Materials, Margins, and Mandates:

The Cradle to Cradle Case for European Electronic Consumer Goods

CRADLE TO CRADLE ELECTRONICS INITIATIVE

CRADLE TO CRADLE NGO

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CRADLE TO CRADLE NGO

Cradle to Cradle NGO is an independent nonprofit founded in 2012 that brings the Cradle to Cradle approach into practice — through education, policy engagement, and transformation projects such as the C2C LAB and Labor Tempelhof. Its large network spans business and municipalities, science, politics and civil society, and each year convenes the C2C Congress, the world's largest platform for the C2C community.

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CRADLE TO CRADLE ELECTRONICS INITIATIVE

The Cradle to Cradle Electronics Initiative (C2CEI) was launched by the nonprofit organizations **Cradle to Cradle NGO, Bertelsmann Stiftung** and **Röchling Stiftung.** It is designed to run over three years with the goal of making Cradle to Cradle the design standard for electronic consumer goods. Under its roof, numerous companies, researchers and civil society run hands-on pilot projects and studies that turn circularity from principle into practice — this joint study with BCG being one example.

1. Setting the scene: Circularity is a strategic necessity

Circularity has always been more than a sustainability agenda. It is a response to a limitation in traditional linear production models: an industrial system built to consume resources once and discard them. Today, circularity has shifted even more to a strategic business imperative for the EU. Beyond reducing emissions by around 22%, it strengthens supply chain resilience, creates new value pools and reduces dependence on imported raw materials.[1] This is becoming increasingly important as global demand for critical materials is expected to outpace supply by 2040; while the EU remains heavily reliant on a small number of supplier countries.[2]

At the same time, circularity is about protecting both human health and the environment. Rising resource demand is increasing pressure on finite supplies and environmental systems, with several widely cited assessments indicating that multiple planetary boundaries have been exceeded.[3] The human cost of the linear economy is equally tangible: hazardous materials in electronics — heavy metals, brominated flame retardants, PFAS — drive measurable health damage. PFAS-related health costs in the European Union are estimated at €64–104bn per year and total quantifiable societal cost of ~€440bn by 2050.[4] These broader societal costs are not yet fully reflected in today's economic frameworks. Circular-economy regulation is moving in this direction but is still under development and has limited impact today: companies already applying circular approaches largely so do within framework conditions still designed for a linear economy.

Cradle to Cradle (C2C) places great emphasis on design. C2C has been a ground framework for the Circular Economy since the 1990ies*. It begins at design and adds two things recycling cannot: **material health** (not just the absence of known hazards) and **products built as material banks,** whose components are designed to return at full value. Recovery rates, repairability and recycled-content quality become design decisions, not downstream outcomes. Every material circulates as a nutrient — in the biological cycle, where it returns safely to nature; or in the technical cycle, where it is recovered and reused at high quality. There is no waste, only materials in the wrong place. A product's purpose is set at the design stage, determining which cycle each component belongs to, which materials are healthy, and how much value can later be recovered through circular business models. C2C products are manufactured with renewable energy, while maintaining or improving the quality of water and soil and applying fair and humane working conditions.

For electronic consumer goods, resilience pressures are particularly visible. The sector — spanning domestic appliances and consumer electronics — accounts for a €250bn EU market** and for around 12–13Mt of material placed on the EU market each year***.

Exposure to material and component supply risks is particularly relevant for segments that are still manufactured in Europe, notably domestic appliances: ~75% of large appliances sold in Europe are manufactured domestically;[5] for consumer electronics it is the minority. Recent disruptions — from China's rare-earth export controls and the Nexperia semiconductor crisis to rising memory-chip prices — have demonstrated how quickly external dependencies can translate into higher costs and supply constraints. In parallel, energy and defense sectors are competing for the same critical materials, while EU regulatory requirements are tightening across the value chain.

Across German industry circularity can help address resilience challenges and turn them into economic upside. The BDI/BCG study "Growth, Competitiveness, and Resilience: Opportunities of the Circular Economy for German Industry" finds that significant circular value pools can be unlocked within today's industrial structures. Under an implementation-oriented pathway, **Germany could reduce its dependence on raw-material imports by 10–20%** while more than doubling annual **circular gross value added from around €60bn today to up to €125bn by 2045.** This potential stems from scaling circular business models across the value chain, including reuse, refurbishment and remanufacturing, and stronger recycling loops. Unlocking this value does not require large-scale investments; the study estimates that ~€20bn across Mobility, Mechanical Engineering, Construction, Energy and Textiles is required — with payback achieved within only a few years.[6]

Building on this foundation, this paper quantifies the C2C-specific upside in electronic consumer goods to support communication of business cases to decision-makers across organizations.

Three strategic imperatives make the case for prioritizing circularity and C2C:

1. Raw-material and component import exposure puts the electronics industry under pressure.
2. Substantial value remains locked in the installed base and is lost at end of use. Resilience is built, not recovered — design for disassembly and recycling, and technical-cycle recovery keep strategic materials in Europe.
3. EU regulation is increasingly repositioning circularity from a sustainability lever to a market-access requirement. Recycled-content targets, repairability and durability rules, the Digital Product Passport (DPP) and eco-modulated producer fees (WEEE directive) shift decisive requirements into the design phase.

* The NEXT Industrial Revolution by William McDonough & Michael Braungart; The Atlantic Monthly, Oktober 1998, Vol. 282, No. 4, S. 82–92
** Based on BCG market models for Consumer Electronics and home appliances
***Break-down based on total EEE put on the EU market (14.5Mt in 2023, see Eurostat WEEE statistics)

2. WHY circularity matters now even more for electronic consumer goods

2.1 Exposure to raw-material and component imports puts the electronics industry under pressure

The EU electronics industry has substantial exposure to critical materials.* **~1.6Mt are embedded in electronic products placed on the EU market each year.** This primarily includes aluminum and copper, as well as rare earth elements, nickel, lithium, cobalt, graphite, and platinum group metals (PGMs). Gold and silver are also considered in this report. Although they are not classified as strategic or critical under the CRMA (Critical Raw Materials Act), their high value and significant price volatility still pose substantial cost risks for manufacturing companies.[7,8]

Critical materials and components are sourced mainly from outside the EU, with China as a dominant supplier. In 2024, ~46% of EU rare-earth imports came from China by weight. When narrowing the lens to the heavy rare-earth elements specifically used in the permanent magnets that drive motors, EU import dependency on China is ~100%, as China refines virtually the entire global supply.[8]

This material-level chokepoint cascades directly into the component layer. Around 94% of NdFeB magnets are produced in China, 5% in Japan and only 1% in the EU. Nearly 80% of suppliers to the EU semiconductor value chain sit outside the EU**. The EU imports 64% of its semiconductor chip needs — 99% for DRAM memory, thereof 46–58% from Taiwan alone.[9]

A December 2025 EU Chamber of Commerce survey of 131 European companies found that many affected firms expect supply chain impact[10]:

- 75% reported that export-license approvals have added more than one, 40% more than two months to delivery times
- 38% expected significant supply chain disruptions or production stoppages if controls are fully implemented
- One in three was already moving to divert sourcing away from China

In Germany ~70% of electronics companies rely primarily on China, with copper, rare earths, nickel, and lithium as the most-needed inputs.[11]

High reliance on imported critical materials leaves Europe's electronics exposed

European Union

Materials	Relevant products and components	Material consumption (in kt)[2]	Economic importance[1]	Supply risk[1]	Import reliance[4]	Main EU sourcing countries[6]
Bauxite (aluminum)	Chassis, heat sinks, cabling in fridges, ovens, microwaves	880 — 920	5.8	1.2	89%	Guinea (62%), Brazil (12%), Greece (10%)
Copper	Motor windings, wiring, PCBs[4] in washing machines, dishwashers	620 — 640	4.0	0.1	48%	Poland (19%), Chile (14%), Peru (10%)
Rare earths elements	Permanent magnets, e.g. in washing machines, headphones and speakers	2.5 — 3.0	Light REE: 5.9 Heavy REE: 4.2	Light REE: 3.7 Heavy REE: 5.1	100%	China (85%-100%)[5], Malaysia (Light REE, 11%)
Nickel	Heating elements in ovens & kettles; batteries in cordless appliances	12 — 15	5.7	0.5	75%	China (33%), Indonesia (12%), Japan (9%)[5]
Lithium	Li-ion batteries in smartphones, laptops or cordless appliances like vacuum cleaners or power tools	7 — 10	3.9	1.9	100%	Chile (79%), Switzerland (7%), Argentina (6%)
Cobalt		6 — 7	6.8	2.8	81%	Congo, D.R. (63%), Russia (7%), Canada (4%)[5]
Graphite		3 — 6	3.4	1.8	99%	China (40%), Brazil (13%), Mozambique (12%)
PGM	PCB[3] contacts in smartphones, laptops; magnetic layers in hard-disk drives	0.05 — 0.1	7.1	2.7	100%	South Africa (94%) Russia (Palladium, 40%)[5]
Gold	PCB[3] plating & bonding wires in smart-phones, laptops, smart appliances	0.03 — 0.06	2.4	0.4	88%	China (10%), Russia (10%), Australia (10%)[5]
Silver	Contacts and relays e.g., in ovens; PCBs[3] in smartphones and laptops	1.2 — 1.5	4.6	0.8	69%	Mexico (24%), Peru (12%), China (10%)[5]
	~11% of electrical and electronic equipment put on the EU market	∑ ~1,600				

