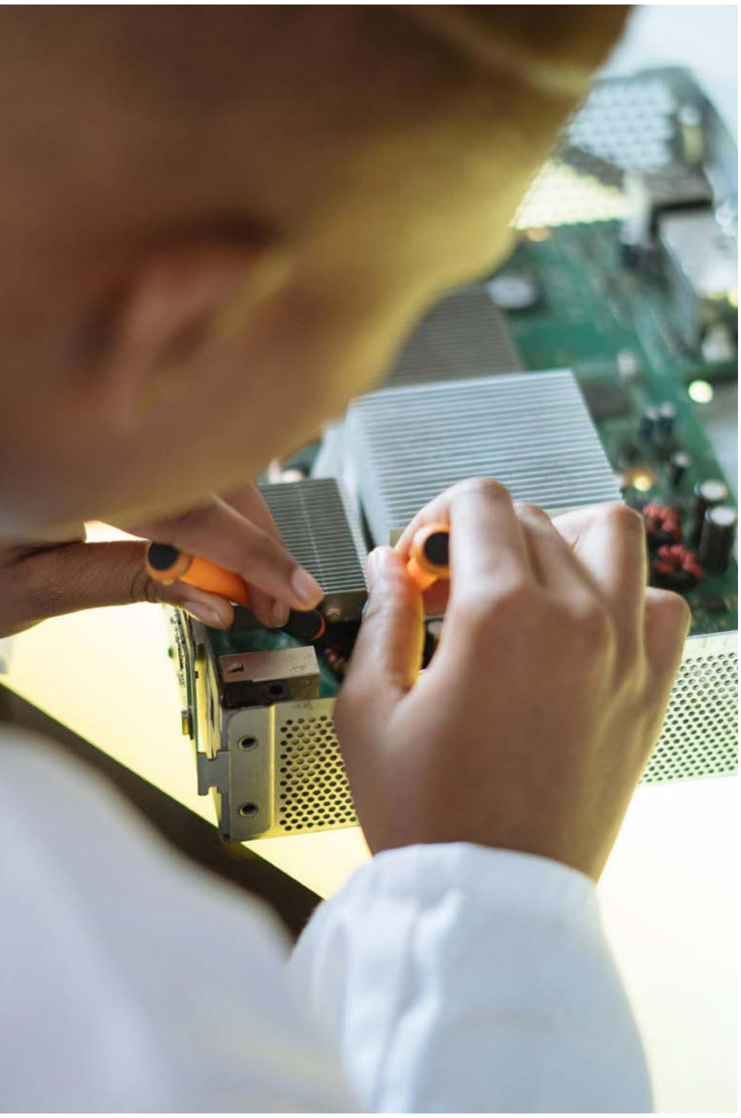
Circular design can be treated as a supply-security measure to improve strategic autonomy. Circular design strategies address supply risk through multiple pathways: lifetime extension reduces annual material demand (Chapter 6 shows reductions of 37–50% for the products analysed), component-level optimisation reduces CRM content per product, and improved recycling infrastructure can recover materials domestically. The April 2025 halt in neodymium magnet exports caused several months of supply chain disruption across the automotive and electronics sectors, showing how quickly concentrated supply chains can be disrupted for political or strategic reasons. Scaling CRM recovery capabilities requires infrastructure investment in collection sorting, processing capacity, and data systems to track material composition through the value chain. Because the timelines for building this infrastructure far exceed typical private investment horizons, there is a role for patient capital and public investment. In the example of NdFeB magnets, the estimated infrastructure investment of €150 million (E9, interview) is modest relative to the strategic value of reduced import dependence.



For connected devices, software obsolescence is as significant a driver of replacement as physical failure. The discontinuation of Windows 10 left 500 million devices with fully functional hardware facing security risks and software incompatibility. Sonos speakers and Neato vacuum cleaners lost core functionality when manufacturers ended software support. EU regulations now mandate minimum security update support periods of five years for certain product categories, but five years is inadequate for products whose hardware routinely outlasts this period (page 13). One alternative is to reduce dependence on cloud services and frequent updates. This goes against current trends toward more connected products.