1. Raw material assessment in accordance with the EU CRMA: 70 raw materials assessed, 34 classified as critical 2. EU-27, for electronic consumer goods: Total consumption derived from material specific associations (IFRI, ICA, WGC, Johnson Matthey, Cobalt Institute, etc.) as well as Eurostat and JRC RMIS; breakdown derived from JRC 'Digital'/'ICTsector' technologies as well as material specific industry associations 3. Printed Circuit Boards 4. (Import — Export) / (Domestic production + Import — Export), shows processing stage for REE, nickel, lithium, PGM and extraction for rest 5. Shows main global producers (2024/2025) as data on EU sourcing countries not available 6. As reported in 2023 (EU study on critical raw materials) | Source: EU-CRMA; EU study on critical raw materials; Eurostat; WGC; Silver institute; BCG analysis

No risk /Low — High; Not critical[1]; Critical/strategic[1]

* Includes Electrical and Electronic Equipment (EEE) as of EU definition. Across the report and for better readability, "critical" includes all strategic and critical materials according to the EU CRMA list plus gold and silver. Calculation as described in Figure 1. ** In 2023 the EU imported 20.8 kt of RE magnets (92% from China) based on German Mineral Resource Agency (2025): NdFeB permanent magnets — raw materials and recycling

Deep Dive: How critical materials affect electronics manufacturers

Memory chip prices double in one year
Apple CEO Tim Cook warned on the company's fiscal Q2 2026 earnings call that it expects significantly higher memory costs in the current quarter, with memory driving an increasing impact on the business going forward. The warning comes amid a global memory shortage driven by surging AI demand. A JPMorgan analysis cited by the Financial Times estimates memory could account for as much as 45% of an iPhone's component costs by 2027, up from around 10% today (CNBC, Apple Q2 earnings call, Financial Times).

The silent margin squeeze: rare earths and silver
China cut rare-earth permanent magnet exports by 74% year-on-year in May 2025 after Beijing tightened controls on seven critical elements used in electronics and EV motors. Silver hit an all-time high of $121/oz on 29 January 2026 (intraday spot price), roughly four times its level a year earlier, among others driven by industrial demand from AI infrastructure and solar. Together, such shocks can squeeze margins, delay product launches and potentially render some devices too unprofitable to make (IEA, CNBC, S&P Global).

The AI data-center boom is crowding out consumer electronics. Bloomberg Intelligence estimates that data centers accounted for around 50% of global DRAM consumption in 2025, up from 32% five years earlier, with AI servers projected to account for more than 60% by 2030. As suppliers allocate more capacity to HBM, server DRAM and enterprise storage, availability for consumer applications has tightened and prices have risen (Bloomberg, IDC, CNBC).

Shortages cause production stops
When the Dutch government intervened in Nexperia, a Netherlands-based chipmaker owned by Mainland China's Wingtech, China restricted exports of Nexperia products from its China operations in 2025 and cheap legacy chips became production-stoppers across end industries. This disrupted supplies of basic but essential discrete components, where Nexperia has significant global share, and European automotive OEMs and suppliers confirmed disruption at their sites (Reuters, Financial Times).

Single-market concentration extends beyond Mainland China. Taiwan accounted for ~92% of the world's most advanced logic chip capacity in 2021, with TSMC alone holding ~70% of the global foundry market in 2025 — manufacturing the application processors in every iPhone, the GPUs powering AI servers and most premium Android processors. Bloomberg Economics estimated that a potential military conflict over the Taiwan Strait could cost the global economy around $10tn — with the single largest hit coming from lost access to Taiwan's advanced semiconductors (high end chips). Even short-term disturbances illustrate the exposure: Two earthquake in 2024 and 2025 briefly paused production at TSMC and Micron plants, with related wafer losses of ~$92mn in 2024 and a further ~$162mn in Q1 2025 (Foreign Policy, Taipei Times / TrendForce, Bloomberg Economics, CNN).

2.2 A significant share of value is locked in end-of-use products and installed base and remains largely uncaptured today

Europe generated 13Mt of e-waste in 2022. Volumes are expected to further grow to 16Mt by 2050. Yet only around 43% is formally collected — still below the 65% EU target. While steel, plastics and other non-critical materials make up >90% of volume, **75% of the value in e-waste comes from critical materials.**[12]

Low formal collection reflects several concurrent leakages: An estimated 13% of WEEE generated is collected through scrap-metal channels in Europe, where recovery often focuses on bulk metals while critical materials are lost. A further 8% enters residual waste, and around 5% is illegally exported. Beyond these leakage flows, substantial volumes remain stored in households: of the 74 electrical items owned by the average household, 13 were being hoarded (nine unused but functional and four broken).[12, 13]

Large household appliances — washing machines, ovens, dishwashers, refrigerators and freezers — account for >40% of e-waste by mass, making them the largest category by weight. They are among the better-collected e-streams, as their bulk discourages hoarding and the WEEE Directive sets its highest recovery targets here (85% recovery, 80% prepare for reuse and recycling). Yet a significant share, particularly metal-rich appliances, is diverted into informal scrap-metal channels where steel is recovered but refrigerants, plastics and critical materials are lost.[12–14]

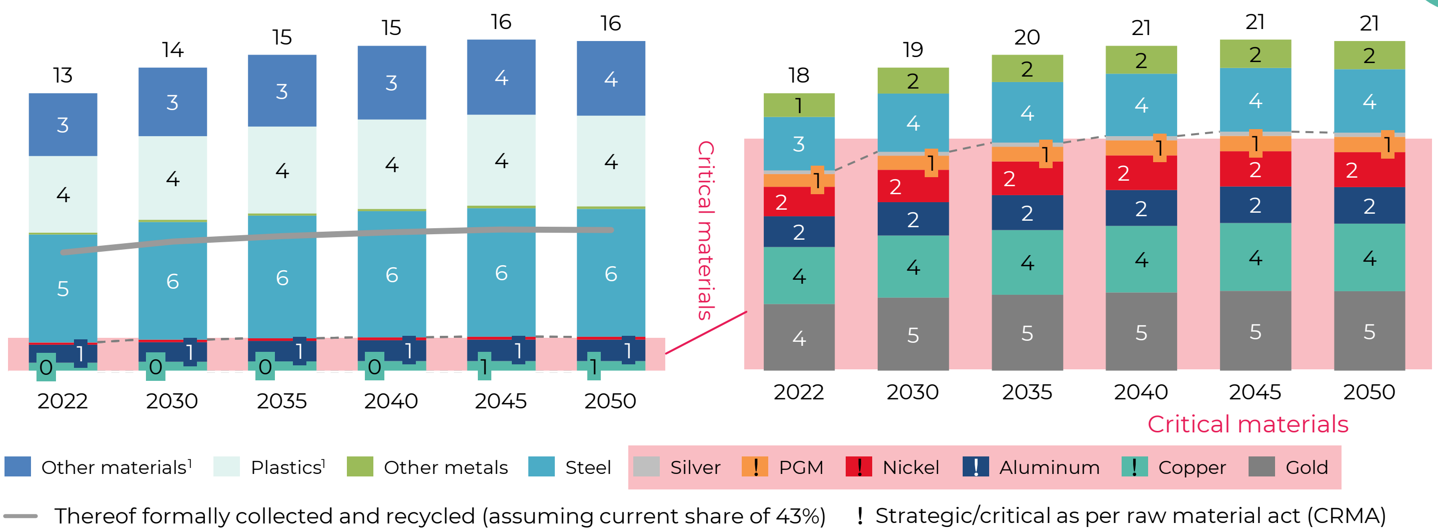
Household appliances and consumer electronics lock in >€65bn of critical material value across the EU.* Almost all of this value sits in the installed base still in use today. As a net-importer, annual end-of-use flows (~ €9bn material value) exceed the value needed for new production (~ €6bn material value) — largely because much of Europe's consumer electronics is manufactured outside the EU.

* Analysis based on bills of material and lifetime data for washing machines, vacuum cleaners and smartphones as three example products representing MDA, SDA and CE. Material flows were extrapolated to the respective product group via scaling factors (accounting for production location and material distribution) and aggregated to the total electronic consumer goods view.

Critical materials make up to 10% of European e-waste volume but account for ~75% of material value

Europe (geographical)

E-waste generated volume (Europe, in Mt) | **E-waste generated value (Europe, in bn €)**



1. Value for plastics and other material assumed to be negligible due to current uncertain recovery economics
Source: Global E-waste monitor; BCG E-Waste model; BCG analysis

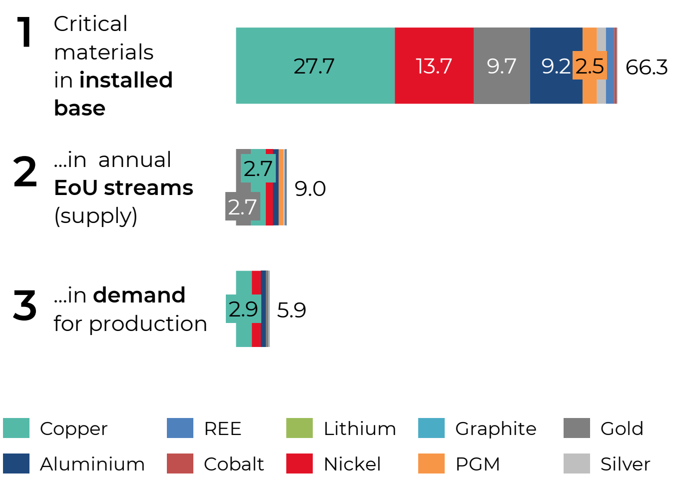
White goods represent a particularly strong resilience opportunity: Washing machines alone hold €6.0bn in critical material value, primarily copper and aluminum. As most large appliances sold in the EU are also manufactured in Europe, closing these material loops could directly strengthen the region’s industrial resilience. Washing machines reaching end of use each year contain around €0.5bn in critical materials — equivalent to roughly 70% of the €0.7bn required for annual EU production.

Every reused component, percentage point of material efficiency or recycled-content uptake translates straight into reduced import dependency for the European manufacturing base. With lifespans of 10–20 years, today's design choices determine the secondary raw material stream of the late 2030s. The logic inverts for consumer electronics and small appliances: EU production is minimal (smartphones <1%, vacuums <20%), but the installed base and end-of-use streams remain in Europe — opening up the circular spectrum from repair and refurbishment to recycling, which can capture material value in Europe.

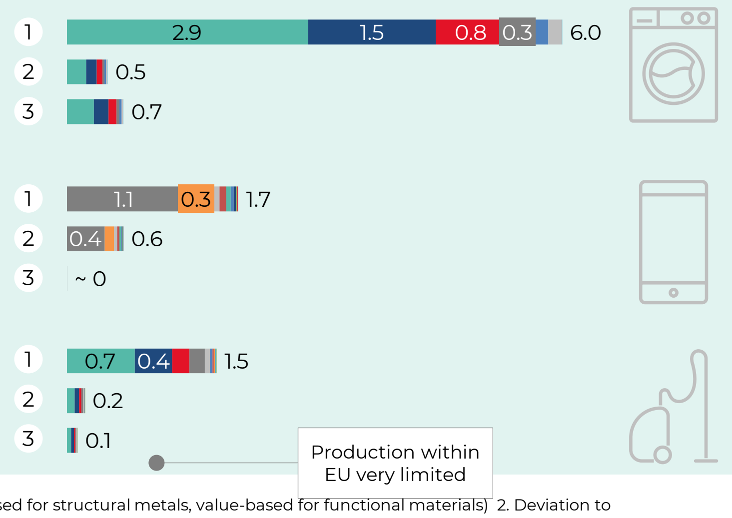
Critical material value is concentrated in EU’s electronics and appliance stock

European Union

> 65bn € material value sits within in-use product stock
Critical materials in electronic consumer goods[1] (EU-27, value in bn €)



White goods account for a large share of embedded value
Critical materials in specific products (EU-27, value in bn €)



1. Example products were extrapolated to MDA, SDA and CE via scaling factors (mass-based for structural metals, value-based for functional materials) 2. Deviation to WEEE statistics comes from scope of products
Source: APPLIA Statistical Report 2023–2024 (MDA), Counterpoint Research / Marketdataforecast 2024 (CE), GfK (SDA); BCG analysis

Going C2C — electronic products as material banks. A material bank treats in-use stock as a store of value: products whose components are designed from healthy, separable materials to be recovered at full material quality, so critical materials re-enter the technical cycle rather than being lost. The concept is often assumed to apply to long-lived goods such as buildings, yet it also holds for electronics. Value is concentrated in small, critical-material-rich components (magnets, batteries, circuit boards), making even a compact, short-lived device a high-grade deposit. Defined replacement cycles return materials in predictable, recurring flows. And the recovery infrastructure — WEEE collection, EPR, the DPP — is being built specifically for these products. What makes a material bank work is design for recovery, not how long any one device lasts.

C2C business model responses can unlock this value and build resilience — through design that enables material effectiveness, disassembly and repairability, use over ownership, material compatibility and recovery in the technical cycle.

2.3 EU regulation is increasingly repositioning circularity into a market access requirement

Upcoming EU regulatory changes are expected to affect the industry over the coming years, and no product group sits more squarely at their intersection than electronic consumer goods.

As planned regulation extends across the entire value chain, decisions taken in the next 18 months can define competitive positioning for the remainder of the decade. Crucially, many of the requirements arising in the source, use and end-of-use phases ultimately feed back into product design.

SOURCE: Secondary materials become a regulated input. The EU targets sourcing 25% of its annual strategic-raw-material consumption from recycling by 2030 (CRMA). Batteries are required to meet recycled-content minimums for cobalt, lithium and nickel (EU Batteries Regulation). A universal PFAS restriction would affect fluorinated materials used in seals, membranes and filter media (REACH).[15–17]

DESIGN: Products are required to be designed and built differently. Repairability, durability and modularity become binding design requirements for electronics from 2028–2029 onwards, with the DPP as the core transparency requirement (ESPR).[18]

USE: Products are required to remain repairable throughout their lifetime. Manufacturers are required to offer repair at a reasonable price, supply spare parts and information, and lift contractual or technical barriers to independent repair — extending obligations beyond the warranty period for up to 10 years for some categories.[19] In parallel, batteries placed on the EU market needs to carry a battery passport from February 2027.[16]

END-OF-USE: Manufacturers become responsible for he product after sale. OEMs carry financial and operational responsibility for collection, recycling and end-of-use treatment of their products — with eco-modulated fees that reward circular design. Member States need to meet a 65% collection target and category-specific recycling targets (WEEE Directive).[14]

MARKET ECONOMICS: Demand and cost signals tilt towards circular. On the demand side, French public institutions are required to source a minimum share of annual procurement spend from refurbished/reused and recycled-content products, covering IT equipment and large household appliances[20]. EU-wide product-specific procurement criteria are expected to follow via ESPR delegated acts. On the cost side, EU off-takers of steel, aluminum and other carbon-intensive inputs are required to pay for embedded carbon (CBAM) — contributing to a more level playing field for recycled material. The CEA (Circular Economy Act) is expected to further tighten market-access requirements by translating circularity principles into binding economic and procurement incentives across industrial value chains.[21]

3. HOW the industry can capture value through Cradle to Cradle

Circularity is emerging as a mechanism for European electronic consumer goods players to address both material resilience and value creation. It is not a single intervention but a staged transition: from a linear, waste-generating model toward an economy in which products are designed from the outset to circulate continuously — components disassemble cleanly, materials remain healthy and traceable, and every part is recovered at full value as a technical or biological nutrient.

Resilience is turning tension into upside — but this is not a new idea. C2C principles and circular business models have been actively applied across industries for over three decades, which means we can now draw on real evidence: what works already and what does it take to make circular business models commercially viable.

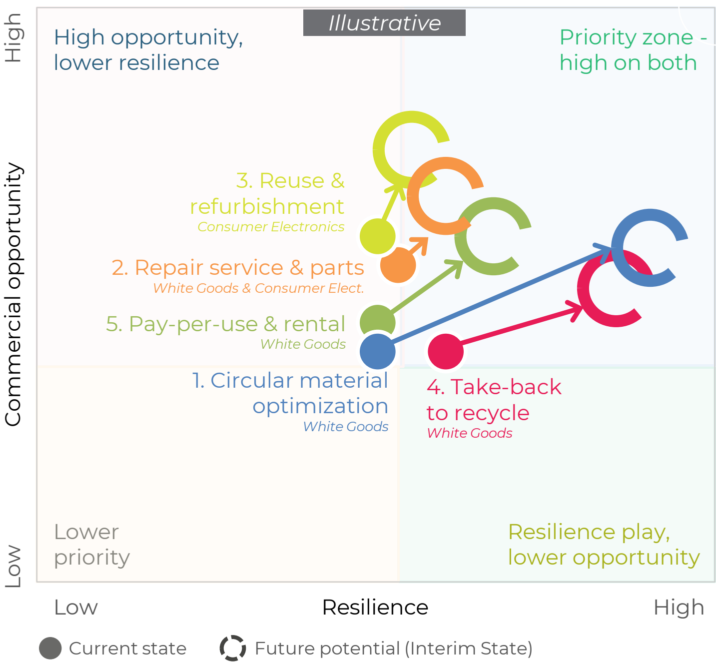
Five business model archetypes together define the resilience and commercial opportunity available to European players today. All five are grounded in purposeful design and are already applied, to very different degrees, by some industry players — what differs is how value is preserved and monetized across the lifecycle. Within each archetype, the application of a holistic C2C approach could potentially create additional opportunities for commercial upside and resilience in circular business models.