Consumer behaviour determines whether circular design achieves its intended effect. The scale of untapped potential is large. Dutch households hold an estimated 230 thousand tons of working but unused electronics, representing 15.8% of total household stock, while broken products account for only 2.5%. Even where second-hand markets are active, reuse displaces fewer new products than commonly assumed (page 12). The challenge is not primarily that products break. Functional products are replaced or set aside, because of new features rather than loss of function (page 36). Warranty rights, including the Dutch legal guarantee that extends the commonly known two-year period to the reasonable expected product lifetime, are largely unknown and therefore unexercised (pages 36-37).

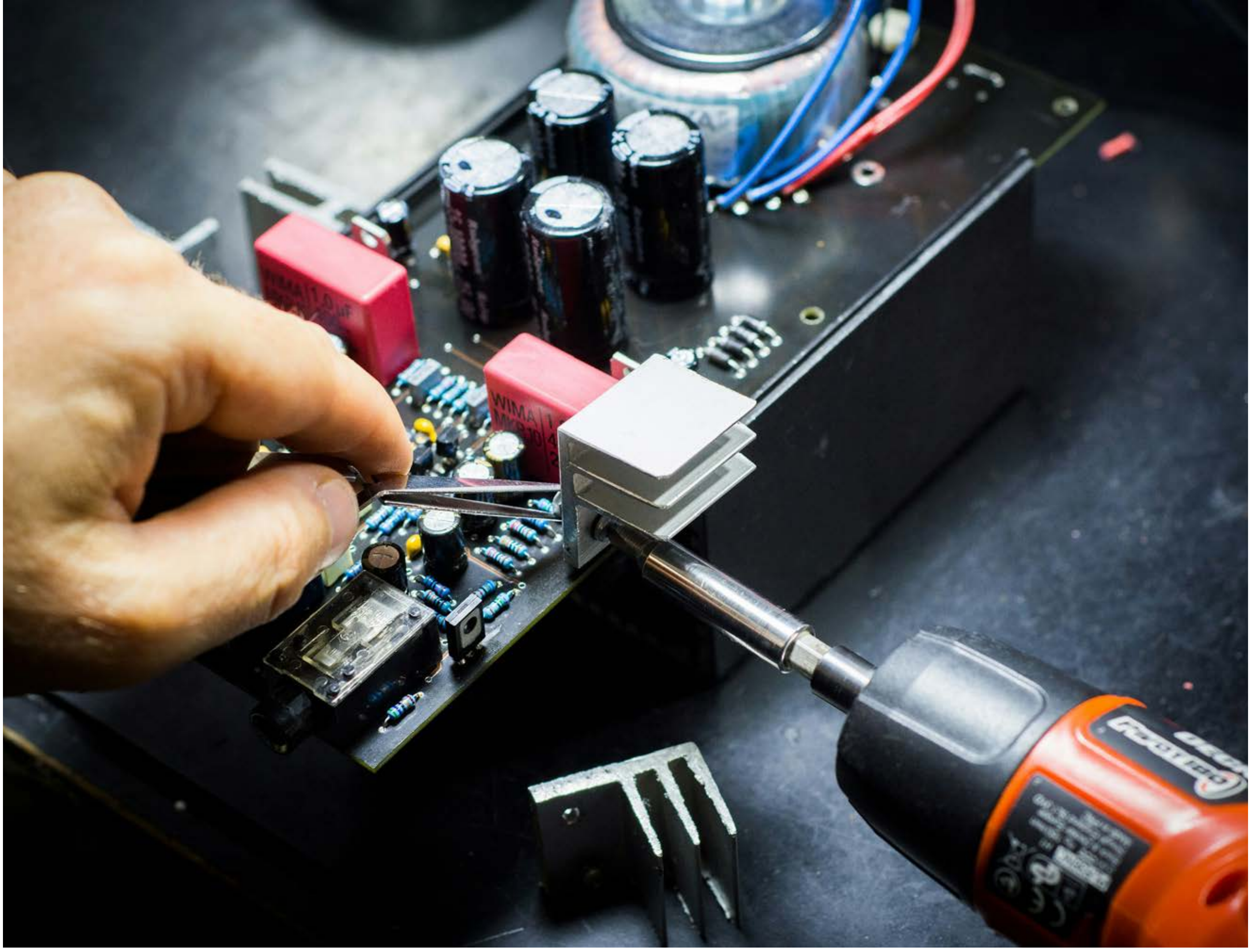
Product design can influence these patterns. Products that appear sturdy through material choice and form factor lead to longer lifetime expectations, independent of actual technical durability (page 13). Products that communicate their status through diagnostic indicators increase the likelihood of repair by providing a concrete trigger for action. Designing for specific user behaviour, including making disposal information visible on the product itself, can improve collection rates for end-of-life recycling.