1. **Circular material optimization** reduces primary material demand before a product is built and cuts import exposure: through higher recycled content, leaner material use, and substitution of critical or hazardous inputs. But efficiency only compounds when the materials are fit for the product's purpose, healthy and circular, so that what is saved today is recoverable tomorrow.
2. **Repair service** keeps products in use longer by restoring functionality rather than replacing the device. Right-to-Repair legislation now mandates parts availability and independent repairer access, making repair an increasingly important commercial topic for manufacturers.
3. **Reuse and refurbishment** extend device life through collection, grading and resale, capturing value at the component and product level rather than the material level.
4. **Take-back to recycle** recovers embedded materials at end of use, closing the loop back into production inputs. For critical and metal-rich components, recycling is both a supply-security play today and a commercial opportunity as regulation and scale mature.
5. **Pay-per-use and product rental** convert a one-off sale into a recurring revenue stream by retaining ownership of the asset and charging for its use. The provider owns, maintains and recovers the product — keeping materials in a controlled loop and earning a multiple of the sale price over the asset's lifetime.

They are not equally mature. Repair service as well as reuse and refurbishment are gaining commercial viability across products. Take-back to recycle and circular material optimization are not yet standalone commercial across all use cases but already deliver a resilience contribution today. Pay-per-use models are suitable only for selected products but are well established in these niches.

The following sections quantify each archetype for the two product groups: washing machines (high domestic-production share, strategic material concentration, mandatory repair pool) and smartphones (limited EU production, but the most developed circular ecosystem in the sector). Across both, the DPP will act as a cross-cutting enabler that lifts the commercial viability of every archetype by making material composition, repair history and component traceability visible at scale.

Resilience and commercial advantage will grow alongside ongoing developments



Source: IBISWorld 2025; Eurostat WEEE 2023; EU CRMA 2024; Right to Repair Directive 2024/1799; BCG analysis

Findings

Current state: Business models are past pilot— the focus now is on market fit and commercials
- Reuse and refurbishment most scaled commercially for consumer electronics
- Take-back schemes exist but recovery is still low — only ~43% of European e-waste formally collected now
- Circular material optimization still nascent with limited margin visibility

Future potential: The five plays expected to develop along different paths, supported by regulation
- Circular material optimization & recycling are resilience plays, strengthened by current market developments
- Regulation aims to enhance commercial viability for repair and refurbishment business models
- Service models, already established for selected products, may expand to other categories

Methodology

Commercial opportunity — valuation based on:
- Current state: Market size and margin achieved
- Future potential: Incremental addressable market, margin expansion potential

Resilience — valuation based on:
- Current state: Share of European production, volume of critical raw materials reduced/replaced
- Future Potential: Additional critical raw material volume reduced/replaced (as % of lifetime revenue)

Washing machines: 5 circular plays with resilience and commercial potential — additional opportunity through C2C

What a washing machine consists of (kg per washing machine, illustrative)

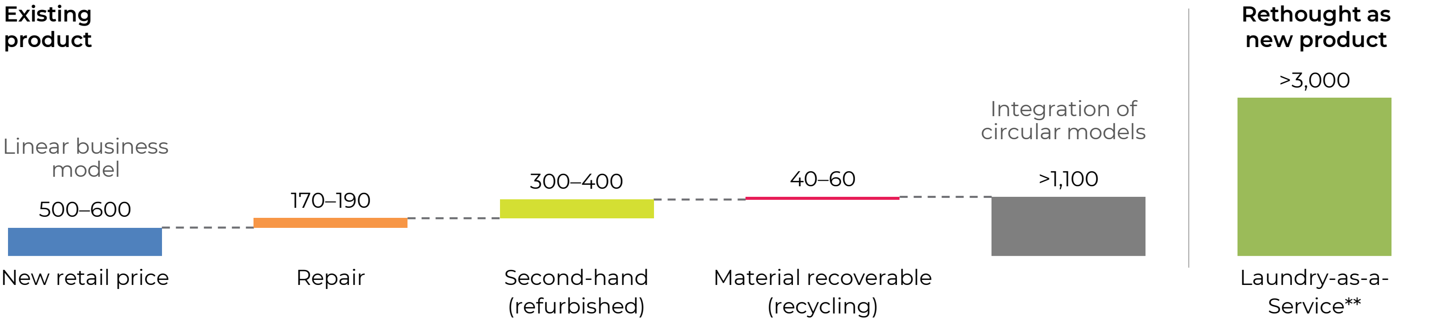
! 4kg (6%) and 30–35 € (>30%) of **critical materials** ● ~50% of material in established metals recycling streams

Drum & lye container		21.5	(32%)
Stainless steel (incl. Nickel)	●	18.0	(27%)
PP (tub & internal housing)		2.0	(3%)
EPDM (cuff, seals)		1.5	(2%)
Door		4.3	(6%)
Glass (window)		1.9	(3%)
ABS (front panel, door frame)		1.7	(3%)
Aluminum (bezel)	!	0.7	(1%)
Counterweight		26.3	(39%)
Concrete		20.2	(30%)
Glass fiber filler		6.1	(9%)
Housing, structural comp.		7.8	(12%)
Steel (sheet)	●	5.4	(8%)
Steel (other)	●	0.9	(1%)
Aluminum (dispenser, brackets)	!	1.1	(2%)
Plastic components (POM, Talc, PMMA, PA, PET, PE, PUR)		0.4	(<1%)

Electronics		1.2	(2%)
Copper (harness, bus bars)	!	0.6	(0.8%)
PVC insulation		0.2	(0.3%)
Sensors electronics		0.4	(0.6%)
Main control board (PCB incl. IC chips, motor inverter)	!	0.1	(0.1%)
Motor & Drive		5.0	(8%)
Electrical steel (laminations)	●	2.0	(3.0%)
Steel (rotor body, bearings)	●	1.0	(1.5%)
Copper (windings)	!	0.9	(1.3%)
Aluminum (motor housing)	!	0.5	(0.7%)
NdFeB Permanent magnet	!	<0.1	(0.1%)
Graphite (Carbon brushes)	!	<0.1	(0.1%)
Pumps, heating, other		1.3	(2%)
PA-GF (housing)		0.5	(0.7%)
Copper (pump motors)	!	0.1	(0.1%)
NdFeB micro magnets	!	<0.1	(0.0%)
PP-GF (detergent dosing pump)	!	0.1	(0.1%)
Stainless steel (heating element)	●	0.4	(0.6%)
Ni-Cr wire (heating element)	!	0.1	(0.1%)

Note: AI-generated picture, Illustrative material composition of a representative front-loading washing machine | Sources: JRC EUR 28042; BCG project experience; CRMA; BCG analysis

Over its use phase, a washing machine can generate revenue for multiple market participants beyond the initial sale (€ per washing machine, illustrative)



	Commercial opportunity:	Resilience:
Circular material optimization: Potential for more material efficiency and recycled content	Lightweighting savings (~18€*) offset by higher recycled material and implementation costs	Reduction of primary material use per machine by up to -50%, thereof 1–2kg critical material
Repair service & parts: Established and increasingly mandatory	Incremental market opportunity of ~€1bn by 2030 (to ~€3bn, ~5% CAGR)	Can decrease embedded material value as a share of lifetime revenue by ~5–10pp (~25-30% in a one-off sale)
Reuse & refurbishment: Small in itself but a lever for other business models	Small, but growing second-hand market; margins thin (price is -30–60% vs. new price)	Can decrease embedded material value as a share of lifetime revenue by ~5–10pp (~25-30% in a one-off sale)
Take-back to recycle: Secures critical materials but loses a machine's component value	~15% gross margins for metals recycling	Value of embedded critical raw materials (4kg) represents 6–11% of a machine's manufacturing cost
Pay-per-use and rental: Niche market with high margin potential	Margin per machine >15pp above one-off sale	Embedded material value as a share of lifetime revenue ~4× lower than in one-off sale

*Subject to material-price, quality and sourcing assumptions **In a sharing concept in communal or managed housing | The figures above reflect today's established circular economy practice in the sector. The C2C core is the same across all five plays: materials chosen for the machine's purpose, healthy and circular by design; applying it can add further resilience and commercial upside per play. Figures reflect BCG model estimates.

Circular material optimization: Potential for more material efficiency and recycled content

Material optimization starts at the design stage, before a machine is built. More recycled content, less material, and substituting heavy or critical materials for lighter ones are cutting primary material demand, embodied CO_2 and CRM supply risk.

Several solutions are already proven at scale, including high-efficiency BLDC motors, thinner steel gauges, and integrated PCBs. As recycled-material supply scales and virgin CRM costs rise, regulatory tailwinds such as CRMA and ESPR are expected to strengthen incentives for resource efficiency and recycled content as product-specific requirements are developed.

This is an important interim step towards full Cradle to Cradle design or redesign, where products are made from healthy materials, designed for circularity, and produced with broader environmental and social responsibility in mind.

Opportunities through C2C design

Moving from less and lighter material to appropriate, effective, healthy, and circular materials converts today's efficiency gains into recoverable value over time. This enables the loops on which the other plays depend, particularly for high-quality materials with strong value-retention potential.

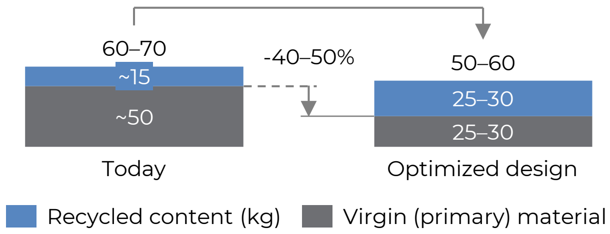
At the sector level, this effect compounds: the more products are designed from the outset with C2C-appropriate materials, the more cleanly sorted these materials enter recycling streams, lifting the quality of the recycled content available to the whole market over time. This makes C2C design a particularly strong lever here.

Key potential

Commercial opportunity: Material cost savings from lightweighting (up to €18*), balanced against higher recycled content, design, and production costs

Resilience: Avoids primary material demand use per machine by up to -50%, thereof 1–2kg critical material

Material input (illustrative, kg)



*Subject to material price, quality and sourcing assumptions | Sources: JRC EUR 28042; World Bank; LME; LBMA; BCG project experience; BCG analysis

Repair service & parts: Established and increasingly mandatory

Today the European home appliance repair market (~€1.5–2.0bn including spare parts and service) is served primarily by OEM service organizations, independent field-service providers and warranty administrators.[5] Demand is structural: 77% of EU consumers would rather repair than replace.[22] Customers directly benefit, and repairability is increasingly reflected in product tests. 66% of specialized German retailers surveyed say repairability is a key purchase criterion for customers, and 58% report frustration when an older device turns out unrepairable.[36] This prompts some OEMs to accept higher design costs to improve repairability.

Yet repair is often blocked by economics: once a repair reaches approximately a third of a new appliance's price, consumers typically replace. [23] ** 67% of retailers cite spare-part costs as the most important obstacle by far. Electronics components are one key factor: dealers estimate they cause over a quarter of out-of-warranty white-goods failures, yet 39% of repair shops cannot fix these components in-house and must order replacements. The barrier can be overcome with refurbished spare parts: components are worth far more than their embedded material, especially the drum, motor/drive and electronics, so reusing refurbished parts improves repair economics while cutting the material footprint. In addition, many appliances cannot be repaired because of their design (62%).[36] Independent repairers handling ~80% of out-of-warranty large-appliance repairs, frequently also lack access to affordable spare parts or technical information and diagnostic software.[24] Regulation now seeks to address these barriers.

Existing Ecodesign rules mandate spare-parts availability for up to 10 years. The Right-to-Repair Directive adds an obligation to offer repairs beyond the warranty period, stronger repairability requirements, and improved access to repair information and diagnostic tools.[19]

Opportunities through C2C design

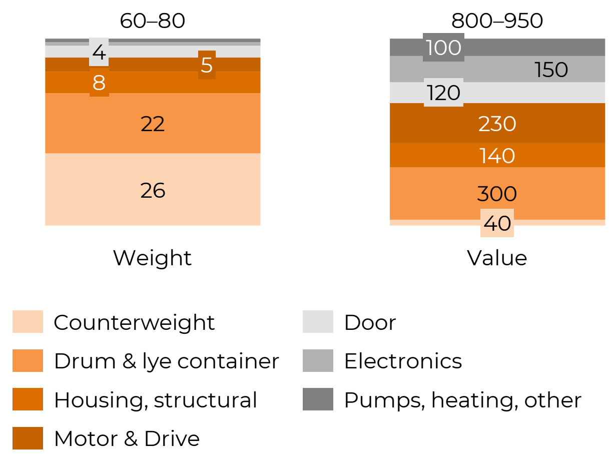
Designing for repair (modular, accessible, mono-material, healthy parts) lowers repair cost and time, moving more repair-vs-replace decisions toward repair and enlarging the viable repair pool.

Key potential

Commercial opportunity: Incremental market opportunity estimated to be ~€1bn by 2030 (to in total ~€3bn, ~5% CAGR)

Resilience: Can decrease embedded material value as a share of lifetime revenue by ~5–10pp (~25-30% in a one-off sale)

Input by component type (kg, €)



** Broader consumer preference survey, not washing machine specific
Source: JRC EUR 28042; published prices via marketplaces & online shops; BCG analysis

Reuse & refurbishment: Small in itself, but a lever for other business models

While ~60–70% of end-of-use machines may technically be reused or refurbished, only ~1–2% of collected machines are resold.[26] OEMs themselves still play only a marginal role, with second-life offerings largely limited to pilots or selected examples.* Today's refurbished supply is therefore mainly driven by platforms and retailers, which test, grade, and resell machines with an added warranty.

Three barriers hold the market back:

Reverse logistics: Scaling resale requires reliable access to sufficient volumes of good-grade machines after first use. But appliances are bulky (high transport cost), and EU waste law sets high hurdles for cross-border collection.** The lever is to control the return channel, e.g., via take-back on new machine delivery or retailer trade-ins.

Consumer trust: Customers remain concerned that used machines may fail sooner. The integration of refurbished machines in rental or pay-per-use models can overcome this barrier.*

Spare-parts cost: Once a repair or refurbishment costs approach ~one-third of the new machine price, replacement becomes the more attractive option.[23] Using refurbished/harvested components (e.g., electronic modules) as spare parts can break this cost equation.*

OEMs that make second life work do not treat refurbishment as a stand-alone resale activity. Instead, they embed it into business models (e.g., rental or repair) and improve the underlying economics.

Opportunities through C2C design

Designing for disassembly and repair — incl. removable, labelled parts, standardized fasteners, modular electronics — lowers refurbishment cost and time and makes component harvesting for spare parts viable.

Key potential

Commercial opportunity: Small but growing europ. second-hand market (€0.3–0.5bn); margins thin (price is -30–60% vs. new price)

Resilience: Can decrease embedded material value as a share of lifetime revenue by ~5–10pp (~25-30% in a one-off sale)

* Source: OEM websites: Electrolux R+vive remanufactured commercial washing machine, Bosch, Miele

** Waste Shipment Regulation: Unless exporters can prove that each unit is functional and destined for direct reuse, the shipment may be classified as WEEE—triggering unit-level testing and documentation and, in many cases, prior notification and consent.

Take-back to recycle: Secures critical materials but loses a machine's component value

A washing machine contains 4kg of critical material, yet much of the value is still lost: On the customer side, large appliances are collected reasonably well (also due to the extended producer responsibility in the WEEE directive). A material share of appliances enters mixed scrap or insufficiently documented treatment routes, limiting the recovery of high-value components and materials. Many products are not currently designed for efficient disassembly: welded or glued assemblies result in greater reliance on shredding. Hence, metals (steel, stainless, copper, aluminum) are downcycled to lower grades, plastics are largely incinerated and the motor's rare-earth magnets are effectively lost.

Closing the loop is therefore a design problem: designing for disassembly — removable, labelled magnets, snap-fit joints instead of welds and glue, and mono-material plastics. The long product lifetime compounds this: material designed for recovery today returns only after ~10–20 years, under conditions that cannot be reliably foreseen.

For the OEM, take-back (and partnering with a recycler) is therefore not a recycling-margin play but a supply-security one. Regulatory developments such as the CRMA and RESourceEU are strengthening the business case, e.g., by permanent-magnet recycled-content targets and planned restrictions on magnet-scrap exports alongside broader market and technology developments.[7]

Opportunities through C2C design

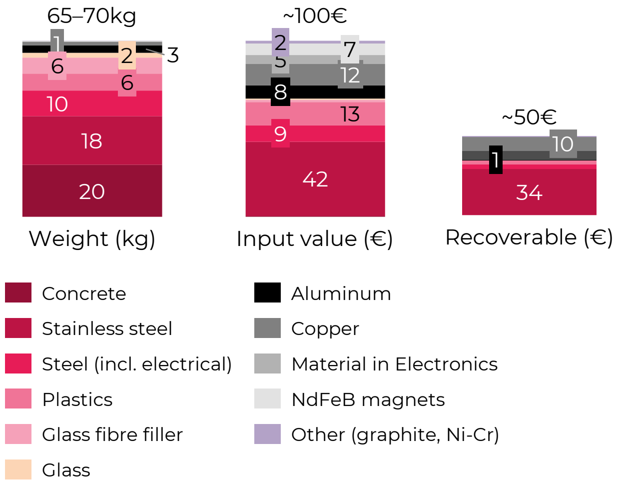
Done by design, take-back shifts from low-value metals recycling to high-value recovery of intact components and critical materials (drum, motor, magnets), kept in Europe.

Key potential

Commercial opportunity: ~15% gross margins for metals recycling*

Resilience: Value of embedded critical raw materials (4kg) represents 6–11% of a machine's manufacturing cost

Input by material (kg, €)



* Differs strongly by metal type

Source: JRC EUR 28042; CRMA; World Bank; LME; LBMA; BCG project experience; BCG analysis

Pay-per-use and rental: Scaling markets with high margin potential

Shifting life-stage and mobility patterns are reshaping ownership preferences. Pay-per-use and rental models target exactly this segment — mobile, urban, life-stage-transitioning households. Consumer use of such models typically takes place in communal or managed housing, where a single provider can operate multiple machines across dormitories or apartment buildings. Direct B2B is more established: commercial and managed laundry for hotels, hospitals and laundromats already runs on leased machines and service contracts.