Current regulation sets the right direction, but it is not enough to shift the market. The ESPR, R2RD, ECGT, and WEEE directive collectively set the policy direction toward circular design, and interviewees characterise them as a step in the right direction. Regulations can be effective even when imperfect: energy labelling significantly improved appliance efficiency despite known loopholes (Section 2.5). The gap lies in implementation and enforcement. Self-assessment schemes are vulnerable to favourable interpretation. For example, products that are effectively unrepairable can still achieve high repairability scores (page 17). Enforcement is uneven, and direct-to-consumer platforms importing from outside the EU face almost no scrutiny with respect to product quality (Section 2.5). Industry engagement tends to move slowly toward circularity when regulation pushes in that direction, but rapidly abandons circular initiatives when political signals shift (pages 36-37).

The barriers to circular design reinforce each other. Economic pressures drive cost reduction and miniaturisation, producing products that are technically difficult to repair. Low product prices make professional repair unattractive relative to replacement, removing any incentives for design for repairability. Consumers adapt to this reality, and repair skills erode across generations (page 37). Organisational structures often make this harder. Separated budgets block total-cost-of-ownership decisions, and buy-back arrangements can have unfortunate accounting effects. In addition, failure-mode data often never reaches design teams (pages 30 and 35). Flat-rate EPR fees provide no financial incentive for better design. Interventions should target leverage points where one change affects several barriers, rather than addressing barriers in isolation.

B2B markets offer the best near-term conditions for scaling circular strategies. Total-cost-of-ownership reasoning is standard in B2B procurement, usage patterns are more predictable, and logistics for product recovery are simpler than in consumer markets. Sectors such as agricultural machinery, industrial equipment, and professional imaging already practice serviceability, modularity, and refurbishment at a meaningful scale (page 33). B2B is a good test bed for circular product design and business models, because the behavioural changes required for B2C is less of a barrier.



Recommendations

Regulations to create a level playing field

- Longer mandatory warranty periods are a central policy lever for incentivising durable design. When manufacturers bear financial responsibility for product failures over extended periods, the economic calculus shifts toward investing in component quality and repairability. A proposed warranty period of 12–15 years for washing machines would exceed the current average lifespan while remaining achievable by best-in-class manufacturers. Extended warranty periods can shift incentives across the system. They make durability (page 35) and repairability (pages 35-36) financially attractive for manufacturers, and they can also shift consumer expectations about product lifetimes (page 36).
- Minimum software and security update support periods should match expected hardware lifespans for connected products. The current five-year minimum is inadequate for product categories where hardware routinely outlasts this period, such as laptops, smart home appliances, and high-end smartphones (page 13). Where extended software support is impractical, products should be designed to remain functional without cloud connectivity or ongoing software updates.
- Repairability scoring systems should incorporate limiting scores that prevent products with fundamental repairability deficits from achieving high overall scores. Current systems allow products that cannot be disassembled in practice to score well on information provision and spare parts availability alone (page 17). Third-party verification or standardised testing protocols would address the weaknesses of manufacturer self-assessment.
- Repair labour should be exempt from taxation to offset high labour costs that currently make professional repair uneconomic for most product categories.
- Producer Responsibility Organisations should differentiate fees based on product recyclability (eco-modulation), creating a direct financial incentive for improved design. This is analogous to the existing differentiation in packaging waste fees (Directive 2018/851, Article 8a(4)(b)).
- Components containing critical raw materials (motors, PCBs, permanent magnets) should be treated analogously to batteries in end-of-life regulation: mandatory removal prior to shredding, either manually or through automated processes achieving equivalent separation quality. Product design changes are needed to make such components accessible in an economically feasible manner.

- Certification cycles that slow the adoption of circular designs should be streamlined. The Right-to-Repair regulation's exemption from new CE-marking when replacing a broken part with an identical or technically equivalent part is a positive precedent. This should be extended to other certification contexts where circular interventions do not alter product safety or performance characteristics.
- Circularity labelling should progress from voluntary information provision toward mandatory minimum performance thresholds, comparable to the approach used in energy efficiency labelling. Labelling is most effective when it enforces a minimum standard and is routinely reviewed and updated with stricter standards (page 9).
- Consistent enforcement of regulations for both EU and non-EU manufacturers is essential. Direct-to-consumer platforms importing from outside the EU currently face almost no scrutiny with respect to product quality, putting compliant EU manufacturers at a cost disadvantage (page 9).

Design and research

- Future design guidance should start from product architecture and treat circular strategies together, not as separate checklists. Tools such as disassembly mapping and Life Cycle Assessment (pages 24-27) help, but designers still lack one method for handling trade-offs between durability, repairability, and recyclability in a single design process.
- Design-for-Recycling guidance should be updated to reflect actual recycling practice. Most existing methods focus on manual disassembly, while large-scale WEEE recycling relies on shredding (page 21). Product designers should observe their products undergoing shredding to understand real end-of-life processing conditions and identify where design changes can improve material liberation.
- Repair and refurbishment feedback should be built into product development processes. When repair operations are outsourced, failure mode data and repair difficulty assessments often do not reach design teams. That blocks iterative improvement (page 35). Companies should establish formal feedback loops between service operations and product development, with repairability formally specified as a design criterion with associated key performance indicators.
- Substitution pathways for critical raw materials should be systematically assessed per product category. Design guides should include substitution as an explicit strategy alongside the existing circular strategies of durability, repair, refurbishment, and recycling.

Critical raw materials recovery

- CRM recovery infrastructure represents an investment opportunity aligned with EU strategic autonomy objectives. European magnet recycling startups are operational at pilot scale, and the technical capability to produce N40–N42 grade magnets from end-of-life feedstock exists (E10, E14, interviews). Scaling requires investment in collection sorting, processing capacity (both short-loop and long-loop recycling), and data infrastructure to track material composition through the value chain. The estimated infrastructure investment of €150 million (E9, interview) is modest relative to the strategic value of reduced import dependence.

Consumer engagement and market development:

- Consumer awareness of existing warranty rights and repair options should be actively promoted. In the Netherlands, the legal guarantee extends beyond the commonly known two-year EU minimum to the reasonable expected product lifetime, but this right is rarely exercised because consumers are unaware of it (pages 36-37). Making this information visible at point of sale and on the product itself would strengthen the demand-side signal for durable design.
- Mobilising the hibernating stock of unused electronics should be a policy priority. Targeted collection campaigns, simplified return logistics, and financial incentives for returning end-of-life devices would increase the volume of material available for refurbishment and recycling.
- B2B markets offer the most immediate pathway for testing and scaling circular strategies. Sectors with high-value, centralised equipment, such as medical devices, industrial machinery, and professional imaging, are particularly promising because total-cost-of-ownership reasoning is standard and product recovery logistics are simpler (page 33).