In a pay-per-use or rental business model the OEM sells the service, not the machine — owning the fleet and handling installation, maintenance and billing. Because the provider keeps the asset, its incentives shift from maximizing turnover to improving durability, while each machine undergoes far more use cycles than it would in a one-off sale.

This converts a one-off sale into a recurring revenue stream over the asset's whole life: a durable, repairable machine earns a multiple of its sale price across its lifetime (~5 years, with refurbishment option). Proof points support the margin logic: industrial equipment services can achieve ~2x the gross margin of equipment sales.[28]

Opportunities through C2C design

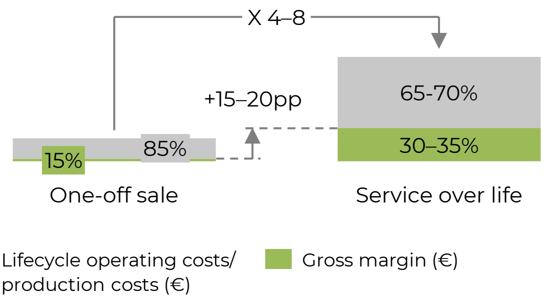
A machine designed for the service use case (modular, easy to refurbish, healthy and circular materials) withstands more maintenance and refurbishment cycles, extending revenue per asset and reducing the fleet's material throughput.

Key potential

Commercial opportunity: Margin per machine >15pp above one-off sale*; addressable European market 2030 ~ €1–2bn for shared housing and ~€2–3bn for B2B

Resilience: Embedded material value as a share of lifetime revenue is ~4× lower as a service than in a one-off sale

Margin structure of product sale vs. Pay-per-Use (€)



* Figures refer to professional washing machines, which are typically used for shared use cases. Operating costs account for lifecycle time, transport, installation, repair, energy, warranty

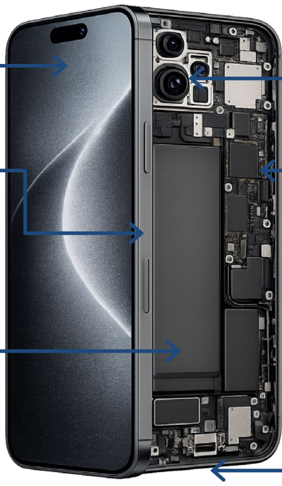
Source: EU ReCiPSS project; Electrolux Professional Group annual report; BCG analysis

Smartphones: Most value lies in keeping devices in use at high value rather than in recovering materials

What a smartphone consists of (g per phone, illustrative)

! 80g (40–45%) and 4–5€ (90–95%) of **critical materials**

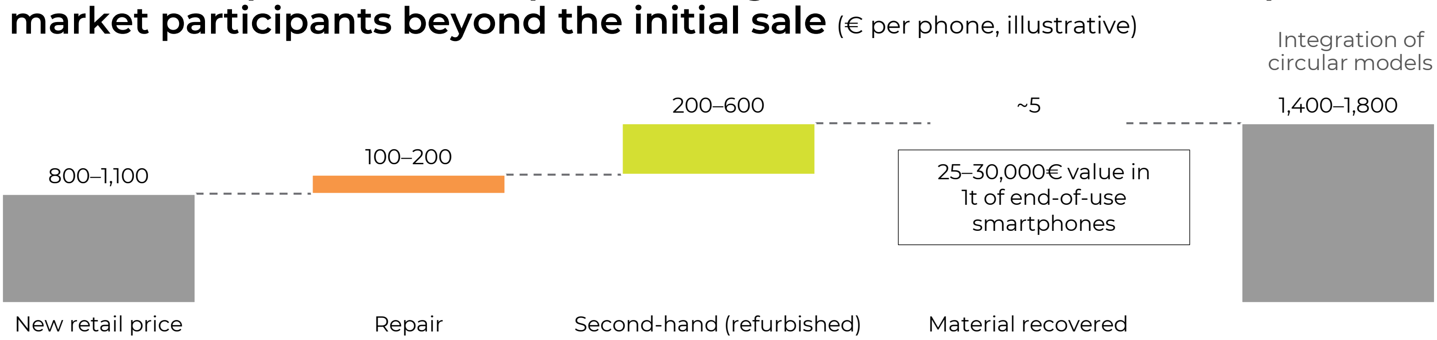
Display		45	(23%)
Glass (chemically strengthened)		32	(17%)
Indium	!	0.01	(<0.1%)
Optical films, adhesives, other		13	(7%)
Casing		45	(23%)
Aluminum	!	26	(14%)
Plastics		8	(4%)
Magnesium	!	4	(2%)
Iron		2	(1%)
Adhesives and other		5	(3%)
Battery		44	(23%)
Graphite	!	12	(6%)
Nickel	!	8.5	(4%)
Cobalt	!	2.5	(1%)
Lithium	!	2	(1%)
Manganese	!	1	(0.5%)
Copper foil	!	5	(3%)
Other		13	(7%)



Camera		10	(5%)
Aluminum (housing)	!	2	(1%)
Glass lenses		5	(3%)
Sensors and others		3	(1%)
PCB		32	(17%)
Copper	!	16	(8%)
Zinc		1.5	(1%)
Tin		1.8	(1%)
Silver, Gold, PGM	!	0.4	(0.2%)
Fiberglass		5	(3%)
Ceramics & silicon		7	(4%)
Speaker		5	(2%)
Bodies (plastic, steel)		4	(2%)
Tungsten	!	0.4	(0.2%)
Neodymium magnet	!	0.1	(<0.0%)
LED electronics and other		13	(6%)

Note: AI-generated picture | Sources: Bookhagen, B. et al. (2020); Singh, N. et al. (2020); Bruno, M. et al. (2022); Fairphone (2020); CRMA; BCG analysis

Over its use phase, a smartphone can generate revenue for multiple market participants beyond the initial sale (€ per phone, illustrative)



	Commercial opportunity:	**Resilience:**
Repair service & parts: Growing aftermarket profit pool driven by regulation	Incremental market opportunity of ~€2bn by 2030 (~5–7% CAGR)	Production in Europe very limited and embedded material value only 1% of retail price
Reuse & refurbishment: Proven & scaling, but gated by the supply of quality used devices	€8bn market size in 2028 (8% CAGR); attractive 15–20% gross margin (EBIT margin 2–8pp above retail)	Production in Europe very limited and embedded material value only 1% of retail price
Take-back to recycle: Strategic source of critical materials, but economics depend on higher collection rates and regulatory demand pull	Not a business case yet, but stored EU device stock contains a modelled material value of €3.5bn	~50k tons critical materials unused in EU's drawers[13] — can be part of material supply for other industries

The figures above reflect today's established circular economy practice in the sector. The C2C core is the same across all plays: materials chosen for the machine's purpose, healthy and circular by design; applying it can add further resilience and commercial upside per play. Figures reflect BCG model estimates.

Repair service & parts: Growing aftermarket profit pool driven by regulation

Smartphone repair is a high-frequency aftermarket touchpoint spanning OEM service networks, insurers, retailers, telecom operators, independent repair chains, and refurbishers. The largest categories remain screens, batteries, charging ports, cameras, and water damage. The market is already relatively mature, with European repair revenues (service and parts) estimated at ~€5.0–6.0bn today, split roughly evenly between parts and labor.

Today's volume is concentrated in years 1–3 of device life and flows through three channels — defect repairs under the 2-year guarantee, accidental-damage repairs funded by insurance and protection plans (largest part), and out-of-pocket out-of-warranty repairs.

Growth is expected to be steady rather than explosive, reaching ~€7–8bn by 2030 (5-7% CAGR). The primary driver is not new device volume but a shift in the repair-vs-replace decision in years 1–3, where residual value is highest. Right-to-Repair and the Ecodesign Regulation aim to accelerate this by opening parts access to independent repairers and — through guaranteed 7-year spare-parts availability, durable 800-cycle batteries, and 5-year OS update availability — raising the expected residual life.[19,20] Surveyed specialist retailers in Germany are divided on the impact on consumer behavior, although 53% see it as an opportunity for new business models.[36]

The most attractive profit pools are likely to remain in parts distribution and warranty programs, and customer ownership, while repair execution itself remains relatively competitive and labor-intensive.[25]

Opportunities through C2C design

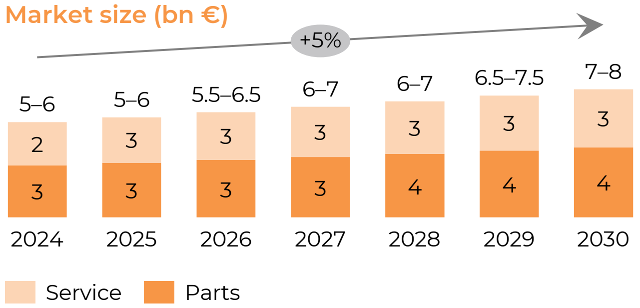
Designing phones for repair (modular, accessible, durable, healthy materials) raises the repairable share and residual life, growing the repair pool beyond what regulation requires

Key potential

Commercial opportunity: Incremental market opportunity of ~€2bn by 2030 (~5–7% CAGR)

Resilience: Production in Europe very limited and embedded material value only 1% of retail price

Market size (bn €)



Bottom-up calculation based on EU Impact Assessment Report supplementing Regulation 2017/13609, Repair Bonus in France and Statista Market Insights; validated with public market reports.

Reuse & refurbishment: Proven & scaling, but gated by the supply of quality used devices

Among circular business models, smartphone refurbishment is one of the most mature and scalable models. Demand is value-led but quality-sensitive: in a five-country European survey, 65% of consumers cite the price advantage vs. new devices as a purchase motive. Market acceptance is already tangible: ~18% of smartphones in use across Europe are second-hand. The ecosystem extends device lifetimes through collection, grading, refurbishment and resale, with consumers typically benefiting from 30–40% cost savings compared with new flagship devices.[31–32]

Devices are sourced through trade-in programs, buyback schemes, direct consumer purchases, bulk auctions and telecom operators, and are processed by marketplaces, refurbishers, retailers, telcos and OEMs. Access to high-quality, refurbishment-ready devices is the key value driver and increasingly the main scaling bottleneck, as supply remains constrained and difficult to predict. Value is created through grading, repairs, component harvesting and resale, while margins are supported by services such as warranties, financing and accessories.

Conditions: Access to refurbishment-ready devices (Grade A flagship iPhones) and supportive regulation, such as refurbished-device procurement targets in public purchasing.

Opportunities through C2C design

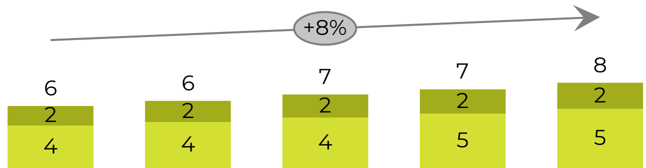
Designing for easy refurbishment and longer support (healthy, separable materials) increases the supply and grade of refurbishment-ready devices, easing the scaling bottleneck this play depends on.

Key potential

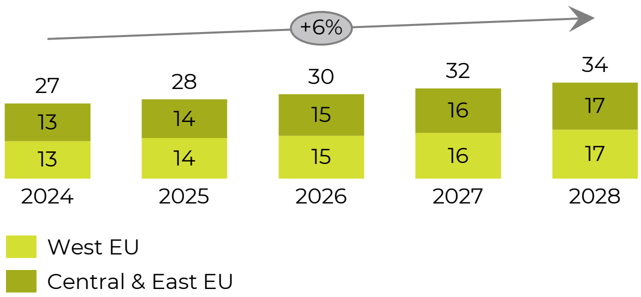
Commercial opportunity: €8bn market size in 2028 (8% CAGR); attractive 15–20% gross margin (EBIT margin 2–8pp above consumer electronics retail)

Resilience: Production in Europe very limited and embedded material value only 1% of retail price

Europe refurb device market size, by value (bn €)



Europe refurb device market size, by # of devices (mn)



Note: West Europe, incl. Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, UK; Central and East Europe, incl. Bulgaria, Croatia, Czech Republic, Hungary, Kazakhstan, Poland, Romania, Russia, Serbia, Slovakia, Ukraine | Source: IDC; CCS Insights; BCG analysis

Player type	Role	
Marketplace	Does not own refurbished devices but operates as a reselling platform	Back Market
Pure play	End-to-end operations covering sourcing, refurbishing, and sales	Swappie, recommerce
Refurbisher	Specializes in refurbishing; sells B2B only with no B2C retail sales	Foxway, Elite
Retail	Resells returns or refurb devices; some players have refurbishing arm	MedieMarkt, Fnac Darty
Telco	Trade-in combined with bundling to get consumers to contract/upgrade	Telefónica, vodafone
OEM	Refurbishes and resells devices from warranty or trade-in	Apple, Samsung

Take-back to recycle: Strategic source of critical materials, but economics depend on higher collection rates and regulatory demand pull

A ton of end-of-use smartphones holds ~€25–30k of embedded raw-material value at today's gold price, with gold making up ~70% of the value. This dwarfs every bulk recycling stream: copper scrap fetches ~€7–9k/t, aluminum ~€1–1.8k/t, steel only ~€300/t, and mixed plastics ~€0–200/t. On paper, phones are the single richest "urban-mining" stream in the waste system.

In practice, barely any of the value returns, for four reasons:

1. Collection is the binding constraint: the EU mobile-phone collection rate is under 5%, with ~700m devices hibernating in drawers.[13, 30]
2. Phones aren't designed to be recycled: glued and non-modular construction of 60+ closely-mixed elements make disassembly and material separation hard.
3. Recovery is selective: integrated smelting reclaims gold, silver, palladium and copper at >95%; rare earths (end-of-life recycling rate <1%) or lithium are oxidized into slag and lost.[34]
4. Per-device economics can be negative: glued, miniaturized assemblies force slow manual dismantling at €2–7/device.[35]

What's changing: New EU regulation is creating demand pull for recycled materials through CRMA and battery recovery targets, while design-for-recycling requirements and improved recycling technologies are making material recovery more feasible.[15, 16] Future economics will depend on achieving sufficient collection rates and access to end-of-life devices.

Opportunities through C2C design

Healthy, separable materials designed for the loop make high-value recovery feasible (including rare earths now lost to slag), turning the richest urban mine from a value-losing stream into a recoverable one.

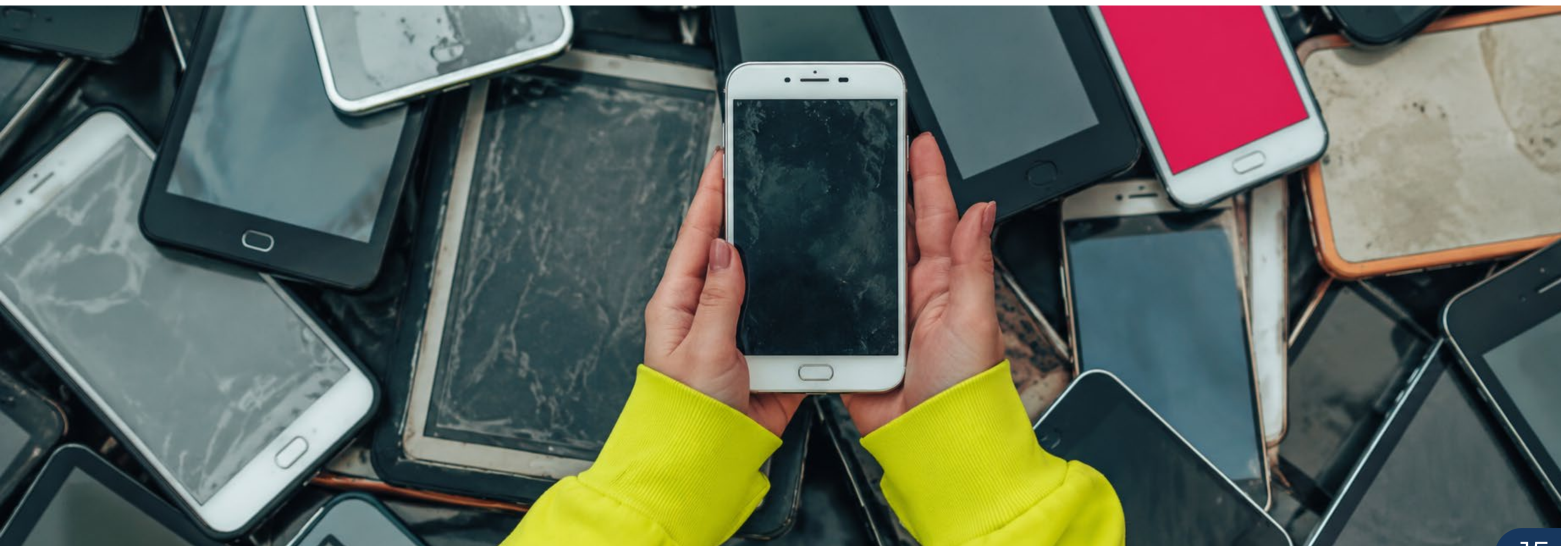
Key potential

- **Commercial opportunity:** Not a business case yet, but stored EU device stock contains a modelled material value of €3.5bn
- **Resilience: ~50k tons critical materials** unused in EU's drawers[13] — can be part of material supply for other industries

100x more gold in a ton of smartphones than in a ton of gold ore

15% of annual global gold production is effectively locked in unrecovered mobile-device waste

Sources: Bookhagen et al. (2020), S&P 2022 (recoverable gold content of US ores); Gomez et al (2023); USGS global report; UN e-waste monitor (2024); European Commission (2023)



4. WHAT the response can look like

Circular value follows different pathways by product. Material value is often concentrated in a small share of product weight, but design choices determine how much of it can be retained or recovered. In washing machines, several circular business models already offer meaningful resilience benefits. In smartphones, value lies primarily in extending product life rather than recovering materials. Chapter 3 has shown how current circular economy practices create value today, while C2C design provides additional opportunities to preserve the value of products, components and materials across successive cycles.