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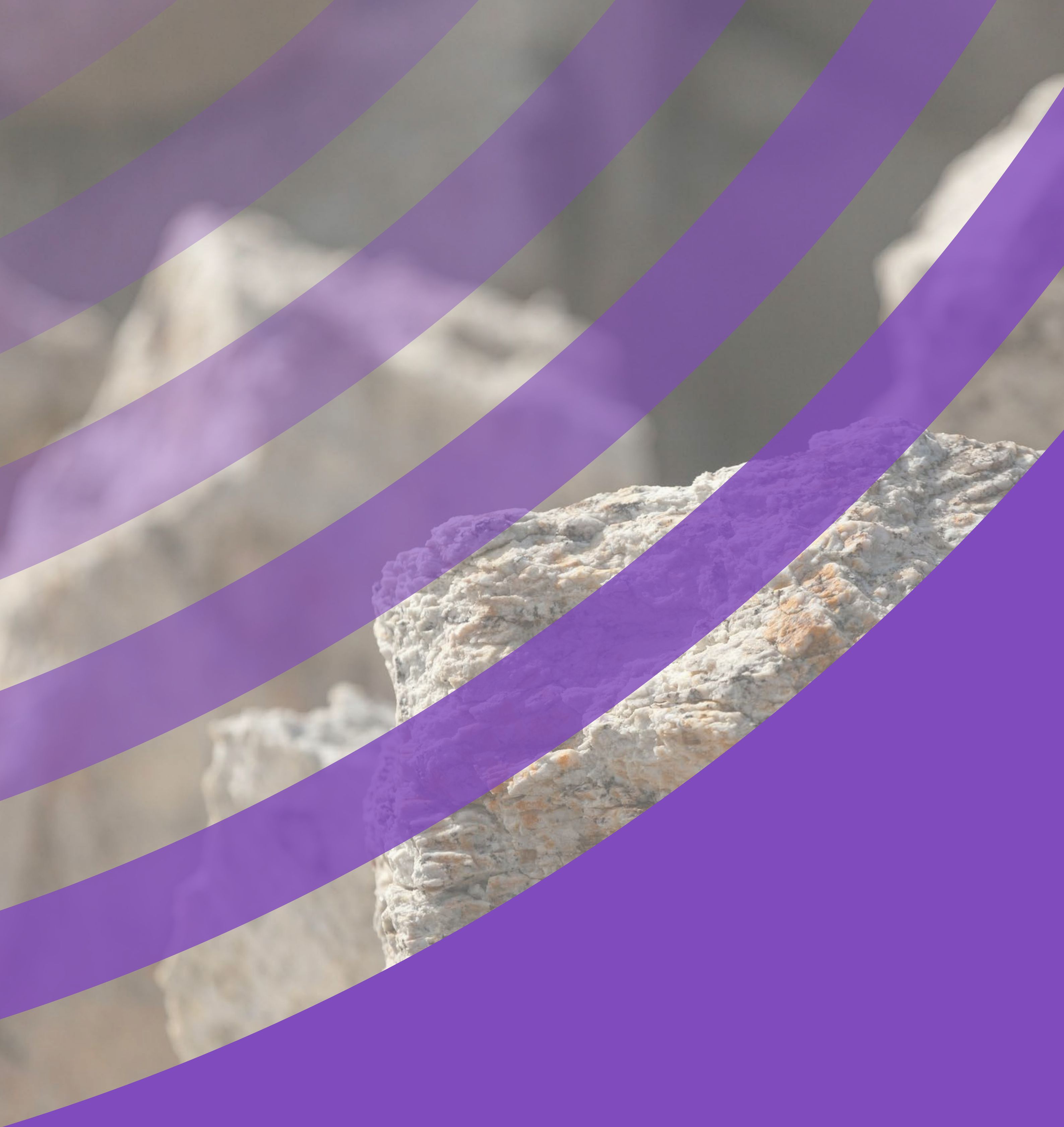
List of Interviewees

Denotation		Description	Date
E1	Expert 1	Researcher in product lifetime extension and circular economy	10/2025
E2	Expert 2	Researcher in design for repair and circular economy	10/2025
E3	Expert 3	Researcher in design for circular economy	12/2025
E4	Expert 4	Researcher in design for sustainable behaviour	12/2025
E5	Expert 5	Researcher in design for recyclability	10/2025
E6	Expert 6	Researcher in circular economy and consumer electronics	12/2025
E7	Expert 7	Researcher in photovoltaic technologies	10/2025
E8	Expert 8	Researcher in photovoltaic technologies	10/2025
E9	Expert 9	Recycler	12/2025
E10	Expert 10	Ecodesign for electric motors and inverters	11/2025
E11	Expert 11	Producer neodymium magnets and magnetic assemblies	10/2025
E12	Expert 12	Product developer in a commercial chain that also sells various consumer electronics	10/2025
E13	Expert 13	Developer and producer of pumps	10/2025
E14	Expert 14	NdFeB manufacturer	11/2025
E15	Expert 15	Researcher in electrochemical energy storage	10/2025
E16	Expert 16	Pump manufacturer	1/2026
E17	Expert 17	Founder of a consultancy specialising in the transition to the circular economy	2/2026

Table 2 | List of consulted experts



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info@c4mr.org www.c4mr.org