The commercial case and the regulatory timeline are converging: the design decisions taken by EU manufacturers now will determine cost position and compliance readiness for the rest of the decade. But the right starting point differs by company. Six questions map where the highest-return entry point lies:

Supply chain traceability: How far does material-origin visibility extend beyond tier-1 suppliers? For those with high critical-material exposure (Cu, Al, Ni, REE, Co, Li), knowing only the immediate supplier is insufficient — concentration risk sits at the refiner or mine level, often invisible from the purchasing desk. Mapping origin by material, country and supplier is the starting point to de-risk supply and de-average exposure across product lines.

Cost exposure: What share of COGS today is exposed to critical raw materials? Where exposure is high, optimizing material input and establishing recycling partnerships become priorities, directly reducing both cost volatility and import dependency — with material choice determining whether those savings remain recoverable in the next cycle.

Product design: How modular is the current product platform or portfolio, and are its materials healthy and fit for purpose? Modularity unlocks repair and refurbishment; healthy, separable materials ensure that value can be retained through these loops and recovered later. Low modularity or mixed and hazardous materials make redesign using C2C principles the essential first step toward most circular business models.

Channel maturity: Is there a direct customer relationship beyond the point of sale? If yes, pay-per-use and rental become viable, with the manufacturer retaining asset ownership and recovering the product at end of use.

End-of-Use infrastructure: Are products already taken back from customers today? If yes, take-back to refurbish, remanufacture and recycle would build on what is already in place.

Making circular models bankable: What combination of demand pull, including recycled-content targets, procurement, collection scale and C2C design turns them into a business case — and what evidence would investors and boards need to see? Some models, such as take-back for recycling and refurbishment, strengthen resilience but are not yet commercially viable across all materials, products or market participants.

Beyond company-specific moves, five cross-industry steps emerge from this study. They define where the Cradle to Cradle Electronics Initiative can create most value over the next three years — building on the workstreams already underway:

Shared design baseline: The sector still lacks common C2C design standards — positively defined healthy materials and design-for-disassembly requirements derived from each product's purpose. Without them, every manufacturer reinvents the same criteria independently.

Ecosystem orchestration: All five archetypes depend on closed value-chain loops that no single OEM can build alone. The initiative can map and de-average the partnerships that already work, define the use cases where new alliances are needed, and bring the right partners together.

Policy co-design: France has shown that targeted regulation (AGEC) can shift business models. Replicating this in Europe at scale would benefit from industry translating concrete business cases into the language of policymakers. This means engaging actively in the ESPR delegated acts, the CEA and EPR harmonization.

Digital Product Passport: Many companies remain uncertain about the DPP despite its substantial potential as a C2C enabler. The initiative can detail the concrete use cases — material composition transparency, repair history, residual-value pricing, second-life routing, eco-modulation evidence — and link them directly to C2C design.

Beyond consumer goods: Europe is especially strong in electronic components, machinery and industrial automotive applications. The same C2C logic applies — material exposure, regulatory pressure, lifetime-value capture — but the economics and operating models differ. A similar analysis for industrial electronics would extend the initiative's reach into the segments where Europe is most competitive today.

Total cost comparison: Cradle to Cradle vs. linear design

In electronic consumer goods, selected circular business models are already reaching commercial viability, and C2C design opens additional opportunities on top. In those cases where circular models still hit their economic limits today the regulatory environment needs to move faster and consistently implement the polluter-pays principle, creating a level playing field where circular solutions can become self-sustaining without subsidy. The full case emerges once broader societal costs are brought into the picture.

C2C design reduces exposure to hazardous materials for workers, consumers, and the environment — lowering the downstream costs that today fall on healthcare systems, remediation budgets, and ecosystems already under pressure. These externalized costs are not yet fully reflected in today's economic frameworks.

Glossary and Abbreviations

Term	Abbreviation	Definition
Biological cycle (biosphere)		In the biological cycle, the nutrients from biodegradable materials are returned to the Earth to regenerate nature. Products composed of biodegradable and non-biodegradable materials must be designed and manufactured in such a way that the different materials can be separated without residue and circulate within their respective spheres.
Carbon Border Adjustment Mechanism	CBAM	Complements the EU Emissions Trading System (EU ETS) by applying an equivalent framework to imports to prevent the risk of carbon leakage, thereby reducing global carbon emissions and supporting goals of the Paris Agreement.
Cradle to Cradle	C2C	Both a school of thought (humans as positive contributors, “beneficials”) and a design concept (products designed so all materials stay healthy and circulate continuously in biological and/or technical cycles). C2C products are manufactured with renewable energy, while maintaining or improving the quality of air, water, and soil and applying fair and humane working conditions
Circular Economy		System solution framework and economic model aimed at closing material, energy, and product loops to reduce the consumption of primary raw materials and the generation of waste. C2C sits within and beyond CE as its design-led, most ambitious form.
Circular Economy Act	CEA	Upcoming EU regulation (Commission proposal expected Q3/Q4 2026). Aims to create a single EU market for secondary raw materials, increase EU's circular material use rate, cut dependence on imported (critical) raw materials, and harmonize rules across member states. Framed as an industrial competitiveness tool and positioned as a pillar of the Clean Industrial Deal.
Critical Material	CRM	Raw materials of high economic importance for the EU, with a high risk of supply disruption due to the concentration of their sources and the lack of any good, affordable substitutes. In context of this study gold and silver are included as "critical" for better readability. They are not classified as strategic or critical under the CRMA, but their high value and significant price volatility still pose substantial cost risks for manufacturing companies.
Critical Raw Materials Act	CRMA	Aims to secure the EU's supply of raw materials critical to the green/digital transition and defense/aerospace. Lists 34 critical raw materials, of which 17 are "strategic" (highest priority).
Consumer Electronics	CE	Devices for entertainment and communication in a domestic/private setting, including smartphones, laptops, monitors, radios, televisions, amplifiers, cameras, wearables, headphones, printers, etc.
Digital Product Passport	DPP	Digital record attached to a specific product that contains structured information about that life cycle and material — accessible by scanning a data carrier. Established under the ESPR.
Electrical and electronic equipment	EEE	Equipment that is dependent on electric currents or electromagnetic fields to work properly, plus equipment for the generation, transfer, and measurement of such currents and fields.
End of Use	EoU	The point at which a product's or material's current use phase ends and it re-enters a biological or technical cycle for reuse, remanufacture, or recycling. Used instead of "End-of-Life" by C2C to signal that products and materials are designed for continued use rather than become waste.
Eco-effectiveness		Aims to first create a materially healthy and recyclable product with added value. This product can then always be made more efficient.

Glossary and Abbreviations

Term	Abbreviation	Definition
Electronic Consumer Goods		Includes Consumer Electronics as well as (small and major) home appliances in the context of this study.
Extended producer responsibility	EPR	Environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle
Ecodesign for Sustainable Products Regulation	ESPR	Regulation (EU) 2024/1781: Framework regulation for ecodesign requirements. Aims to improve the circularity, energy performance and other environmental sustainability aspects of products placed on the European Union market.
Major Domestic Appliances	MDA	Large, typically fixed or hard-to-move household appliances, including refrigerators/freezers, washing machines, dryers, dishwashers, cooking equipment, electric heating appliances, air conditioning equipment. Also referred as white goods
Neodymium-Iron-Boron magnets	NdFeB	Most widely used type of rare-earth magnet and the strongest commercially available permanent magnets, used e.g., in electric vehicle drivetrains, wind turbine generators, industrial robots, electric motors, heat pumps, and consumer electronics
Printed Circuit Board	PCB	Mechanically supports and electrically connects electronic components. Are found in nearly all electronic devices and a key WEEE waste stream containing recoverable critical raw materials (e.g., gold, copper, palladium).
Per- and polyfluoroalkyl substances	PFAS	Defined by the OECD (2021) as substances containing at least one fully fluorinated methyl or methylene carbon atom.
Platinum Group Metals	PGMs	Cluster of six closely related transition metals: Platinum, Palladium, Rhodium, Ruthenium, Iridium, Osmium. Used for catalytic converters, printed circuit boards (PCBs) and electronic contacts/connectors or chemical catalysts
REACH Regulation	REACH	Registration, Evaluation, Authorization and Restriction of Chemicals. Regulation (EC) 1907/2006: The EU's chemicals law, administered by ECHA.
Small Domestic Appliances	SDA	Smaller, portable household appliances, e.g., vacuum cleaners, irons, toasters, coffee machines, kitchen equipment (mixers, deep fryers, scales), clocks, alarm clocks, hair dryers, shavers, electric toothbrushes etc.
Technical Cycle (technosphere)		Materials such as metals or plastics circulate in the technosphere. They are available in limited quantities on earth and must therefore be maintained at a consistently high quality. In the technical cycle, products and materials are kept in circulation through processes such as reuse, repair, remanufacture and recycling.
Waste Electrical and Electronic Equipment	WEEE	EEE that ends up in waste streams, including all components, sub-assemblies, and consumables that are part of the product at the time of discarding. Governed by the EU WEEE Directive (2012/19/EU), which sets collection, treatment, and recycling requirements to reduce waste and recover raw materials from discarded electronics.

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